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Hongxiao Liu[a,b,c], Perrine Hamel[*c,d,e], Léa Tardieu[e,f], Roy P. Remme[c,g], Baolong Han[h], Hai Ren[a]

[a] CAS Engineering Laboratory for Vegetation Ecosystem Restoration on Islands and Coastal Zones, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou, 510650, China

[b] Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), 511458, China

[c] Natural Capital Project, Dept. of Biology and Woods Institute for the Environment, Stanford University, Stanford, CA 94305 USA

[d] Asian School of the Environment, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

[e] CIRED, AgroParisTech, Cirad, CNRS, EHESS, Ecole des Ponts ParisTech, Université Paris-Saclay, F-94736 Nogent-sur-Marne, France

[f] Present address: TETIS, Univ Montpellier, AgroParisTech, Cirad, CNRS, INRAE, F-34093 Montpellier, France

[g] Present address: Institute of Environmental Sciences CML, Leiden University, Einsteinweg 2, 2333 CC, Leiden, The Netherlands

[h] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China.

***Corresponding author**: Perrine Hamel perrine.hamel@ntu.edu.sg

Hongxiao Liu: liuhx@scbg.ac.cn, michellewinter@126.com

Léa Tardieu: lea.tardieu@inrae.fr

Roy P. Remme: royremme@stanford.edu, r.p.remme@cml.leidenuniv.nl

Hai Ren: renhai@scbg.ac.cn

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Abstract

Incorporating nature-based recreation into urban planning analyses requires understanding the accessibility, quality, and demand for urban greenspace (UGS) across a city. Here, we present a novel tool that lowers the barriers to such information by (i) providing a spatially-explicit assessment of recreational UGS supply and demand; (ii) differentiating results by population group or UGS type; and (iii) using an accessible open-source software platform that facilitates scenario comparison and communication. In a case study in Paris, France, we demonstrate how the tool helps address important urban planning questions. We show that between 42% and 55% of the population is currently below the UGS target of 10 m^2 per person, depending on the accessibility criteria used. Using revealed preference data, we demonstrate that older adults are disproportionately affected by the UGS deficit. Our assessment of future scenarios reveals that UGS targets set by public policies are largely insufficient (500 to 2800 ha are planned by 2030, while more than 4000 ha are needed to meet the policy target). By combining the strengths of established geospatial methods, the tool helps researchers and practitioners produce a more nuanced analysis of the recreation benefits of UGS implementation.

1 Introduction

Recreation in nature benefits people in many ways such as providing aesthetic experiences, enhancing people's physical and psychological health, and increasing social cohesion (Liu et al. 2020, WHO 2016, Keeler et al. 2019), thus representing an important category of ecosystem services (ES). Urban greenspace (UGS) such as parks, residential gardens, or sports and recreation areas, provides urban inhabitants with a major, if not only, opportunity for recreation, relaxation, socializing and interacting with plants and animals in cities (Soga and Gaston 2016). Despite the multiple benefits of nature experiences, people worldwide are spending less and less time in contact with nature (Soga and Gaston 2016). An important driver is the decline in accessible UGS as populations have rapidly concentrated into urban areas that are largely man-made and highly segregated from nature (Grimm et al. 2008, Turner et al. 2004). As 68% of the global population will reside in cities in 2050 (United Nations, 2019), it is crucial to ensure UGS provision in urban planning to secure the opportunity for natural-based recreation.

Advances in urban ES science are expected to fundamentally change decision-making (Cortinovis and Geneletti 2018a, Wilkerson et al. 2018, Hamel et al. 2021). Modelling tools can greatly propel this process by quantifying, mapping, and exploring the impacts of possible land use decisions (Guerry et al. 2015). Although recreation is far more studied than other cultural ecosystem services, modelling tools are still under-developed (Luederitz et al. 2015). One impediment is that modelling recreation requires information on population's diverse preferences and use regarding UGS (Bateman et al. 2014, De Valck et al. 2017), which is often unpractical or costly to collect for entire cities (Ives et al. 2017). Alternatively, recreation is modelled at the neighborhood or community level, relying on surveys of people's use of and preferences for different UGS types. Accessible and reproducible data are essential to develop practical modelling tools to integrate recreation in UGS planning, especially when the purpose is to serve a wide range of cities and decision contexts (Hamel et al. 2021).

Both the quantity of UGS and recreational needs, i.e. where and what type of UGS people might use, should be considered in planning. Among simple approaches for modelling the recreation service, UGS standards—minimum targets for the amount of UGS that should be accessible (e.g., 10 m^2/cap) (Byrne and Sipe 2010)—have been widely used (Maruani and Amit-Cohen 2007; González-García et al. 2020). However, UGS standards provide limited practical insights for urban planning since setting a UGS standard of 10 m^2/hab does not indicate where and what type of UGS is needed the most (Badiu et al. 2016, Wilkerson et al. 2018). Needs-based approaches, relying on survey on residents' preferences and use of UGS, were developed to address diverse recreation preferences (Byrne and Sipe 2010) but they often concern smaller areas. Urban ES assessments provide a useful framework to provide spatial information on both UGS quantity and recreational needs (Baró et al. 2016, González-García et al. 2020, see Literature review). ES modelling tools that can translate UGS data into accessible and actionable information about where, how much and what type of UGS should be created will greatly help the implementation of UGS policies (Hamel et al. 2021).

