



Assessing the potential of strategic green roof implementation for green infrastructure: Insights from Sumida ward, Tokyo

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ABSTRACT

Urban green spaces, and green infrastructure more generally, provide multiple benefits that can enhance urban livability and sustainability. These range from the mitigation of air pollution and urban heat island (UHI) effect, to multi-dimensional benefits to human wellbeing and biodiversity. However, the expansion of urban green spaces is not always feasible in many cities. In such urban contexts, there have been proposals to utilize rooftops as green roofs in order to gain some of these benefits. This study spatially identifies areas where roofs have the potential to provide different types of benefits associated with urban green spaces if they are retrofitted with green roofs. Through a GIS-based approach we catalogue available roof space in Sumida ward in Tokyo for green roof implementation, and subsequently evaluate the potential of each roof patch to offer four types of benefits if retrofitted with a green roof, namely UHI effect mitigation, air pollution mitigation, and benefits to subjective wellbeing and biodiversity. Approximately 25% of the total roof surface in Sumida ward can potentially be used for green roof implementation. Furthermore, about 5.2% and 59% of this area has a respectively high and moderate potential to provide all four benefits if retrofitted with green roofs. This could increase the extent of green spaces by 10% and 120% respectively across the Sumida ward. In this sense, green roofs can become a major element of green infrastructure with ripple positive effects for urban livability and sustainability through the provision of UHI effect and air pollution mitigation, and benefits to subjective wellbeing and biodiversity.

1. Introduction

Urban activity has numerous negative environmental impacts at different scales. For example, cities are the largest source of anthropogenic greenhouse gas (GHG) emissions (IPCC, 2014). Furthermore, the built environment has a high proportion of impervious surfaces that significantly alter the energy exchange and hydrological cycles (Crawford et al., 2017; Gunawardena et al., 2017). Cities are also pollution hotspots through diverse sources such as industries, transport, and the built environment, among others (Grimmond, 2007; Kumar et al., 2016). Urban expansion and consumption patterns in cities are also major drivers of direct and indirect land use change at multiple scales, having negative effects for biodiversity and ecosystem services through habitat change, loss and fragmentation (IPBES, 2019; Ke et al., 2018,

Chen et al., 2020a; Lepczyk et al., 2017). At the same time the hectic urban lifestyle, dense infrastructure and buildings, and the lack of green spaces create a stressful environment for urban residents (Krefis et al., 2018; Pykett et al., 2020).

Thus cities should arguably be at the core of mitigation efforts against the adverse impacts of urbanization (Mi et al., 2019). However, at the same time improving urban livability and enhancing urban sustainability have become key policy and practice priorities in many parts of the developed and developing world (Alderton et al., 2018; Lowe et al., 2020).

Green infrastructure¹ is central in meeting such objectives through several ways (Ting, 2012; Li and Yeung, 2014). For example, numerous studies have pointed to the positive multi-dimensional impacts of urban green spaces on urban livability and sustainability. For example, the

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¹ For the purpose of this paper we define green infrastructure as “strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services” (European Commission, 2013).

ecosystem services provided by urban green spaces have been found to have a positive effect on multiple aspects of human wellbeing, ranging from physical health to subjective wellbeing (Bertram and Rehdanz, 2015; Larson et al., 2016; Wang et al., 2016). Related to the latter even a limited exposure to nature (and related ecosystem services), such as greenery views outside windows or the presence of plants within view, are positively correlated with subjective wellbeing improvements for the users of different building types (e.g. housing, offices, hospitals) (Aries et al., 2010; Li and Sullivan, 2016a). Furthermore, green spaces regulate urban microclimates, reducing, for example, temperatures and lowering both the potential for the Urban Heat Island (UHI) effect formation, as well as its intensity (Norton et al., 2015; Hiemstra et al., 2017). It is also well documented that urban vegetation and urban green areas can remove some types of air pollution such as NO₂, SO₂, CO, PM₁₀ and tropospheric ozone (Currie and Bass, 2008; Escobedo and Nowak, 2009; Xu et al., 2020).

However, in many cities green spaces are lost, fragmented and/or simply located too far from each other, often resulting in fragmented and ineffective green infrastructure. Furthermore, the quality of green spaces has been decreasing in some cities (Colding et al., 2020). This can both reduce the provision of ecosystem services by green spaces and their contribution to the wellbeing of urban residents (Wolch et al., 2014), as well as their ability to mitigate the UHI effect and air pollution, and maintain their biodiversity and ecological functions (Fahrig, 2003; Russo et al., 2017; Zambrano et al., 2019).

In many urban contexts it is difficult to increase the extent of conventional urban green spaces such as parks and urban forests for green infrastructure due to the locked-in infrastructure, and the lack and high prices of available space, among many other factors (Haaland and van der Bosch, 2015). As a result, there have been efforts to identify other approaches towards urban green infrastructure development to enhance urban livability and sustainability. Roofs are increasingly identified as a promising option to enhance the extent of urban green spaces and form elements of green infrastructure, as they account for between 20% and 30% of urban surface space, and are largely unused or underutilized (Akbari et al., 2009; Byrne et al., 2015; Liberalesso et al., 2020; Langemeyer et al., 2020).² In this context, retrofitting existing and empty roof spaces into green roofs could offer an attractive alternative to green space and green infrastructure provision, as they can serve as non-traditional urban green areas providing multiple sustainability benefits (Milanovic et al., 2018; Cascone et al., 2018; Langemeyer et al., 2020; Calheiros and Stefanakis, 2021; Venter et al., 2021).

Green roofs are generally divided into three categories, namely extensive, semi-intensive, and intensive. Extensive green roofs have shallow substrates (usually <15 cm), are lightweight, have low maintenance needs, are relatively cheap, and can be easily retrofitted onto existing buildings (Shafique et al., 2018). Extensive roofs use most commonly plants from the Sedum genus due to their resilience to drought, ability to survive in harsh environments, and virtually negligible maintenance needs (Morokinyo et al., 2017). Semi-intensive green roofs have deeper substrates, usually require irrigation and are heavier, therefore requiring buildings with a certain structural capacity to support their weight (Cascone, 2019). While they require more maintenance, their more complex system layers can support a wider variety of plants, ranging from grasses to shrubs (Peng and Jim, 2013). Intensive green roofs resemble more closely urban parks and often support an even wider variety of plants ranging from grasses, to flowering plants,

² Beyond green spaces, roofs can accommodate several other options that can enhance urban sustainability such as cool roofs, solar water heaters and solar PVs. For instance, solar photovoltaics can serve as a cleaner energy production option and contribute to climate change mitigation (Taminiau and Byrne, 2020). Cool roofs are designed to reflect more sunlight than conventional roofs and can thus reduce heat to urban environments and the necessity for air conditioning (Coutts et al., 2013).

shrubs and trees (Zhang et al., 2012). In order to support such vegetation, they have deeper substrates (usually >15 cm), and require irrigation and intensive maintenance, which makes them the costliest among the three types (Sailor, 2008; Getter et al., 2009; Berardi, 2016; Theodoridou et al., 2017).

Green roofs have multiple sustainability benefits compared to conventional roofs. For example, studies on commercially available green roofs in the Philippines found their benefits across multiple sustainability indicators namely longevity, water retention, cost, use of locally sourced materials, and frequency of maintenance (Orozco and Madriaga, 2021). Similarly, reviews of LCA studies found green roofs to be more sustainable compared to conventional roofs across multiple indicators, and suggested that their sustainability can be further enhanced by design considerations (Shafique et al. 2020). Furthermore, a growing literature suggests that strategic green roof implementation can enhance urban sustainability through the provision of multiple ecosystem services (Langemeyer et al., 2020; Venter et al., 2021; Hoeben and Posch, 2021). Several studies outlined below has manifested some of the sustainability benefits of green roofs in relation to UHI effect mitigation, air pollution mitigation, contribution to human wellbeing and provision of habitat for species.

First, green roofs can mitigate UHI effects by enabling cooling (Lazzarin et al., 2005; Susca et al., 2011), lowering local temperatures (Klein and Coffman, 2015; Alcazar et al., 2016), and providing insulation to buildings (Chan and Chow, 2013). Therefore, green roofs located in close proximity to urban areas with high potential for UHI formation such as urban canyons (Hart and Sailor, 2009; Hamilton et al., 2013; Koomen and Diogo, 2017), have been found to have particularly high potential to mitigate UHI effects (Djedjig et al., 2014; Ouldboukhitine et al., 2014). UHI effect mitigation has been linked to significant benefits to human wellbeing, and especially physical health through reduced heat exposure and its associated risks (Heaviside et al., 2017; Nyelele et al., 2019; Venter et al., 2020).

Second, green roofs can mitigate certain types of air pollution such as NO₂, SO₂, CO, PM₁₀ and tropospheric ozone (Yang et al., 2008; Currie and Bass, 2008; Speak et al., 2012). In particular, they can serve as filters by intercepting pollutants in their canopy layer through aerial transport or gravitational deposition (Litschke and Kuttler, 2008; Nowak et al., 2013), and absorbing gaseous pollutants through leaf stomata (Nowak et al., 2014). Although green roofs cannot provide urban air pollution mitigation benefits to the same extent as trees (Currie and Bass, 2008; Rowe, 2011), they can be beneficial for air pollution mitigation at any setting, especially when placed close to pollution sources such as roads and industrial areas (Pugh et al., 2012; Speak et al., 2012). Similar to above, air pollution mitigation has been linked to significant benefits to human wellbeing, and especially physical health through reduced risk of asthma incidence and general improvement of respiratory health due to improved levels of PM_{2.5} and NO₂ (Schindler et al., 2009; Garcia et al., 2019), and increased life expectancy due to reduced particulate matter exposure (Pope et al., 2009), among others.

Third, green roofs have also been found to have a positive effect on subjective wellbeing.³ For example, exposure to green roofs has been linked to decreased stress and increased attention and restorative healing levels among study participants (Lee et al., 2015; Loder, 2014). In particular, green roofs that are fully visible and in close proximity to offices reportedly have positive self-reported impact on the subjective wellbeing of office workers (Loder, 2014).