Here we present a software tool to assess recreational UGS supply and demand to facilitate the incorporation of recreation service in UGS planning. This tool is available on a web-platform and is designed to be implemented as the "Urban Nature Access model" in InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)—a free, open-source software suite that models multiple ES delivered by nature (Hamel et al. 2021, Sharp et al. 2020). The model is easy to use and allows users to rapidly assess recreational UGS supply, demand and the supply-demand balance with flexible data requirements. Based on our review of the literature (Section 2), the tool application illustrated in this article improves on existing options to support decision making in several ways: (i) it allows for rapid calculation of recreational UGS supply and demand to aid assessments based on commonly available data; (ii) it is compatible with both a "UGS standard" approach and needs-based UGS assessments; (iii) it is supported by an online calculation and visualization platform that facilitates comparison and communication of impacts of different UGS planning scenarios. After describing the new model in Section 3, we present a case study in the administrative region of Paris, France, to demonstrate how it supports UGS planning with different data requirement.

2 Literature review

2.1 Recreational UGS supply assessment

Recreation service supply is defined as the biophysical capacity of ecosystems to provide recreational opportunities (Plieninger et al. 2015). The biophysical UGS attributes including types, area, size, accessibility, configuration, facilities, safety, maintenance, aesthetic, biodiversity, soundscape etc. have been considered as factors impacting recreation potential (Komossa et al. 2018, Paracchini et al. 2014). These factors can be broadly categorized according to availability and quality (La Rosa 2014, Stessens et al. 2020, Stessens et al. 2017).

2.1.1 UGS availability assessment

UGS availability measures the quantity of UGS within a defined area or distance threshold (Tratalos et al. 2016). Such measures are aimed at quantifying how much UGS is accessible for the population from a given location, usually residential areas. A number of studies have shown that availability of UGS correlated with actual use for physical activity (WHO 2016). In particular, Schipperijn et al. (2010) reported that use of UGS in Denmark is determined by area and distance to home, along with other factors. Three types of UGS availablity measurements have been studied.

First, cumulative opportunity indicators, such as UGS area per person, or the relative amount of green space (UGS area divided by total land area), within an area, often a predefined administrative boundary (Ekkel and de Vries 2017). For example, in UK's national ecosystem assessment, the percent of 17 types of environmental spaces within Local Authority District is mapped as culture ES availability indicator (Tratalos et al. 2016).

Second, proximity based indicators, i.e., presence of UGS of certain size within a distance threshold (termed as "accessibility" (Ekkel and de Vries 2017). The rationale behind this approach is that the size of a UGS determines the range of service the UGS is able to support (Stessens et al. 2017), and the UGS should be easily reachable for most of the nearby population. For example, the WHO Europe regional office recommends at least 0.5 ha UGS within 300 m linear distance from home (WHO 2016).

More advanced, the gravity model conceptualizes the service provided by UGS as declining with “resistance” (often proxied by distance), which can be described by a decay function (Liu et al. 2020, Baró et al. 2016). Accessible UGS is calculated by summing up the UGS areas corrected by the decay function within an area served by a given UGS (Liu et al. 2020). The two step floating catchment area method (2SFCA) further modifies the gravity model by introducing “floating search radius” since different age, social status may be willing to travel different distances for different types of UGS (Luo 2004, Xing et al. 2018).

As with many ES, it is important to note that the majority of UGS availability literature is concentrated in the global North and developed cities in Asia with few case studies from the global South and less developed Asian cities, despite their high urbanization rates (Boulton et al. 2018). A wide range of UGS availability has been reported in that literature, ranging from very low supply, for example 2.65 m^2/cap UGS in Hong Kong (public, collective and private UGS all included, (Jim and Chan 2016)), 2.5 m^2/cap in Schwerin, Germany (Wüstemann et al. 2016), and 4 m^2/cap in Macedonia, Spain, and southern Italy, to very high with 200 m^2/cap in some cities of German, Belgium and Austria (Fuller and Gaston 2009). Methodological studies found that data sources, UGS classification systems, distance thresholds, analysis techniques, and types of distance (network v.s. Euclidean distance) can greatly impact results (Mears and Brindley 2019). There is a call to develop standard ways to UGS quantification to interpret individual studies and understand differing results (Badiu et al. 2016, Mears and Brindley 2019).

Although there is no international standard for availability of UGS, the United Nations' objective is to provide universal access to safe, inclusive and accessible green and public space no less than 300 meters from each inhabitant residence by 2030 (Sustainable Goal 11.7, United Nations Department of Economic and Social Affairs 2014). In the literature, distances between 300m and 800m are often used as UGS accessibility standards with most European cities using 300m or 500m (Boulton et al. 2018).

2.1.2 Quality assessment

UGS includes a varied range of ecosystems and is able to provide a diverse kind of "quality" and satisfy different recreational needs (Rupprecht et al. 2015). The concept of UGS "quality" is complex and multifold. It is challenging to assess UGS quality, especially when integrating user's preference with spatial information (Stessens et al. 2020). At the landscape level, indicators such as naturalness, land cover, presence of or distance to water, protection status, diversity of landscape, and view shed etc. are used to assess and map recreation quality (Komossa et al. 2018, Paracchini et al. 2014). Indicator selection is usually based on literature or assumptions with a few exceptions that are derived from user's preferences (De Valck et al. 2017, Tardieu and Tuffery 2019).