Fourth, green roofs can provide habitats for plants, insects, and even larger animals such as birds and bats (Bauman and Kasten, 2010;

³ More broadly, urban green spaces have been linked to many subjective human wellbeing benefits, including, among others, self-reported psychophysiological improvements such as decreased stress and anxiety levels, and increased cognitive functioning and restoration (Lee et al., 2015; Wang et al., 2016).

Schindler et al., 2011; Pearce et al., 2012; Madre et al., 2014; Joimel et al., 2018; Yildirim and Ozden, 2018). In particular, green roofs on buildings that are in close proximity to conventional urban green spaces such as parks and urban forests can be colonized by some of the animal species living within those areas (Kim, 2004; Braaker et al., 2014). Building height can affect species colonization on green roofs, with green roofs on lower buildings being more easily accessible by most species (Tonietto et al., 2011). Consequently, green roofs can serve as corridors connecting isolated green patches in urban areas offering a more expansive habitat for urban wildlife, sometimes increasing their survivability (Kim, 2004; Joimel et al., 2018).

The above suggest that by greening rooftops and essentially altering the urban fabric to resemble natural spaces, can contribute towards achieving more sustainable and resilient cities (Schettini et al., 2016; Teotónio et al., 2018; Koroxenidis and Theodosiou, 2021). Furthermore, green roofs are increasingly seen as essential elements of green infrastructure (Liberalesso et al., 2020; Langemeyer et al., 2020; Venter et al., 2021), and have been thus promoted and implemented in several countries around the world (Banting et al., 2005; Köhler, 2006), particularly in Europe and North America (Liberalesso et al., 2020).

However, few studies have adopted a multi-dimensional approach in their assessment, and how they can spatially vary contingent on the characteristics of the urban environment (e.g. Karteris et al., 2016; Grunwald et al., 2017; Langemeyer et al., 2020; Venter et al., 2021). Furthermore, there is a limited number of studies assessing how green roofs can be distributed to maximize their benefit at broader scales. For example, Karteris et al. (2016) investigated the potential for large-scale green roof implementation in Thessaloniki (Greece), utilizing GIS, remote sensing, and modelling in order to determine the potential green roof implementation and the benefits it would bring to urban sustainability. The results suggest that in the study area the green roof potential was 17% out of total built up area, and that by installing green roofs could enhance carbon sequestration by 2.5%, reduce energy consumption from heating (by 5%) and cooling (by 16%), and retain 45% of water runoff (Karteris et al., 2016). A similar study in Braunschweig (Germany) spatially analyzed the potential for green roof distribution for maximum benefit provision in terms of thermal climate, air quality improvement, water retention, and biodiversity (Grunwald et al., 2017). Studies on green roof potential in Madrid (Spain) and Oslo (Norway) identified where green roof interventions would be most necessary (e.g. areas with low green spaces coverage, high levels of traffic and, pollution, high population concentration) (Velázquez et al., 2019; Venter et al., 2021). Langemeyer et al. (2020) spatially evaluated green roof implementation potential in Barcelona (Spain) to assess the most desirable benefits of green roofs considering the area-specific topography, identifying that the priority areas for green roof implementation for maximum benefit provision would be the densely populated urbanized neighborhoods and the city center. However, to the best of our knowledge there are no studies in Asian cities that examine green roof potential at large scale and across several benefits they provide. These are major knowledge and practice gaps, which can inform decision-makers on how to efficiently utilize urban space, especially in contexts where the expansion of conventional urban green spaces is complicated.

The aim of this study is to spatially identify roof areas that have the potential to provide different sustainability benefits associated with urban green spaces if they are retrofitted with green roofs, and thus assess their potential of becoming part of green infrastructure. We focus on four types of sustainability benefits associated with conventional urban green spaces, namely UHI effect mitigation, air pollution mitigation, subjective wellbeing benefits, and biodiversity benefits. We focus on the Sumida ward in Tokyo, Japan, for several reasons. First, Japanese cities such as Tokyo are densely built, which often makes the expansion of conventional green spaces difficult and increases the fragmentation of green infrastructure. This is particularly true for Sumida ward that has some of the lowest urban green space cover in

Tokyo (Section 2.2). Second, Sumida ward has a very diverse urban fabric consisting of areas with modern buildings and infrastructure, intersecting with areas with rather traditional buildings (Section 2.2). This allows for a comparative analysis of the possible sustainability benefits of green roofs across city areas with different characteristics.

Section 2 outlines the methodology of the study. Section 3.1 estimates the available roof stock for potential green roof implementation in the study area using GIS-based approaches. Sections 3.2–3.6 identifies the areas of the ward where green roof implementation has the potential to offer the highest benefits for UHI effect mitigation, air pollution mitigation, subjective wellbeing, and biodiversity respectively. Section 4 critically discusses how the outcomes of our analysis can be used to inform the strategic implementation of green roofs in Tokyo (and beyond), in order to provide optimal benefits in urban contexts where the expansion of conventional green spaces is complicated.

2. Methodology

2.1. Research approach

Fig. 1 visualizes the conceptual framework of this analysis and the methods used to identify the areas where green roofs can offer the highest potential for the study benefits. In summary, in Step 1–2 we estimate the available surface for green roofs in the study area using the data outlined in Table 1 (Section 2.3.1–2.3.2). For this analysis we use data collected from the Geospatial Authority of Japan in polygon format on building footprints, green spaces, primary land uses, and road networks, as well as a raster format Digital Elevation Model (DEM) (5 m resolution).

During Step 3 we conduct a series of analyses to estimate the benefits of green roofs namely on UHI effect mitigation (Section 2.3.3.1), air pollution mitigation (Section 2.3.3.2), subjective wellbeing (Section 2.3.3.3) and biodiversity increase (Section 2.3.3.4). These benefits were selected as they are particularly relevant for the study area (Section 2.2). For each of these analyses we (a) identify through a literature review the mechanisms through which green roofs can provide these benefits and the factors affecting their delivery, and (b) estimate normalized values of benefit delivery. When estimating the latter we follow the GIS-based method of ranking green roofs proposed by Grunwald et al. (2017). This approach examines specific green roof attributes and assigns a numerical score for the high (score of 1), moderate (score of 2), or low (score of 3) delivery of benefits. During Step 4 the individual scores are summed into a final score of benefit delivery from green roofs (Grunwald et al., 2017) (Section 3.4).

It is worth noting that while we adopt the ranking method from the literature, the areas of potential benefits, as well as their individual parameters are adjusted to our literature review outcomes, dataset availability, and the characteristics of Sumida ward (Section 2.2).

We should point that in our analysis we do not consider possible constraints posed to green roof implementation by building age, construction material and building height, as well as possible implementation benefits due to proximity effects. Below we explain these methodological decisions in greater depth.

First, to the best of our knowledge, building age and construction material are two of the most difficult datasets related to the built environment to obtain in Japan. Where available, these datasets tend to be highly incomplete and have inconsistent quality. In addition, given the large number of (and heterogeneity between) buildings in the study area it would be prohibitively time consuming and uncertain to collect this data for individual buildings. Although we do not consider the building age and structure in this study, we still believe this does not affect our results. The reason is that the locally available green roof suppliers

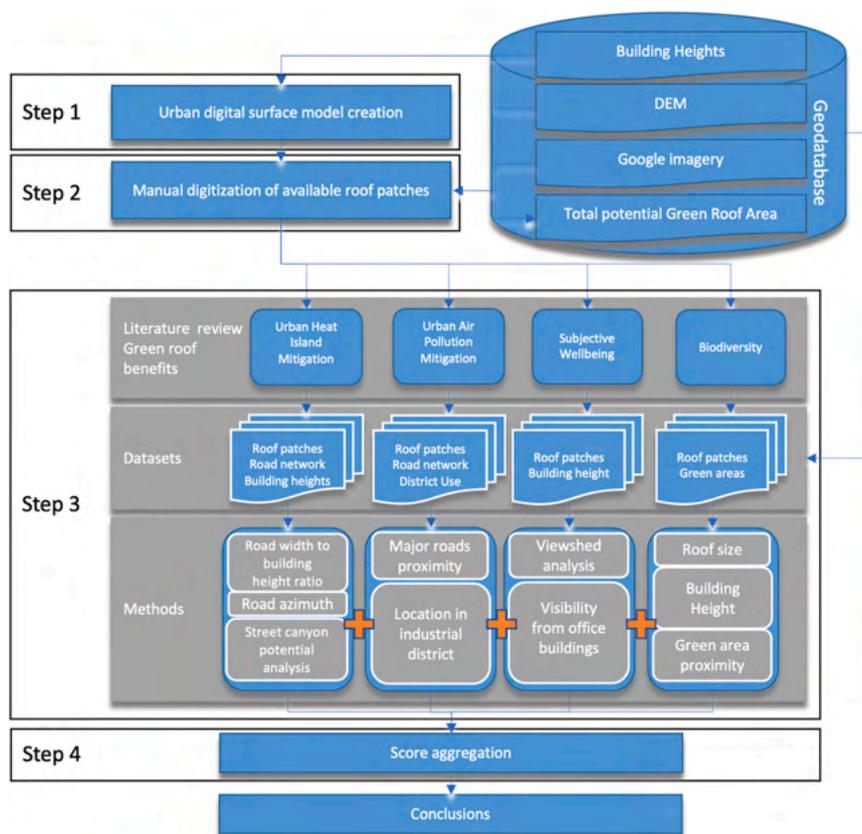


Fig. 1. Conceptual framework.

Table 1
GIS datasets and related sources.