At a finer scale, in-situ observational evaluative indices are developed to assess

UGS quality (Knobel et al. 2019). Generally, UGS size, recreational amenities such as water features or trails, facilities, and areas with organized recreational activities are common attributes associated with higher recreation quality (Donahue et al. 2018). However, these attributes are difficult to map at larger scales since some indicators (e.g., facilities or programming) rely on detailed and on-site investigation of individual UGS. New data sources, such as street view images, unmanned aerial vehicle images, and Google Earth images, are making such assessments possible. These data can be applied to delineate and classify urban environments at high accuracy and large scale (Pardo-García and Mérida-Rodríguez 2017). However, these approaches still constitute a research frontier, especially at larger scales.

2.2 Recreational UGS demand assessment

Understanding citizens' recreational needs is critical to design UGS that encourages urban dwellers to travel longer and spend more time to recreate (Byrne and Sipe 2010). There are significant differences in recreation preferences based on a number of demographic or social characteristics, such as age, gender, race, ethnicity, socioeconomic status (De Valck et al. 2017).

People's recreation preference and demand have been modelled using multiple approaches such as travel cost model (Binner et al. 2017, Tardieu and Tuffery 2019), discrete choice model (Vaara and Matero J 2011, De Valck et al. 2017, Ta et al. 2020) and hedonic pricing method (Loret de Mola et al. 2017, Sander and Haight 2012), and various data sources, many of which rely on surveys. Preference and visitation are collected through questionnaires, participatory mapping, or through on-site observations of usage of UGS (Bjerke et al. 2006, Polat and Akay 2015, Tardieu 2017). Demand and preference can be determined by extracting statistical relationships between UGS characteristics, personal characteristics of respondents and visitation choices (Tardieu and Tuffery 2019). The merit of surveys is that multi-dimensional variables can be collected, allowing in-depth analysis of demands and preferences. The disadvantage is that they are resource intensive and difficult to apply at large scales, and local case studies use a variety of measurements and survey protocols which makes it difficult to synthesize findings and develop generic models. To our knowledge, only the UK, Finland and Denmark conducted national monitoring of UGS use which provide multiple dimensional recreation profiles of the citizens (Fish et al. 2016, Kenter et al. 2014, Schipperijn et al. 2010, Toftager et al. 2011, Vaara and Matero 2011). Comprehensive, long-term and large-scale research on recreational use of UGS is lacking which hinders the development of widely applicable models.

Another line of research relies on collecting data from a large group of population through social media. Flickr (Donahue et al. 2018), Instagram (Schwartz and Hochman 2014), Twitter (Hamstead et al. 2018) and STRAVA (Sun et al. 2017) have been used to explore the relative use of UGS. Recently machine learning algorithms have been jointly used with crowd-sourced images to detect the type of interaction with nature (Richards and Tunçer 2018). Scholars have emphasized new opportunities provided by large crowd-sourced data for images, videos, and other sources such as activity tracking applications. These data provide new potential through near real-time monitoring, but also raise concerns regarding sampling bias, data structure and a lack of socio-economic information about visitors (Boyd and Crawford 2012).

2.3 Existing recreation service modelling tools

Multiple reviews on ES assessment tools have discussed recreation service modelling (Bagstad et al. 2013, Brown and Fagerholm 2015, Carter et al. 2012, Grêt-Regamey et al. 2017). Among the most popular models, Social Values for Ecosystem Services (SolVES) relies on a survey on public values and preference for locations to predict and map recreation value in landspape. SolVES can reveal heterogenous preferences for recreation but is problematic to transfer the results to unstudied area. The InVEST Recreation ("Visitation") model approximates visitation using Flickr photos and builds a regression model with environmental attributes layer (Sharp et al. 2020). However, the current InVEST recreation model (entitled "Visitation: Recreation and tourism", v3.8) is not suitable for quantifying daily recreation in UGS, as it relies on a dataset with a bias towards highly attractive areas. For example, a leisure walk in a pocket park is unlikely to result in a post on Flickr. The Benefit Transfer Toolkit developed spreadsheets based on a meta-analysis of existing case studies (Loomis et al. 2018). It allows quantifying the economic benefits of the recreation service in unstudied area, but the limited sample cases lead to high uncertainty in the approach. The ESTIMAP recreation model calculates three indicators that can be used for a European assessment of nature-based recreation: the Recreation Potential (RP), the Recreation Opportunity Spectrum (ROS), and the share of the population that can potentially profit from nearby nature for recreation purposes. RP is a composite indicator which estimates the capacity of sites to provide recreation services based on their naturalness, protection status and water component. ROS is derived by overlaying the RP indext and a proximity index. RP and ROS are used to derive the third one through a zonal analysi with population raster (Zulian et al. 2013). Other existing "off-the-shelf" recreation service assessment tools include ROS developed by U.S. Department of Agriculture for managing forest recreation, Outdoor Recreation Valuation (ORVal) tool developed by the Land, Environment, Economics and Policy Institute of UK, Natural capital planning tool (NCTP) developed by Consultancy for Environmental Economics & Policy of the UK, and on-site evaluation tools such as Quality of Public Open Space Tool (POST) and Neighborhood Green Space Tool (NGST). They are reviewed and compared in Supplementary Information A.