Type	Source	Year
Building Heights	Geospatial Authority of Japan	2018
Building Footprints	Geospatial Authority of Japan	2018
Building Use	Geospatial Authority of Japan	2018
District Use	Geospatial Authority of Japan	2018
Google Earth Imagery (<1 m)	Google	2018
Digital Elevation Model (5 m)	Geospatial Authority of Japan	2018
Available Roof Space	Manual Digitization based on Google imagery of 2018	2018

Note: The resolution of Google imagery ranges between 15 m and 15 cm. However, in our study area the resolution was high enough to distinguish air conditioning units, pipes, and other similar structures on the roofs. Although the resolution varies depending on the area of the Sumida ward, we did not encounter any areas with resolutions < 1 m.

provide a type of extensive green roof that can be installed even on fragile structures such as bicycle parking lot roofs.⁴ These roofs are usually very lightweight and made of aluminum. In this sense our assumption is that any house roof is stronger compared to these structures, and thus would be able to support at least an extensive green roof of that type.

Second, we did not consider building height as a potential constraint for green roof installation and wider implementation. Theoretically there should be no major constraint in transporting materials for green roofs to the roofs of buildings of > 3 floors as they will be accessed from

the inside of the building using elevators. There are many examples of green roofs in high rise buildings in Tokyo (e.g. Tokyo University of Agriculture, Shinagawa Gotenyama Project, Toyoshimaya building, Hewlett-Packard Japan building, and Roppongi Hills among others) (MLIT, 2016). However, building height might pose challenges to the economic feasibility of green roof implementation (e.g. many more trips or complicated logistics to create green roofs in very high rise buildings) rather than the estimation of areas with high potential to provide benefits if mounted with green roofs as done in this study.

Finally, we do not consider possible benefits to green roof implementation due to proximity or clustering effects. First, to the best of our knowledge there is no literature establishing empirically whether, how and the extent to which the clustering of green roofs affects benefit delivery, as for other types of urban green spaces (Grafius et al., 2018). While proximity effects have been identified as possibly important considerations for green roof implementation (Calheiros and Stefanakis, 2021), to the best of our knowledge this has not been explored in depth or observed in practice for green roofs. Current studies related to green roofs usually make the case that it is the actual extent/volume of green roofs that affects benefit delivery and not their proximity to each other. For example, Mora-Melià et al (2018) find that the flood prevention and mitigation benefits of green roofs manifest after a certain minimum total surface is reached. Similarly Dong et al (2020) suggest that the air-cooling benefits of green roofs increase with increasing roof sizes, but this is again linked to total volume and not proximity. As our study does not quantify the exact benefit of green roof implementation, but the areas with high potential to provide benefits from green roof implementation, we believe that even if such proximity effects do exist for green roofs, they will be more relevant for studies quantifying the absolute levels of the benefits.

⁴ For some examples refer to <https://ryokka.org/lineup/byc.html> and <http://www.nichipure.co.jp/showroom/green.html>

2.2. Study Area

Our study is the Sumida ward, which is one of Tokyo's 23 municipalities known as special wards (Fig. 2). The administrative area of Sumida ward spans 13.77 km², and its border is defined in its entirety by the Sumida River in the west, and the Arakawa River in the North-East. According to the 2015 census, its total population was 255,999 residents, 30% of which are > 65 years old, and roughly 7% are > 80 years old (Statistics Bureau of Japan, 2015). This age group is generally characterized as more vulnerable to environmental stressors (Rikkert et al., 2009; Simoni et al., 2015).

Sumida ward is a densely built-up area, which contains very distinct built-up patterns within it. The Southern part contains many high-rise buildings and follows a grid pattern. The Northern part largely consists of small wooden buildings following the centuries old land distribution pattern. This makes Sumida ward an ideal area for this study, as it can allow for a comparative understanding of the type of benefits that green roofs can provide (and their magnitude) in areas with very different built-up patterns.

In more details, the Northern part of Sumida ward has largely remained undamaged by the Great Kanto earthquake and WWII (and their subsequent fires). Therefore, it follows a sprawling pattern based on the land distribution system, which started during the Edo period of the 17th century. Most buildings in this part of the ward are low and mid-rise, with essentially 70% of the area containing closely packed, small wooden buildings (Fig. S1, Supplementary Material). The area also has rather narrow roads (<4 m wide), which makes the access of emergency services such as ambulances and fire trucks difficult (Fig. S1-S2, Supplementary Material). The strong land ownership rights in Japan have made it very difficult for the Sumida ward government to redevelop this area. One of the few notable developments in this part of the ward is the 620 m tall Tokyo Skytree, which is one of the tallest buildings in the world and serves as a broadcasting and observation tower attracting millions of visitors.

On the contrary, the Southern part of the Sumida ward was greatly damaged during the 1923 Great Kanto earthquake and WWII (and their subsequent fires). As a result, the area has undergone land readjustment and was rebuilt into a grid. This resulted in the rather large number of high-rise buildings in comparison to the Northern part (Fig. S3, Supplementary Material). Furthermore, the road network is more extensive, with roads being much wider in most areas of this part of the ward.

Due to its specific characteristics, Sumida ward and its residents face different types of environmental issues. In particular, Sumida ward at 1.53 m²/capita has the third lowest green space coverage out of Tokyo's 23 wards (Sumida City, 2018a). As mentioned earlier, due to the strong land ownership rights the local government has difficulty in securing land for green spaces, particularly in the Northern part. As an alternative, the local government installs "pocket parks" on land patches where old houses are demolished (Fig. S4, Supplementary Material). Furthermore, although the whole of Tokyo faces strong UHI effects, the Sumida ward is among the 6 wards where it is felt the worst for several decades, and among the three worst in terms of nighttime UHI intensity (TMG, 2003; Sumida City, 2018b). What is even more worrying is that the UHI effect is projected to worsen in the future (Shimoda, 2010). Both the UHI effect and the lack of green areas pose a greater risk for the ageing population (Heaviside et al., 2017), which, as discussed above, accounts for an increasingly larger fraction of the ward's population.

The Sumida ward government has enacted several plans seeking to improve the biggest environmental issues the ward is facing. These started with the Sumida ward Basic Green Plan in 1995, which was amended and supplemented with the Sumida Environmental Zone Declaration and Sumida ward Ordinance for Governance Promotion in 2009. These plans aim at increasing green spaces to mitigate the UHI effect, enhance biodiversity as well as provide a healthier environment to their citizens (Sumida City, 2011). The focus has mainly been on riverbanks and eventually on rebuilding of the dense areas of the ward.

However, the latter could potentially take decades due to land ownership issues described above, if at all possible. It is this policy and built-up context that we believe makes the study of the possible benefits provided by green roof implementation highly topical both within the specific area, and more broadly.

2.3. Data collection and analysis

2.3.1. Step 1: urban digital surface model creation

In order to create a digital surface model for Sumida ward we combine two datasets: (a) a 5 m digital elevation model, and (b) the building heights included in the building footprints dataset (Table 1). We convert the polygon building footprint dataset into raster format, retaining the height attributes in the raster values. Subsequently we add the two layers of the DEM and building heights into a single layer producing a digital surface model that includes natural terrain and building height information.

2.3.2. Step 2: manual digitization of available roof space

Readily available geospatial data for Sumida ward are provided in the form of building footprints in polygon format. However, these footprints do not match with the actual available roof space that inform the implementation of green roofs. Through Google imagery we observe several discrepancies between the building footprints and the actual roof space. First, the data present tilted roofs or complex roofs as flat rectangles, which is not the case in reality (Fig. S5, Supplementary Material). In addition, roofs often contain objects such as air ducts or tubing, air conditioning units or other installations such as solar panels that make some parts of the roof unusable (Fig. S6, Supplementary Material). Finally, even if some roofs are empty and there is a perfect match with the geospatial data, they could still be unusable for green roofs. Such examples include roofs used as parking spaces, school roofs with distinctive naming, rescue helicopter landing pads, or existing green roofs (Fig. S7-S9, Supplementary Material). Collectively, the above can result both in the overestimation of available roof space for green roofs and the possible benefits.

For that reason, we manually digitize available roofs using Google imagery, and catalog available roof patches according to the extent of green roofs they could support. The images used are for the year of 2018. When visually inspecting each roof during this process of manual digitization, we excluded all roofs that are sloped, named, or used as helipads and parking spaces (see Section 3.1). On individual roofs, we excluded areas covered by pipes, air conditioning units, and other extrusions such as solar panels (see Section 3.1).

2.3.3. Step 3: assessment and visualization of green roof benefits

2.3.3.1. Urban Heat Island effect mitigation potential. Studies have found green roofs to be beneficial in decreasing the temperature in areas with pronounced UHI effect (Hart and Sailor, 2009; Djedjig et al., 2014; Ouldoukhitine et al., 2014; Koomen and Diogo, 2017).

Urban geometry can correlate with the formation of heat islands (Oke, 1981), whose occurrence and intensity is largely affected by two types of factors, namely the design of the urban environment (e.g. density of built up areas) and the meteorology (e.g. wind speed and direction) (Rajagopalan et al., 2014). The underlying logic is that areas with high urban street canyon formation potential, also have higher likelihood of experiencing UHI effect (Hamilton et al., 2013; Koomen and Diogo, 2017), especially if they are aligned with the dominant wind direction during the hotter months of the year (Chen et al., 2020b). Fig. S10 in the Supplementary Material provides a flowchart of the steps followed for the urban street canyon formation analysis outlined below, and the visualization of the method used in GIS.