3 Model description

The following section describes the model algorithm. Our approach links recreation quality to different types of UGS in cities, in accordance with (Handley et al. 2002) and using a decay function to represent UGS availability. The interface of the online tool is described in Supplementary Information B.

3.1 Recreational UGS supply modelling

3.1.1 Default supply modelling

We adopted the 2SFCA method to model recreation supply (Luo 2004). This approach relies on rasterized data for population and UGS and involves two steps

(Figure 1).

In the first step, for each UGS pixel j (green pixel in Figure 1a), the algorithm computes the greenspace to population ratio (Rj) by dividing UGS area in pixel j (Sj) by population (p_k) in the search radius. Since visitation on UGS declines with distance to residential areas, a decay function $f(d_{kj})$ is applied to population values (Eq. 1).

$$R_j = \frac{S_j}{\sum_{k\in[d_{kj}\le d_0]} p_{k\times f(d_{kj})}} \quad (1)$$

Where Rj is the UGS to population ratio of UGS pixel j; Sj is the UGS area in pixel j (m^2); p_k is the population in pixel k; d_{kj} is the Euclidean distance between pixel k and j; d_0 is the search radius; $f(d_{kj})$ is the decay function describing the decline of service against distance. Five different forms of decay functions are available to use in the software: Dichotomy, Power function, Gaussian function, Kernel density function, and Poisson regresson function.

In the second step, for each pixel in the study area, the algorithm sums up Rj values from UGS pixels within the search radius (Figure 1b). Thus, UGS supplied to pixel i (Sup_i) is calculated as (Eq. 2) :

$$Sup_i = \sum_{j\in\{d_{ij}\le d_0\}} R_j * f(d_{ij}) \quad (2)$$

Where i is any pixel in the study area; Sup_i is the greenspace per capita supplied to pixel i (m^2/cap); Rj is the UGS-population ratio of a UGS pixel j; d_{ij} is the Euclidean distance between pixel i and j; d_0 is the search radius.

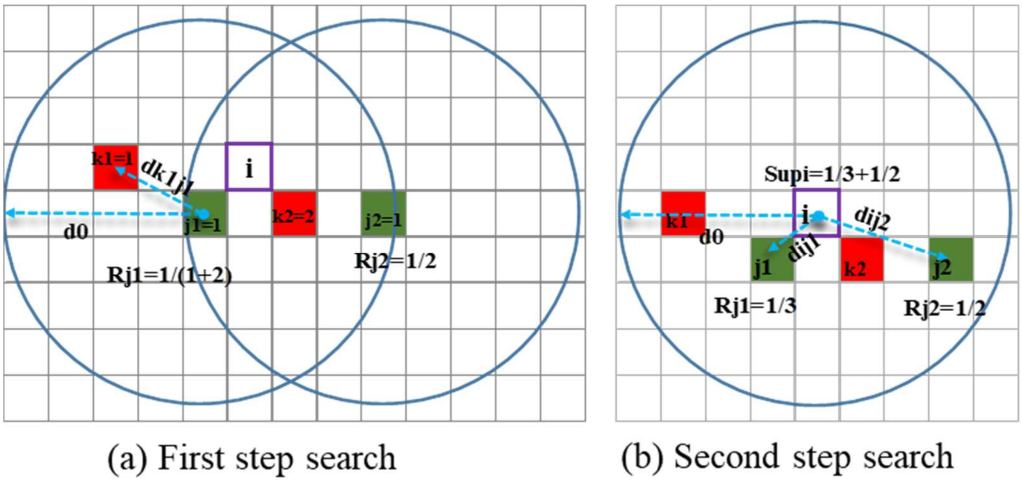


Figure 1. Two-step floating catchment area (2SFCA) method to calculate urban greenspace (UGS)-population ratio (a) and UGS supply (b). Green pixels represent UGS, red pixels represent inhabited pixels. Blue circles indicate the search radii around UGS pixels (step 1) and then any pixel in the landscape (step 2). Rj1 and Rj2 are the UGS-population ratios for pixels j1 and j2. Dk1j1 is the distance between pixels j1 and k1. Supi is the total UGS supply for pixel i. The dichotomy function is used in this example.

3.1.2 Modeling supply of different UGS types

The model allows users to distinguish between different types of UGS, e.g., forest, municipal park, and community park, which will impact recreation differently because of their qualities.

If r is the type of UGS and j is a UGS pixel of type r, and $d_{0,r}$ is the search radius for UGS of type r, the $R_{r,j}$ is calculated by the area of UGS in pixel j divided by the population within the radius. The recreation service supply of UGS type r to pixel i ($Sup_{r,i}$) is calculated by summing up the $R_{r,j}$ of UGS type r within the radius. The total UGS supplied to pixel i (Sup_i) is calculated by summing up the $Sup_{r,i}$ of all types of UGS:

$$R_{r,j} = \frac{S_{r,j}}{\sum_{k \in [d_{kj} \le d_{0,r}]} p_k * f(d_{kj})} \quad (3)$$

$$Sup_{r,i} = \sum_{j \in \{d_{ij} \le d_{0,r}\}} R_{r,j} * f(d_{ij}) \quad (4)$$

$$Sup_i = \sum_{r=1}^{r} Sup_{r,i} \quad (5)$$

3.1.3 Modeling UGS supply to different population groups

The model can take into account the different search radii of subgroup populations, which changes the supply of UGS. g represents the factors in which to split the population (e.g., age group g_1, g_2, …, g_N). Then the UGS supplied to g_n group of people in pixel i can be calculated as:

$$R_j = \frac{S_j}{\sum_{k\in[d_{kj}\le d_{0,g1}]} p_{k,g1} * f(d_{kj}) + \sum_{k\in[d_{kj}\le d_{0,g2}]} p_{k,g2} * f(d_{kj}) + \cdots + \sum_{k\in[d_{kj}\le d_{0,gn}]} p_{k,gn} * f(d_{kj})}$$

$$= \frac{S_j}{\sum_{n=1}^{N} \sum_{k\in[d_{kj}\le d_{0,gn}]} p_{k,gn} * f(d_{kj})} \quad (6)$$

$$Sup_{gn,i} = \sum_{j\in\{d_{ij}\le d_{0,gn}\}} R_j \times f(dij) \quad (7)$$

Where $Sup_{gn,i}$ is the UGS supplied to group g_n at pixel i; $p_{k,gn}$ is population of group g_n at pixel k; $d_{0,gn}$ is the search radius for group g_n; $f(d_{kj})$ and $f(d_{ij})$ is the decay function.

3.2 Recreational UGS demand modelling

We define demand as *the amount of UGS per capita within proximity*, described by two parameters: distance (d_0, in m) and amount (Dem_{cap}, in m^2/cap). The parameters can be calibrated by preferences from a survey, which represent preferences for UGS area and promixity (d_0 and D_{cap} can be differentiated according to sub population groups' preferences for more accurate assessment). Alternatively, users can define demand by applying a policy standard—for example, the Netherlands set the target of a minimum greenspace provision of 60 m^2 per-capita within a 500 m radius around households (de Roo, 2011).

3.3 Supply-demand balance at multiple scales

The per-capita UGS supply-demand balance is defined for each pixel i by calculating the difference between per-capita UGS supply and demand ($Balance_{cap,i}$) (Eq. 8).

$$Balance_{cap,i} = Sup_i - Dem_{cap} \quad (8)$$

To determine the balance for all people in pixel i ($Balance_i$), $Balance_{cap,i}$ is multiplied with population at pixel i (p_i), which indicates how much UGS is under-supplied or over-supplied at pixel i.

$$Balance_i = Balance_{cap,i} \times p_i \quad (9)$$

The administrative level supply-demand balance ($Balance_{adm}$) is the sum of the pixel level supply-demand balance ($Balance_i$) in an administrative unit (Eq. 10). $Balance_{adm}$ indicates how much UGS (m^2) is under- or over-supplied in an administrative unit. Since the UGS surplus in one pixel cannot compensate for a deficit in other pixels due to inaccessibility, Def_{adm} is calculated as the sum of only deficit UGS values which indicate real shortage of UGS (Eq. 11).

$$\mathrm{Balance}_{adm} = \sum \mathrm{Balance}_i \quad (10)$$

$$Def_{adm} = \sum |\mathrm{Balance}_i| \ \ if \ \mathrm{Balance}_i < 0 \quad (11)$$

If $Balance_{cap,i} < 0$, it indicates that people in this pixel are under-supplied with UGS compared to the defined standard. Summing up population in these pixels within an administrative unit will provide the number of inhabitants with less than recommended UGS in an administrative unit ($pop_{def,adm}$, Eq. 12).

$$pop_{\text{def,adm}} = \begin{cases} \sum p_i\,, & \text{if } Balance_{cap,i} < 0 \\ 0, & \text{if } Balance_{cap,i} > 0 \end{cases} \quad (12)$$

4 Application

4.1 Study area

Our study focuses on Paris, France and the surrounding region of Île-de-France (France). The region has an area of 12,061 km^2 and is home to a population of about 12 million people (Figure 2, Figure S5 in Supplementary Information, INSEE 2015). Since 2012, the amount of UGS has started increasing after a long period of decrease (Ta et al. 2020). However, the city of Paris remains a very densely populated area with a low amount of UGS per capita[1]. In 2013, the Île-de-France region adopted a masterplan that set a regulatory objective regarding UGS access, which should be achieved by 2030: supplying 10 m^2 of UGS per inhabitant in the region, giving priority to municipalities with less than 10% of open and natural areas (Institut Paris Région 2013). To reach this goal, the Green Plan ("Plan Vert") aims to create 500ha of additional UGS (Region Ile de France 2017), and the regional master plan aims to create 2300ha of additional UGS (Institut Paris Région 2013).

In this context, our study addresses three questions: (1) Where is the policy target of 10 m^2/cap met? (2) Which population groups are disproportionally affected by UGS deficits? (3) How would the implementation of planned UGS change the UGS

[1] According to the Green View Index (GVI) developed by the Massachusetts Institute of Technology, calculated using Google Street View panoramas, showing the percentage coverage of the canopy of a pixel: http://senseable.mit.edu/treepedia/cities/paris.

deficits?