First, we use a GIS-based approach to determine the building height to road width ratio, and the azimuth of the roads. This is because (a)

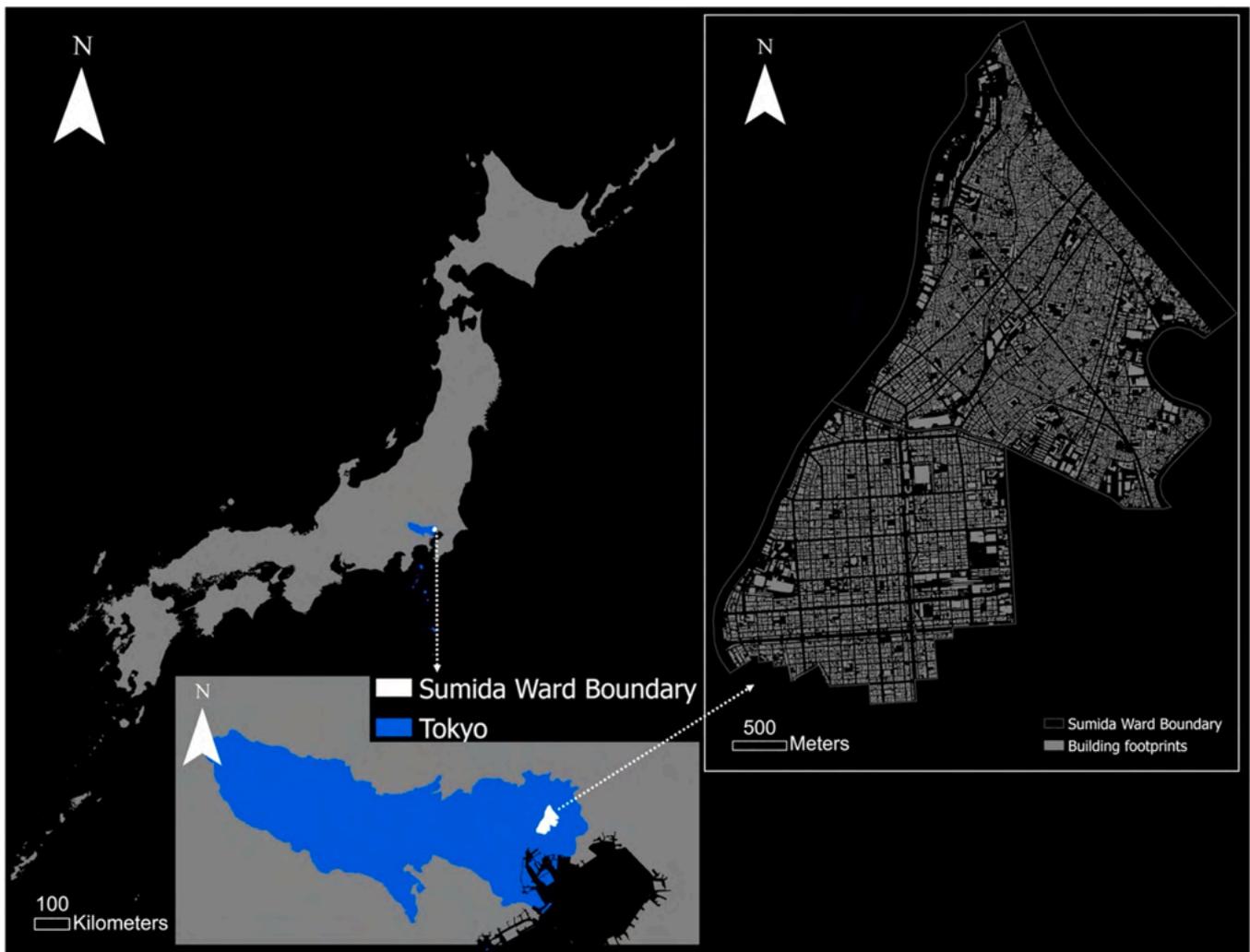


Fig. 2. Location of Sumida Ward in Tokyo, Japan.

height to width ratio is a classification metric often used in identifying street canyons (Oke, 1988; Hu et al., 2020), where large building height to road width ratios reduce cooling rates in urban areas (Oke, 1987), and (b) roads with a high ratio, and an azimuth perpendicular to the dominant wind in summer months, have the highest potential of forming urban street canyons and in turn high UHI effect intensity potential (Choi et al., 2018).

Initially we calculate the azimuth of the roads. As the dominant wind direction during the summer months is South (Weatherspark, 2019), see Fig. S11 (Supplementary Material) for the wind roses for the average wind direction for the period 2007 – 2020. All roads with an azimuth of 90 or 270 degrees have the highest potential for urban street canyon formation. We separate the road network dataset into two layers, one from 0 to 179 degrees and one from 180 to 360 degrees and convert them to raster format. For both layers we run a Gaussian fuzzy membership analysis, which assigns the maximum value of 1 to roads with 90 and 270 degrees, and the minimum value 0 to roads with 0, 180 and 360 degrees. All other roads with different azimuths are assigned appropriate values.

To calculate the building height to road width ratio, we estimate the average building height at 0.5 m intervals in the entirety of the road network. First, we densify the road network vertices to 0.5 m, and from each vertex we create perpendicular transects of 25 m in length. We then create a separate endpoint layer at both ends of the transect, and use the extracted values to points tool in order for the endpoints to obtain the height of the buildings they intersect. We then spatially join the

endpoints to the transects keeping the average value of the two endpoints of each transect, and then create points at every 0.5 m vertex of the roads, and spatially join them with the transects (Fig. S10, Supplementary Material). The points at the vertices end up containing both road width and building height information, and thus can be used to calculate the building height to road width ratio. We convert these points into raster format and run a linear fuzzy membership analysis in order to convert the values into a range between 0 and 1.

Finally, we add the raster layers of the azimuth and the building height to road width ratio. The roads now have values ranging between 0 and 2, with 2 denoting the highest potential for street canyon formation (Fig. 3a). We classify the values using natural breaks and create three categories of high (0.9–2) moderate (0.6–0.9) and low (0–0.6) potential for street canyon formation. Following that, we create 10 m buffers, the average distance from the middle of the road to encompass adjacent buildings from the roads with high and moderate street canyon formation potential. Table 2 explains in greater detail the considerations for the buffer zone selection.

Using spatial selection, roof patches within the buffer of roads with high canyon formation potential are associated with high potential UHI mitigation benefits (score of 1). Similarly roof patches within the buffer of roads with moderate canyon formation potential are associated with moderate potential UHI mitigation benefits (score of 2), and all other green roof patches outside both buffer zones are associated with a low potential benefit (score of 3).

We should note that we were unable to incorporate building

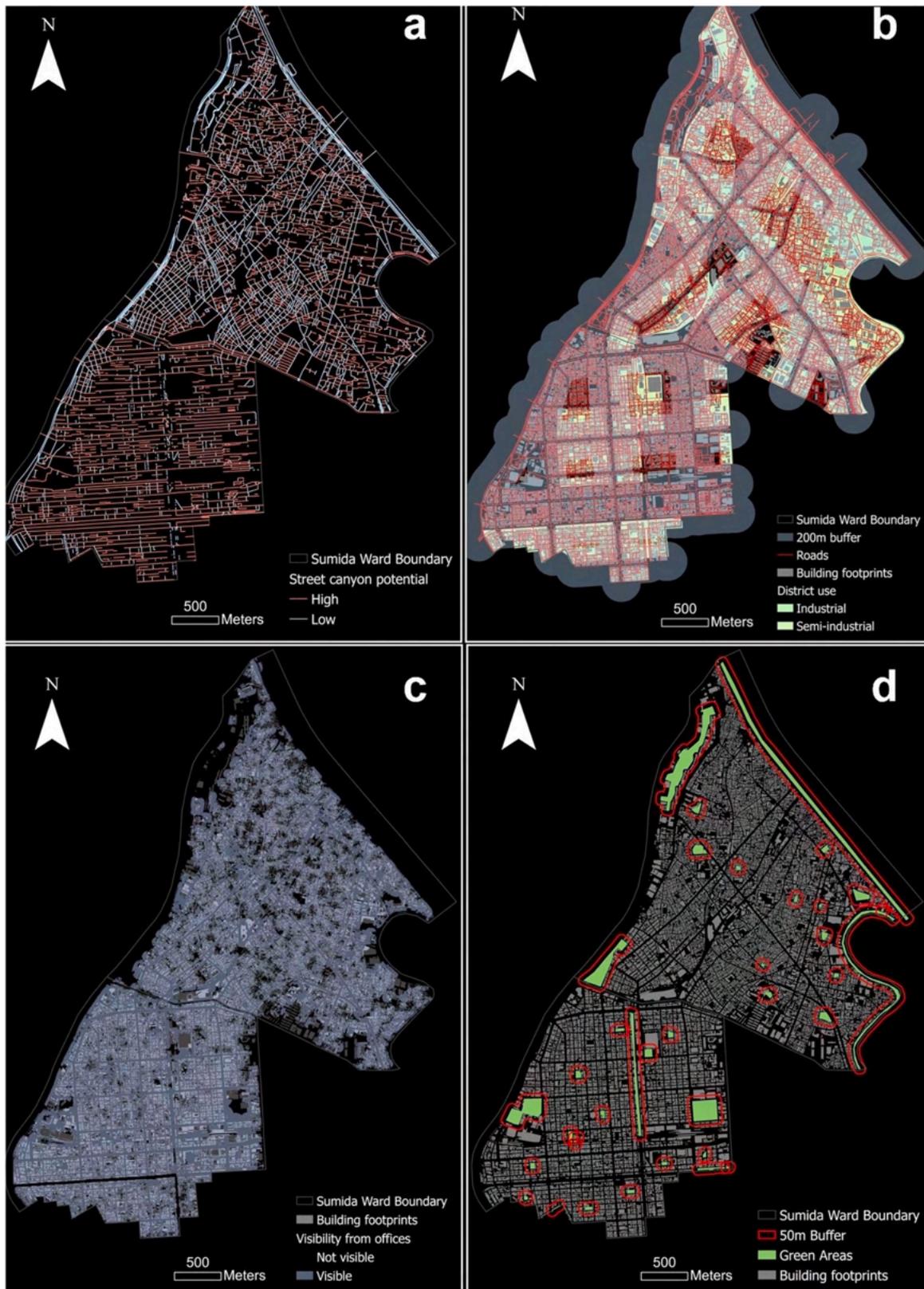


Fig. 3. Urban street canyon potential (panel A), industrial and semi-industrial zones with 200 m buffer zones from major roads (panel B), viewsheds from office buildings (panel C) and 50 m buffer zones from green spaces (panel D).

Table 2
Criteria selection for the analysis of each benefit category.