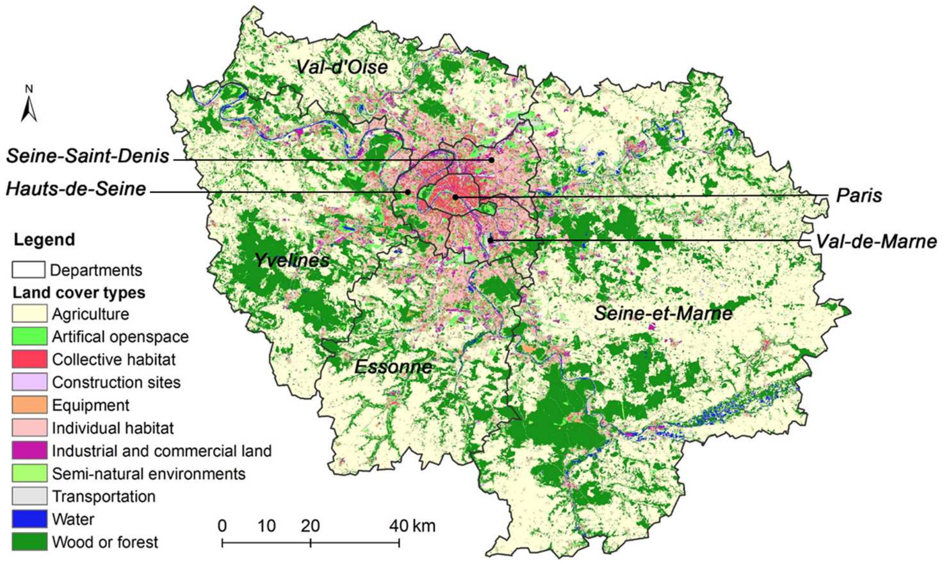


Figure 2. Land use map of Ile-de-France (based on MOS, 2017)

4.2 Data processing

4.2.1 Urban greenspace

We derived UGS data from an existing dataset for 2017 with 81 land use types (MOS 2017). UGS considered in the analysis include: (1) *forests* (MOS land cover code 1-4, including wood or forests, sections or clearings in the forest, poplar, open spaces with shrub or herbaceous vegetation); (2) *grassland* (MOS 7); (3) *water banks* (MOS 5, banks of waterways without harbor or storage activities); (4) *public parks and gardens* (MOS 13 and 25, parks and gardens, animal parks, zoos, amusement parks); (5) *free slots for camping and caravanning* (MOS 24). We did not include private gardens, outdoor sports fields, and golf course due to their restricted access. The total UGS area is 3859 km^2, equating to 31% of the study area.

4.2.2 Population

A disaggregation approach was used to produce a population grid at 100m resolution. We used IRIS level population census data collected by the National Institute of Statistics and Economis Studies in 2015 (vector, INSEE 2015). An IRIS unit is the smallest census unit available, which comprises between 1,800 and 5,000 inhabitants, with an average area of 10 ha. The population census data also include sociodemographic characteristics such as age, median available income[2], education etc. We projected the population from IRIS units based on the MOS land cover information (29 to 34, individual habitat, identical individual housing sets, rural habitat, continuous low habitat, continuous collective housing, discontinuous collective housing). The derived population map is as in Supplementary information (Figure S5).

4.2.3 Future scenarios

To illustrate the use of the model for urban planning, we have developed two spatial scenarios with additional UGS that represent alternative futures (Supplementary information Figures S6-7). First, we applied a scenario based on the Plan Vert that aims to create 500 ha of additional UGS by 2030 (Région Ile de France 2017). Second, we applied a more ambitious scenario based on the regional master plan ("SDRIF") with the objective to create 2800 ha of additional UGS by 2030 (Région Ile de France 2013). The two scenarios provide insight into what is possible

[2] The IRIS perimeters are joined with socioeconomic data from a large dataset on localized social and tax file (FiLoSoFi) provided by the national statistics institute (INSEE). The median available income corresponds to the median income (among residents in the IRIS) actually available to a household to consume or save, that is the primary income + transfer income - compulsory taxes.

with various degrees of greening in the region.

To develop the spatial scenarios, we first extracted all deficient pixels from the supply-demand balance at pixel level ($Balance_i$) for the current situation (i.e., with negative values). A 300m radius focal statistic analysis using ArcGIS was applied to this selection to incorporate all affected pixels in the subsequent selection steps.

For the 500ha new UGS scenario, we selected municipalities that were identified as *highly deficient* by the Plan Vert. Within these municipalities, 5557 pixels (about 500ha) with the highest UGS deficiency values for land use types *vacant land* (MOS 28), *open air parking* (MOS 75), and *quarries* (MOS 79) were converted to UGS to obtain the scenario map.

For the 2800ha new UGS scenario, we selected municipalities that were identified as *deficient* by the Plan Vert. Within these municipalities, 31111 pixels (2800ha) with the highest UGS deficiency values for land use types *vacant land* (MOS 28), *open air parking* (MOS 75), *quarries* (MOS 79), and *industry and business* (MOS 43-50 and 52) were converted to UGS to obtain the scenario map. The *industry and business* land use types were applied in this scenario to include more highly deficient areas in the Paris inner city.

4.3 Model set-up

To reflect the objectives from the regional masterplan (Région Ile de France 2013), we set the per capita UGS demand criterion (Dem_{cap}) to 10 m^2 for all analyses.