Benefit category	Justification
UHI effect	In this study we set a 10 m buffer. This is because in UHI studies, urban canyon formation considers buildings adjacent to roads (TMH, 2020). In our study site, a 10 m distance on each side from the center of the roads identified as street canyons encompasses all buildings adjacent to it.
Air pollution	Studies assessing the dispersal of air pollution from major roads have shown high pollutant concentration for up to 200 m away from major roads (Patton, et al., 2017; Evans et al., 2019). Concentrations of air pollutants decrease significantly past that threshold (Zhang et al., 2017) therefore using buffers over 200 m away from major roads becomes unreliable (Hoek et al., 2008). In addition, studies have shown adverse health effects for people living in close proximity to major roads (McConnell et al., 2010), specifically in distances < 200 m (Weinmayr et al., 2015; Yorifuji et al., 2015). For example, a study by Edwards et al., (1994), showed higher incidence of hospital admissions for children living within 200 m from a major road. In this study we set a 200 m. The represents the range of elevated pollution level dispersal (Evans et al., 2019).
Subjective wellbeing	In this study we set 50 m and 100 m buffers. Many studies have employed the concept of the viewshed as a tool for assessing greenery visibility (e.g. Sahraoui et al., 2016; Nutsford et al., 2016). To the best of our knowledge there are no studies that have indicated an optimal visibility distance for green roofs for generating subjective wellbeing benefits. However, 50–100 m has been identified as the minimum greenery proximity distance for subjective wellbeing benefits in numerous other studies in green spaces (Dadvand et al., 2012; Markevych et al., 2014; Elsadek et al., 2020). We used the 100 m visibility distance buffer for tall buildings and halved it to 50 m for shorter buildings.
Biodiversity	In this study we set a 100 m buffer. To the best of our knowledge there are no studies directly assessing biodiversity dispersal from green roofs. However, studies for other urban green infrastructure such as parks and house gardens have found the dispersal distance thresholds to range between 13 and 50 m (e.g. Donath et al., 2003; Thomson et al., 2011) for various plant species, insects, and birds (Wang et al., 2017). For some species the dispersal has been found to be insignificant when reaching the 100 m threshold (Cain et al., 2000).

population data in this analysis, as the highest resolution of population data from the official census is in the form of a 250 m resolution mesh.⁵ This is because the Japanese Government considers the number of residents and/or workers in a building to be personal data, and they do not release them for public or research use. As our UHI approach outlined above uses a 0.5 m resolution analysis based on the road network, the data incompatibility is within a very wide margin. For this reason, we do not incorporate building population estimation in our analysis.

2.3.3.2. Air pollution mitigation potential. To identify the areas with a high potential for urban air pollution mitigation through green roofs, we start with the premise that green roofs closer to stationary sources of pollution (e.g. industrial areas) (Litschke and Kuttler, 2008; Pugh et al., 2012) and major roads also have the higher potential to remove air pollutants from vehicle emissions (Cabaraban et al., 2013; Hewitt et al., 2020). These are the major source of urban air pollution (Kumar et al., 2016), such as NOx and PM10 (Baik et al., 2012; Speak et al., 2012).

We create buffer zones of 200 m, representing the range of elevated pollution level dispersal (Evans et al., 2019) around all major roads in Sumida ward as classified by Ministry of Land, Infrastructure, Transport and Tourism of Japan.⁶ Table 2 explains in greater detail the selection of the buffer zone.

⁵ For more information refer to: <https://www.e-stat.go.jp/gis/statmap-search?page=1&type=1&toukeiCode=00200521>

⁶ For further information refer to: https://www.mlit.go.jp/road/road_e/q2_definition.html

Subsequently we use the building floor dataset representing vertical proximity to the pollution source to assign to all building roof patches the number of floors of the building they belong to, categorizing them through the ASHRAE standard. The standard classifies as low-rise buildings with < 3 stories or less for, mid-rise with 4–5 stories, and high-rise with > 6 floors.⁷

Finally, we employ the district use to determine the area in which each roof patch is located (Fig. 3b). Through attribute and spatial selection, each roof patch is then assigned an appropriate score representing its potential to mitigate urban air pollution. Roof patches belonging to the low and mid-rise building categories located in industrial areas and within 200 m of major roads are associated with high potential air pollution mitigation benefits (score of 1). Roof patches located in low to mid-rise buildings within 200 m of major roads and roof patches within industrial areas (but outside 200 m of major roads) are associated with moderate air pollution mitigation benefit (score of 2). All other roof patches are associated with low air pollution mitigation benefit (score of 3).

2.3.3.3. Subjective wellbeing benefit potential. We determine the areas where green roof implementation would be most beneficial for subjective wellbeing, in terms of their visibility from office buildings. In Tokyo, roof access varies depending on legislation and building management regulations, but it is generally restricted to prevent suicides, and related responsibility and litigations. Given this generally lower access to roofs we only consider in this study visibility from inside the building and not via physical access to roofs. Fig. S12 in the Supplementary Material provides a flowchart of the approach used to assess the subjective wellbeing potential for green roofs.

In more detail, we conduct a viewshed analysis at buffer zones of 50 m from low- to mid-rise office buildings, and 100 m from high-rise office buildings. As observer positions, we use the entire perimeter of the building footprints, and we offset the height of observation by – 2 m from the office building height, to ensure that the roof patches are visible from inside the building. We reclassify the viewshed results into a 1×1m cell size raster with values of 0 for non-visible and of 1 for visible (Fig. 3c). To determine the fraction of each roof patch that is visible, we conduct zonal statistics using the roof patches as zones. As the cell size of the viewshed is 1×1m the sum of pixels enclosed in each roof patch translates into the total visible area surface for each patch. We then divide the visible area by the total area of each patch to determine which fraction of the patch is visible, and then use natural breaks to classify the visibility.

We select green roof patches that are within 50 m from low to mid-rise office buildings and/ or within 100 m from high-rise office buildings. The selection of this buffer is explained in greater detail in Table 2. Roofs that are 70–100% visible are associated with high potential for subjective wellbeing benefits (score of 1), roofs that are 30–70% visible are associated with moderate potential subjective wellbeing benefits (score of 2), and roofs that are < 30% visible are associated with low potential subjective wellbeing benefits (score of 3).

2.3.3.4. Biodiversity benefit potential. Urban green spaces are separated by buildings and are often too far apart to create green corridors necessary for biodiversity, while also leaving local species vulnerable to invasive species (Fahrig, 2003; Russo et al., 2017; Zambrano et al., 2019) (see also Section 1). Increasing urban green areas and connecting green patches through corridors is perhaps the most crucial aspect for conserving urban biodiversity (Beninde et al., 2015). Green roofs can provide habitat and steppingstones for some species to both colonize and spread from nearby established green areas (Kim, 2004; Toniello et al., 2011). Green roofs on lower buildings tend to be more beneficial for

⁷ ANSI/ASHRAE/IES Standard 90.1. (2010)

biodiversity, as it does not hinge vertical mobility therefore increasing the potential for species (Brenneisen, 2006, Pearce and Walters, 2012; Macivor, 2014). Therefore, to determine the roof patches with the highest potential to benefit biodiversity through green roof implementation, we investigate their proximity to urban green spaces and the height of the respective building.

For this analysis we combine the green spaces dataset provided by the Geospatial Authority of Japan, and the digitized roof patches dataset. Following the rationale explained in Table 2, we create 50 m buffer zones from urban green spaces and select all buildings within those buffers (Fig. 3d). Roof patches in low-rise buildings, or with surface of $> 100 \text{ m}^2$ in mid-rise buildings located inside the buffer zones, are associated with high potential benefits to biodiversity (score of 1). Roof patches within the buffer zone, and with $< 100 \text{ m}^2$ surface in mid-rise buildings or $> 100 \text{ m}^2$ in high-rise buildings, are associated with moderate potential benefits to biodiversity (score of 1). Finally, roof patches $< 100 \text{ m}^2$ on high-rise buildings within the 50 m buffer, or roof patches $> 100 \text{ m}^2$ on low and mid-rise buildings outside the 50 m buffer are associated with low potential benefits to biodiversity (score of 3).

2.3.4. Step 4: benefit score aggregation

The final step of this assessment entails the aggregation of the scores for the four individual benefits. For each green roof patch, the respective scores of all four benefits are directly added, resulting in a range of values between 4 and 12. We classify the aggregate benefit values as high (score of 4–5), moderate (score of 6–8) and low (score of 9–12) using equal interval classification. This additive approach implies that we consider all of the four benefits to be equally important, and thus have the same weight.

Arguably, this aggregation approach can offer valuable information for the strategic placement of green roofs in existing roof spaces. An aggregate score classified as high (4–5) implies that the specific roof patch has high potential to provide more benefits if retrofitted with a green roof. Thus, through this approach we care more about the quantity of benefits, rather than their importance relative to each other.

3. Results

3.1. Available space for green roofs

In total, there were 51,474 building footprints across the Sumida ward in the dataset for 2017. Through our manual digitization we catalogue of 44,015 roof patches, out of which, 22,715 are designated as available for green roof implementation. Omitted roof patches include those on sloped roofs (20,351 patches), named roofs (25 patches), or used as helipads and parking spaces (16 and 20 patches respectively). When compared to the original building footprints dataset, the manually digitized roof patches are often smaller, with single roofs often subdivided into multiple patches that are fit for green roof implementation. As buildings in Tokyo are relatively small, the average size of available patches fit for green roofs in the study area is 52 m^2 .

Overall, the amount of space that is available for green roofs is 1.18 km^2 , with $620,000 \text{ m}^2$ located in the Northern area and $560,000 \text{ m}^2$ in the Southern area. This corresponds to roughly 8.5% of the total area of the ward, and 25% of total roof surface area. Interestingly, green roofs currently occupy only 0.46% of total roof surface space in Sumida ward while solar panels occupy approximately 1.6% of the current roof space. Considering the relatively limited number and

extent of green spaces in the ward (Section 2), the area identified as fit for green space implementation is roughly double the current extent of green spaces. The above show the rather high potential for green roof expansion across the ward.

3.2. UHI effect mitigation

Approximately 56% (i.e. $650,829 \text{ m}^2$) of the roof area fit for green roofs estimated in Section 3.1 has a high potential for UHI effect mitigation, 14% a moderate mitigation potential (i.e. $153,858 \text{ m}^2$), and 30% a low mitigation potential (Fig. 4a; Table 3).

There are no significant differences in these fractions between the Northern and the Southern part of the ward, despite major differences in the road network. In particular, road azimuths in the northern part vary greatly. However, the potential for UHI formation is not influenced by the dominant wind direction, and is thus distributed more evenly across the area. Conversely, the road network in the Southern area follows a grid, with those roads with azimuths of 90 or 270 degrees going against the dominant wind direction in the summer months, thus having higher potential for UHI effect. In any case, the differences are fairly minor with 57%, 16%, and 27% of the identified patches in the Northern area having high, moderate, and low potential to mitigate UHI effect (Table 3). The respective fractions in the Southern area are 53%, 10% and 37% (Table 3).

This broad similarity in potential is rather unexpected considering the significant differences in urban form in the two areas (Section 2.2). However, this similar potential for UHI effect mitigation is due to different reasons. Considering the high built-up ratio in the Northern part coupled with the sprawling road network, this area has many clusters of closely built low-rise buildings that form many hotspots of UHI formation. On the other hand, in the Southern part UHI formation hotspots follow more closely the pattern of urban street canyons, where wind dispersal ability is impaired due to the nature of the urban grid, forming thus many hotspots along major roads (Fig. 4a).

3.3. Air pollution mitigation

Approximately, 32% ($381,620 \text{ m}^2$) of the identified roof patches fit for green roofs have a high air pollution mitigation potential, 50% ($585,029 \text{ m}^2$) a moderate mitigation potential, and 18% ($215,481 \text{ m}^2$) a low mitigation potential (Fig. 4b; Table 3). As traffic is the main contributor of urban air pollution in the ward, most roof patches associated with a high potential for air pollution mitigation are distributed along the major roads of the ward (Fig. 4b; Table 3).

However, when compared to the UHI effect mitigation potential, we observe more unbalanced potentials across the ward. For example, in the Northern part of the ward, 41% of the identified roof patches fit for green roofs have a high potential for air pollution mitigation, 46% moderate potential, and 13% low potential (Table 3). This is possibly due to the fact that a considerable proportion of this part of the ward is characterized by sprawl with narrow roads and lower buildings. Conversely, the Southern part follows a grid pattern, with 23% of the total roof space fit for green roofs having a high potential for air pollution mitigation benefit, 54% moderate potential, and 23% low potential (Table 3).

When looking more closely on the spatial distribution of this potential, in the Northern part the roof patches with high potential for air pollution mitigation are clustered around major roads. Since a large proportion of the buildings in this area are closely-built, small detached houses, the road buffer encompasses far more buildings. Secondly, the industrial areas in this part of the ward are also comparatively small and are mainly located near major roads. These characteristics enable a good clustering of the potential for air pollution mitigation. Conversely, the Southern part contains much larger industrial areas, with the roof patches with high benefit potential being mainly clustered in those areas.

⁸ There are few studies on green roofs and urban biodiversity in relation to roof size. Studies suggest that limited biodiversity benefits start manifesting from roofs as small as 50 m^2 , and increase with size (Ksiazek-Mikenas et al., 2018). Studies for other urban green spaces such as parks and gardens (e.g. Strohbach et al., 2013; Hejkal et al., 2017) have suggested that stand-alone green surfaces of $100\text{--}150 \text{ m}^2$ can support some level of biodiversity.



Fig. 4. Spatial distribution of scores for benefit potential of UHI effect mitigation (panel A), air pollution mitigation (panel B), subjective wellbeing increase (panel C), and biodiversity increase (panel D).

Table 3
Extent of roof area with different potential to deliver the study benefits following green roof implementation.

Benefit	Potential	Sumida ward		Southern area		Northern area	
		(m ²)	(%)	(m ²)	(%)	(m ²)	(%)
UHI effect mitigation	High	650,829	56	295,527	53	355,302	57
	Moderate	153,850	14	57,244	10	96,605	16
	Low	357,451	30	208,739	37	168,712	27
Air pollution mitigation	High	381,620	32	127,892	23	253,727	41
	Moderate	585,029	50	302,305	54	282,676	46
	Low	215,481	18	131,265	23	84,216	13
Subjective wellbeing benefit	High	614,826	52	321,139	60	293,686	46
	Moderate	289,882	25	120,300	22	169,582	26
	Low	277,442	23	95,855	18	181,566	28
Biodiversity benefit	High	97,054	8	43,483	8	53,571	10
	Moderate	277,764	24	110,846	20	166,917	26
	Low	807,312	68	407,174	72	400,131	64
Aggregate benefits	High	61,728	5.2	27,898	5	33,829	5.5
	Moderate	694,860	58.8	310,544	55	384,309	62
	Low	425,543	36	223,061	40	202,401	32.5

3.4. Subjective wellbeing benefits

More than half, (52% or 614,826 m²) of the identified roof patches in Sumida ward fit for green roofs have a high potential to provide subjective wellbeing benefits, with 25% (289,882 m²) and 23% (277,442 m²) having respectively a moderate and low potential to provide subjective wellbeing benefits (Fig. 4c; Table 3). Approximately 46% of the identified roof patches in the Northern part have high potential to offer subjective wellbeing benefits, 26% moderate potential, and 28% low potential (Table 3). Conversely, in the Southern part these proportions are 60%, 22%, and 18% respectively (Table 3).

This discrepancy is because the Northern part is characterized by a higher proportion of residential and mixed residential areas consisting of detached houses, and numerous office buildings. In contrast, the Southern part has some business districts and therefore a larger number of office buildings, while the residential areas are comparatively smaller. However, while the residential buildings tend to be shorter in the Northern area, so do the office buildings, allowing thus for similar visibilities as in the Southern area. Indeed, this high prevalence of office buildings across the full extent of the Sumida ward creates a high potential to deliver subjective wellbeing benefits from green roof implementation.

3.5. Biodiversity benefits

Approximately 8% (97,054 m²) of the area suitable for green roofs has a high potential to provide biodiversity benefit, with 24% (277,764 m²) having moderate and 68% (807,312 m²) low potential (Fig. 4d; Table 3). This reflects the low current green space coverage in the ward (Section 3.1). Nevertheless, if the identified roof patches with high potential to generate biodiversity benefits are retrofitted with green roofs, it would increase the green space extent in Sumida ward by 16.6%. This breakdown is similar across the different parts of the ward. Specifically, in the Northern part 10% of the identified roof patches fit for green roofs have high potential to provide biodiversity benefits, 27% moderate potential, and 64% low potential (Table 3). The respective results for the Southern part are 8%, 20%, and 72% respectively (Table 3).

In more detail, the Northern part is bordered by rivers on its west, north and east. Most of these riverbanks serve as parks and account for a considerable fraction of the total green space found in the Northern part of the ward. For this reason, in this part of the ward we identified a continuous strip of roof patches with high potential to provide biodiversity benefits (Fig. 4d), with limited such areas in the remainder of this part of the ward. Conversely, due to its redevelopment the Southern part contains more parks that are also more evenly distributed across the area. Hence the identified roof patches with high potential benefit for

biodiversity are also equally distributed in this part of the ward (Fig. 4d).

3.6. Aggregated benefits

When looking across all four benefit types, we find that only 5.2% of the identified roof space fit for green roofs (61,728 m²) has the potential to provide high levels of aggregate benefits. Conversely, 58.8% (694,860 m²) has the potential for moderate benefits, and 36.0% (425,543 m²) has the potential for low benefits (Fig. 5; Table 3). If only the roof patches with potential for high benefit provision were retrofitted with green roofs, this would increase the total green area of Sumida ward by 10.5%. However, if the moderate benefit class is also retrofitted, this would increase the total green area by as much as 120%.

When comparing the potential to deliver aggregate benefits across the different areas, we do not find any major differences between the two areas. In more detail, in the Northern part 5.5% of the identified roof area has the potential to provide high levels of aggregate benefits, 62% to provide moderate levels, and 32.5% low levels (Table 3). In the Southern part these fractions are 5% for high potential, 55% for moderate potential, and 40% for low potential respectively (Table 3). Interestingly, in both parts of the ward these potential areas are scattered across the entire area (Fig. 5).

Spatially, we observe a distribution of roofs based on location that shows some discernable patterns regarding their potential to offer aggregate benefits. Fig. 6a shows an area in the North part of Sumida ward where most buildings have a moderate potential to offer benefits (green color). This can be explained by the absence of green spaces and major roads in this part of the ward, as well as the smaller average sizes of roof patches on detached buildings, which reduces potential to offer UHI effect and air pollution mitigation, as well as biodiversity benefits. In contrast, Fig. 6b shows a cluster of roof patches with high potential to offer benefits, which is located around a green space in the north park. That area of Sumida ward has many office buildings as well, which contributes to most roofs having a high and moderate potential to offer benefits, especially associated to subjective wellbeing and biodiversity.

In the South part of the Sumida ward, Fig. 6c indicates an area with multiple roofs having low potential to offer benefits, again due to the absence of green spaces in close proximity, as well as major roads that could contribute to UHI formation and high levels of air pollution. Finally, Fig. 6d shows an area with multiple buildings with moderate and high potential to offer benefits, especially associated with UHI effect mitigation considering the grid type road network.