Model set-up for question (1): areas meeting the policy target

To assess where the per capita demand was met by the existing UGS (question

(1)) and demonstrate model calibration using only the policy target set by the SDRIF for 2030 (Région Ile de France 2013) (i.e., 10 m^2/capita), we used three distance thresholds (d_0) in accordance with the UN's goal and literature (Section 2.1): 300 m, 500 m and 800 m, which equal about 5, 10 and 15 min walking distances, respectively. The model was run without disaggregation of UGS or population groups and the dichotomy function was used (Table 1).

Model set-up for question (2): population groups disproportionally affected by UGS deficits

To assess which population groups are disproportionately affected by UGS deficits (question (2)) and demonstrate model calibration, we used a survey conducted in the region between April 15th and May 24th 2018. In total, 320 individuals have been face-to-face interviewed. They were asked to identify their residence, their most visited park during the year preceding the survey, their travel time to reach the UGS and the used travel mode. We also asked their number of visits in the park, and socio-demographic characteristics. The survey details and description of the sample can be found in Ta et al. (2020).

The travel distance between the most visited park and individuals' residence is calculated with Google maps, by calculating the distance between the respondent's municipality centroid and centroid of their most visited park. Distances were double-checked with the stated travel time declared by respondents.We assumed a 3.6 km/h speed by foot, 16 km/h by bike, and 60 km/h by car and public transport. To obtain the search radii for different age groups, a Poisson regression was applied to the stated number of visits. The count data models such as the Poisson or negative binomial are commonly used to analyse visitation data, as this type of models is particularly accurate when the dependent variable is an integer that takes few different values, such as visitor trips to a destination site (Shaw, 1988, Englin and Shonkwiler, 1995, Baerenklau et al. 2010, Roussel et al. 2016, Tardieu and Tuffery, 2019). When plotting the data, we found that the Poisson function best described the decay of visitation against travelled distance to greenspace in our dataset. This is confirmed by likelihood ratio test on alpha, representing the dispersion parameter in our regression, which showed that our dataset was not overdispersed, justifying here the use of a Poisson model over a negative binomial model. Visits have been regressed according to age class (coded as a dummy variable 1 if older adult: above 60 and 0 if adult: 18-60), and distance. The regression results can be found in Supplementary information Table S4. Accordingly to this Poisson regression, we derived the expected number of visits in a year and the expected distance traveled by the two age groups accordingly to the distance decay estimated for each group. Results showed that being older than 60 years old increases the probability of visits compared to being younger but decreases the willingness to travel implying a search radius for older adults lower than the one for adults (Figure 3). The search radius for adults ($d_{0,\ adult}$) has been estimated at 2860m in average, and the search radius for older adults ($d_{0,\ elder}$) at 1060m in average. We used the Poisson regression function as the decay function in the tool.

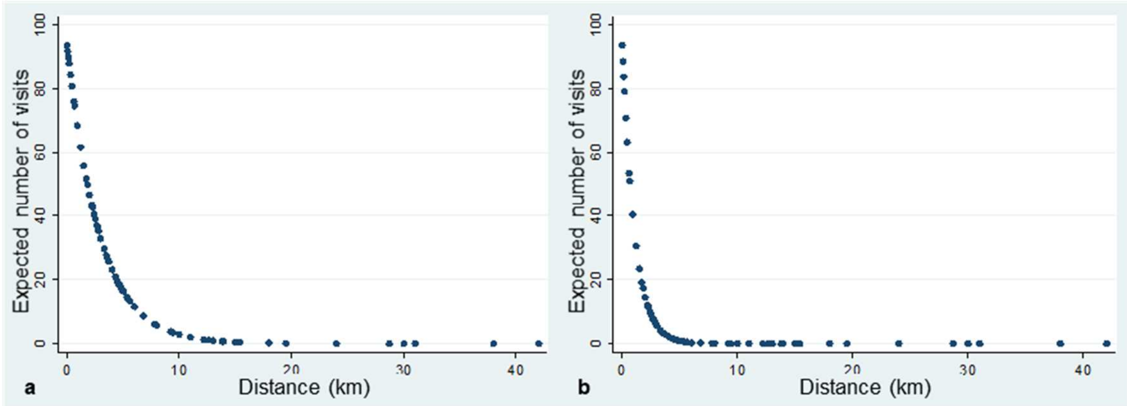


Figure 3. Distance decay effect on the expected number of visits to UGS for population under (a) and over (b) 60 years-old

Model set-up for question (3): expected change in UGS deficits

To assess how the scenarios would impact the UGS supply and demand (question (3)), we used a search radius of 300 m and the "dichotomy" decay function. To understand the impacts of the UGS planning scenarios on poplation subgroups, we analyzed the income level of the population for whom UGS supply improved.