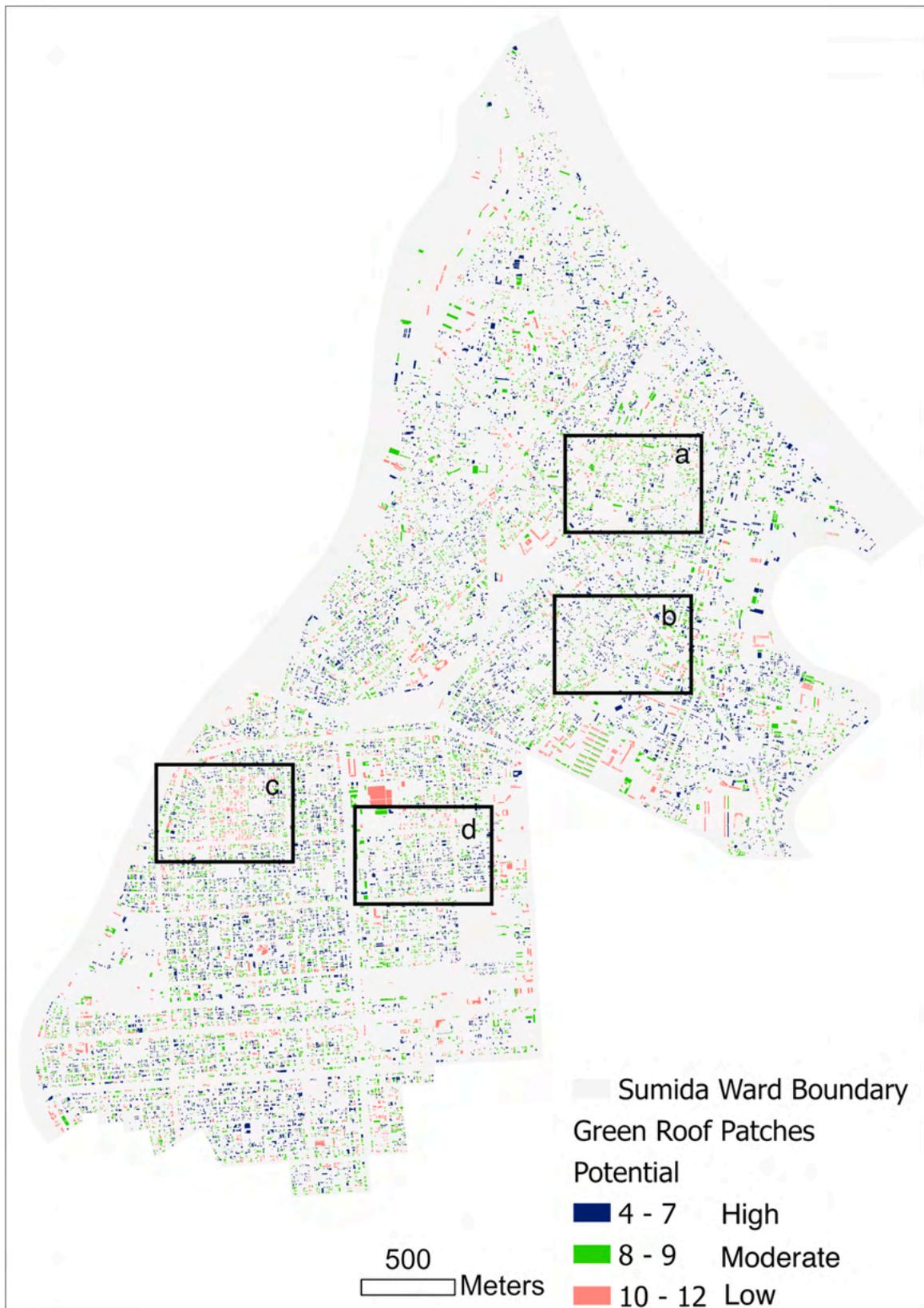


Fig. 5. Spatial distribution of aggregated benefit score potential in the Sumida ward.

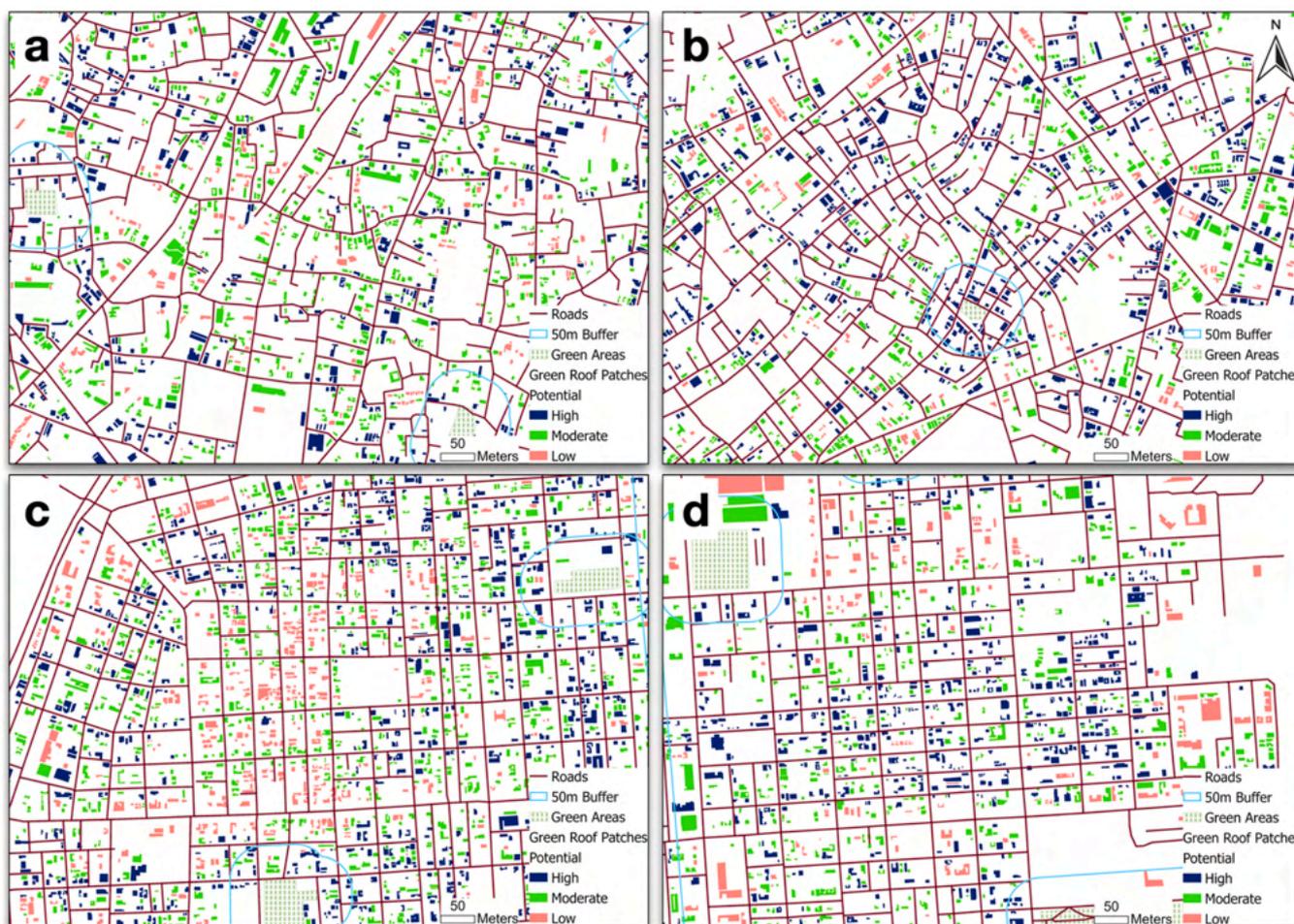


Fig. 6. Spatial distribution patterns of aggregate green roof benefit potential in selected areas of the Sumida ward.

4. Discussion

4.1. Rationalizing scenarios of green roof potential for green infrastructure

Several studies have shown that despite the often-high policy ambition towards green roof implementation in many urban contexts as critical components of green infrastructure for enhancing urban sustainability, there is still very little actual implementation in many parts of the world (Ismail et al., 2012; Versini et al., 2020; Yuliani et al., 2020; Liberalesso et al., 2020; Dong et al., 2020). Similarly, while the Tokyo Metropolitan Government (TMG) has initiated various programs and incentives to increase green roof area by 1200ha by 2015 (TMG, 2018), this target was not met (MLIT, 2018). Our analysis indicates that green roofs occupy only 0.46% of the total roof surface area in the study site (Section 3.1). However, when also considering the low extent of green spaces in the area, there is great scope for promoting green roofs in the study area as critical components of green infrastructure for the multiple benefits they can offer.

Most studies exploring the large-scale implementation of green roofs tend to rely on simulations, which often either make the unrealistic assumption that 100% of roof area can be used for green roofs, or assume arbitrary greening fractions. For example, studies in Rome, Singapore, and Taiwan have assumed 100% roof coverage when exploring the potential and benefits of green roofs (Battista et al., 2016; Li and Norford, 2016; Sun et al., 2012). Similarly studies in Toronto and Beijing have used arbitrary coverage assumptions to explore the possible impacts of green roofs, namely 50% in the former study and 10% in the

latter (Bass et al., 2002; Li et al., 2012).

One of the major insights of our study is that the extent of available space for roof greening (and thus integration in green infrastructure) is much lower in reality. In particular, based on the manual digitization, we are able to quantify more accurately the roof surface in Sumida ward that can be used for green roofs. In contrast to most of the studies cited above, we find that the usable surface was 23% and 27.5% of the building footprints in the Northern and Southern parts respectively (25% across the entire ward). Such coefficients could be used in other urban contexts with similar characteristics in order to form the basis of more accurate predictions of the available green roof area in future studies. Such information can go a long way towards offering more realistic expectations about the potential extent and benefits of large-scale green roof implementation for green infrastructure across different expansion scenarios, including in areas where green roofs can complement urban green spaces.

Therefore, the approach followed here can have practical applications in government level decision making processes, such as targeted mandates for green interventions. Moreover, it can be of use in smaller scales to businesses and individuals interested in determining whether their planned retrofits would be optimal for a green roof or other options. Regardless of the scale, ultimately the goal of the proposed method is to support decisions in cases of areas with several competing roof or other sustainable interventions.

4.2. Maximizing sustainability benefits through the strategic identification of green roof location

A second major finding of this study is the variability in the potential of green roofs to provide different urban sustainability benefits depending on the benefit category and the location in the urban fabric. Studies have shown that the location of green roofs can affect the level of benefits they provide (Speak et al., 2012; Janhäll, 2015; Langemeyer et al., 2020; Venter et al., 2021). For example, in terms of air pollution mitigation, green roofs are more efficient in street canyons than open roads (Abhijith et al., 2017).

This is supported numerically and spatially by the results of our study where, depending on the type of benefit and location of roof patch, only 56% of the identified roof patches had a high potential for UHI mitigation, 32% for air pollution mitigation, 52% for subjective wellbeing improvement, and only 8% for biodiversity (Sections 3.2–3.5). Moreover, only 5.2% of the identified roof patches had a high overall potential to deliver simultaneously all four benefits (Section 3.6).

When considering the above, studies assuming that green roofs can be located on the entire available roof stock in a given area, might end up overestimating the potential of delivering one or more of the studied benefits when uniformly extrapolated from a few experimental sources. This overestimation could be more extensive when considering the actual implementation of, for instance, semi-intensive and intensive green roofs, where the structural integrity of each building has to be considered individually due to the weight restrictions of this intervention. To ensure that green roof implementation could bring high levels across multiple benefits it would require extensive spatial analysis, which increases study complexity, data requirements, and processing time as the analysis for each benefit might vary (Section 2.3.3). In this case, it might be that the more benefits of green roofs explored or aspired, the less overall area might be available to achieve them simultaneously. In whichever case, such studies seeking to identify the location of green roofs to achieve the maximum benefits should be informed and guided by the priorities set by different relevant stakeholders such as local governments.

The above can have major practical applications in our study area and beyond, e.g. when planning the implementation of roof-based interventions to enhance urban sustainability. For example, in many cities around the world there are competing policies for the implementation of roof-based interventions such as green roofs and solar PVs on both existing and new buildings. Our approach could be integrated in toolkits seeking to assist practitioners and policymakers in making more informed decisions on which technologies to implement depending on area-specific priorities. For example, if the Sumida ward government is prioritizing the mitigation of climate change-driven increases in UHI effect or the extreme lack of green areas in the area, then the local government could promote the implementation of green roof installation in areas where they have the highest potential for UHI mitigation and biodiversity benefits, and promote the implementation of other technologies (e.g. solar PVs) in locations where green roofs would not be as useful. Such decision-making scenarios are relevant in every city in the world but depend on context. The approach used in this study is quite flexible and can be used to inform local governments in identifying promising areas for green roof implementation based on their individual needs. The actual policy instruments and incentives (e.g. subsidies, green credits) should be informed through further research designed to explore the most appropriate approaches for enhancing and rationalizing the adoption of roof-based urban sustainability interventions.

Another consideration is that the type and characteristics of green roofs might affect the actual level of possible impacts. Intensive green roofs generally tend to offer higher benefits compared to extensive roofs (Silva et al., 2016), but their implementation depends on the structural integrity of buildings (Berardi, 2016) and are generally more expensive both in terms of installation and long-term maintenance (Theodoridou et al., 2017). Whenever possible, intensive green roofs should be

considered during implementation in order to maximize benefit provision. Table 4 summarizes some of the desirable types and characteristics of green roofs for each of the benefits explored in this study. Depending on the desirable benefits of green roofs in a given context (see above), practitioners could prioritize green roofs with such characteristics in areas that have high potential to offer the prioritized benefit category. However, final selection should depend on further considerations such as building stability and economic cost-effectiveness.

4.3. Exploring large-scale green roof implementation for green infrastructure

When planning for green roof implementation in larger scales (e.g. to develop wider green infrastructure), whenever possible, green roof retrofitting should be aimed towards maximizing volume, as larger coverage further enhances benefit provision (Mora-Melià, 2018; Dong et al., 2020). For example, out of the four impact categories considered in this study, the identified roof patches had the lowest potential for biodiversity benefits. This benefit could be enhanced not only by the presence of multiple green roofs, but also, with green roofs of larger sizes, as they could serve as green corridors connecting green areas in an urban environment to aid species movement and enhancing urban biodiversity (Vergnes et al., 2013; Dang, 2017).

This is also true for UHI effect mitigation, for which green roofs can provide higher cooling benefits if they are of larger sizes and of the intensive type. For example, it was found that green roofs have a significant cooling effect up to 100 m from the roof, with this cooling effect increasing by 0.4 °C for each additional 1000 m² of green roof surface in a given area (Dong et al., 2020). A study investigating the green roof effect on UHI mitigation showed that temperatures decreased with an increasing green roof fraction, from 1 °C where 25% of roofs were green to 3 °C with 100% green roof coverage (Sharma et al., 2016).

4.4. Limitations and future research

Despite its extensive focus and robust results, this study has a series of limitations that future studies should seek to build on. First, we identified the priority locations for green roof implementations in terms of their comparative potential to provide certain benefits. We did not calculate the actual delivery of the different benefits, as apart from

Table 4
Desirable characteristics and types of green roofs for each benefit category.

Type of benefit	Desirable green roof characteristics	Type of green roof	References
UHI effect mitigation	<ul style="list-style-type: none"> • Deeper substrate • High proportion of plant cover • High Leaf Area Index (LAI) • Irrigation 	Extensive and intensive	Sun et al., 2014; Berardi, 2016; Yang et al., 2018
Air pollution mitigation	<ul style="list-style-type: none"> • Rigid plants such as grass and shrubs 	Intensive	Currie and Bass, 2008; Yang et al., 2008; Li and Babcock, 2014
Subjective wellbeing increase	<ul style="list-style-type: none"> • High proportion of plant cover • Grasses and trees rather than flowers 	Semi-intensive and intensive	Nordh et al., 2011; Williams et al., 2019
Biodiversity increase	<ul style="list-style-type: none"> • High habitat complexity • Landscape elements such as tree logs and stones • Varying vegetation layers • Native vegetation and soil 	Extensive and intensive	Brenneisen, 2006; Madre et al., 2013; Consalves et al., 2021

location these benefits can depend on various factors such as the type of green roof, the species, and economic and cultural considerations. In this sense future studies should delve deeper in the quantification of the actual benefits exploring different green roof implementation scenarios. Such studies could be conducted with the participation of local governments which could adjust scores to suit their planning priorities and specific needs (e.g. see Langemeyer et al., 2020). For example, if specific urban areas experience severe UHI effects, then green roofs most beneficial for UHI mitigation can be given a higher weight compared to other benefits to adjust the total score in favor of more pressing issues.

Second, the employed methodology allowed us to analyze the potential for green roof implementation more accurately due to the manual investigation and digitization of approximately 50,000 individual roofs. This was a taxing, and time-consuming process, and may be difficult to adopt in study areas of similar size or larger, without the investment of significant resources. While this approach is more accurate than the usual assumptions in studies exploring green roof potential and could be transferable to other urban contexts, the exact implementation will have to vary depending on data availability and resources. Their availability could directly affect the scale and depth of the analysis. It should be noted that although the selection of the four benefits explored in this study was based on a literature review and the main policy considerations in the study area, additional benefits can be added depending on the study context to provide more context-specific results.

Third, due to large discrepancies in the resolution of some datasets it was not possible to add certain features in the analysis of some individual impact dimensions. For example, it was not possible to add building by building population density in the UHI effect analysis (see Section 2.3.3.1), despite the fact that human activity is one of the contributing factors to UHI formation (Magli et al., 2015). Furthermore, we did not consider building height to be a potential constraint to green roof implementation, as the roofs of most mid to high-rise buildings in Japan can be accessed via elevators (Section 2.1). However, this might not be true for other cities outside Japan where building height would add a possible complication for green roof implementation and make it more costly. While such omissions do not affect in practice the identification of the most promising areas for green roof implementation as done in this study, it could be an important consideration for the final selection of actual implementation areas. This is because it might be more cost-effective to prioritize green roof retrofits in areas that do not only have high UHI effect mitigation potential, but also high population density in order to maximize the reach of the possible benefits. In this sense, subsequent analysis could estimate the actual population of buildings in promising areas through household surveys or other techniques to add further nuance in the final selection process.

Finally, we do not consider building age and construction material in our analysis as these datasets are highly incomplete for our study area and do not affect our results. When it comes to Tokyo, there are light-weight green roofs produced locally that could be installed on most surfaces (Section 2.1), however that might not be the case in other areas. Nevertheless, the structural integrity of buildings needs to be assessed individually for the installation of semi-intensive and intensive green roof types as part of the final selection process.

5. Conclusions

This study employed a GIS-based approach in a highly diverse urban area in Sumida ward (Tokyo) to identify the roofs that have the potential to provide different types of urban sustainability benefits associated with urban green spaces if retrofitted with green roofs, and whether they can become integral elements of green infrastructure. Our results suggest that in Sumida ward there are 22,715 roof patches currently available that can in theory be retrofitted with green roofs, spanning a total area of 1.18 km². When comparing the potential to offer different benefits, most patches have a high potential to provide subjective wellbeing benefits, followed by UHI effect mitigation, air pollution

mitigation and biodiversity benefits. If all roof patches that have potential to provide all these benefits are retrofitted with green roofs, this could increase the current extent of green space in Sumida ward by 10.5%, while it can double it if patches with moderate potential are retrofitted as well. Despite the marked differences Northern and Southern parts of the ward in terms of urban structure, there is no significant difference in terms of the spatial distribution of the roofs with different potential to provide the study benefits. This suggests that green roofs could become an integral element of green infrastructure in an urban area that is currently lacking it, as a means of increasing urban sustainability.

CRedit authorship contribution statement

Jelena Aleksejeva: Conceptualization, Methodology, Software, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Gerasimos Voulgaris:** Data curation, Software, Visualization, Writing – original draft. **Alexandros Gasparatos:** Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.ufug.2022.127632](https://doi.org/10.1016/j.ufug.2022.127632).

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