Table 1. Input data and model settings for analyzing each UGS question (see text for details)

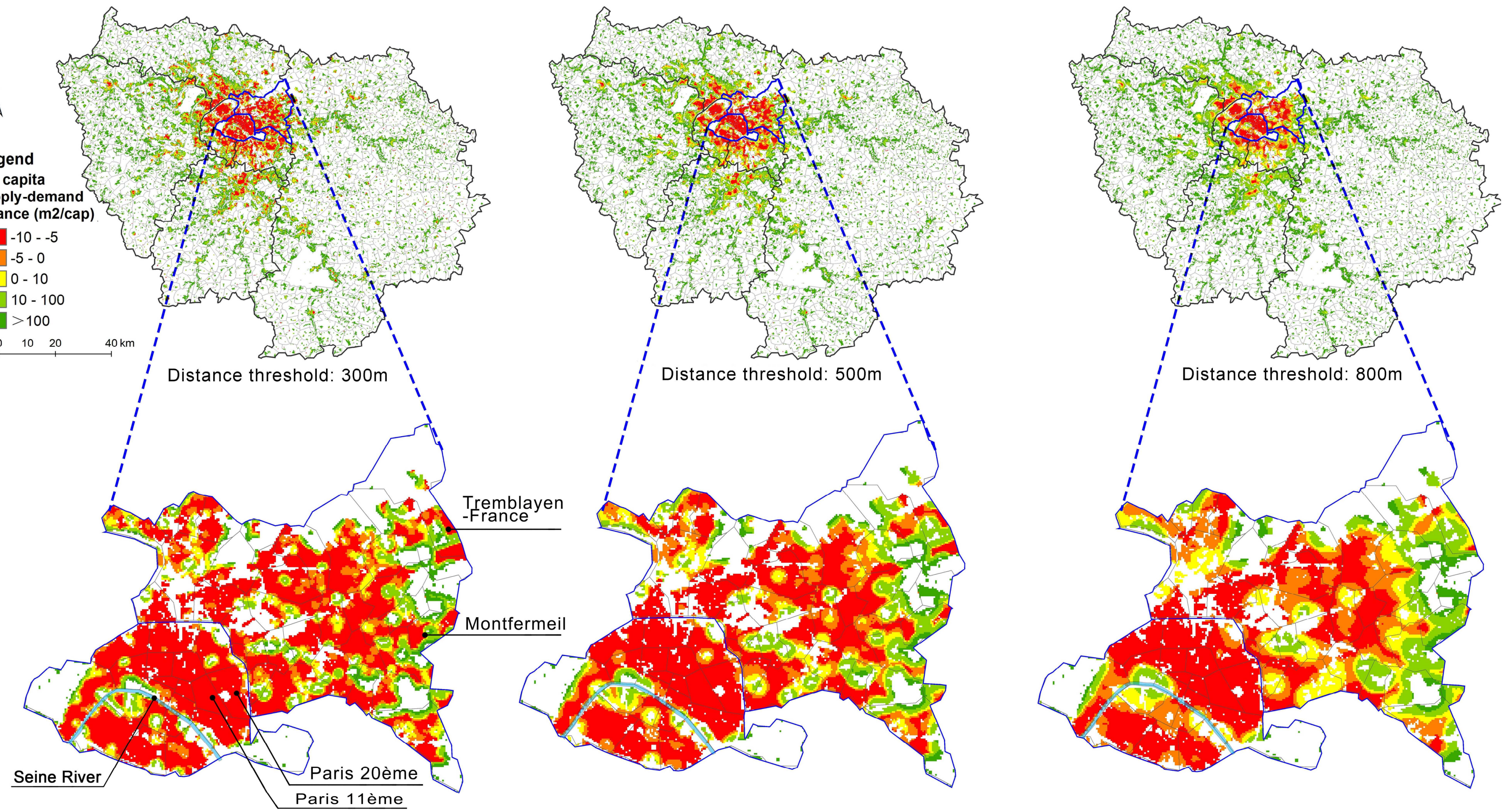
Input data	Question 1	Question 2	Question 3
Greenspace	MOS81[a]	MOS81[a]	Scenarios[b]
Population raster	100m raster[c]	100m raster[c]	100m raster[c]
Population structure	Census data [c]	Census data [c]	Census data [c]
Model expansion	Default	Split population	Default
Demand	$10m^2$/cap[d]	$10m^2$/cap[d]	$10m^2$/cap[d]
Search radius(m)	300, 500, 800[d,e]	Adult: 1060[f] Older adult: 2860[f]	300[d]
Decay function	dichotomy[d]	Poisson [f]	dichotomy[d]
Data sources	[a]: MOS 81 categories for the year 2017, available upon convention with the Institut Paris Region. MOS 11 available at https://data.iledefrance.fr/explore/dataset/mode-doccupation-du-sol-mos-en-11-postes-en-2017/information/ [b]: Scenarios developed as in section 4.2.3 [c]: iris population census data available at: https://www.insee.fr/fr/statistiques/3627376 [d]: policy target; [e]: literature [f]: survey in section 4.3 *Model calibration for question (2)*		

4.4 Recreation service in Île-de-France

4.4.1 Recreational UGS supply-demand balance against policy standard

The per capita UGS balance at pixel level is shown in Figure 4. Most deficit areas are located in the city center where population density is high. For the Paris city limits, the majority of people live in areas with a UGS deficit (300m threshold), although residential areas near large parks and along the Seine river have a UGS surplus. For municipalities close to large UGS, the deficit decreased as the distance thresholds increased from 300m to 800m (e.g., Montfermeil, Tremblay-en-France). However, for municipalities in Paris limits, the deficit remains even distance thretholds increases (e.g., Paris 11ème and Paris 20ème).

The UGS deficit area and percent of population under the recommended standard aggregated at the municipal level are shown in Figures 5 and 6. In accordance with pixel level results, deficit municipalities are mainly concentrated in inner-city areas and their number decreased with increasing distance thresholds from 300m to 800m. Many municipalities have a small or no UGS deficit: 505 and 1084 out of 1300 municipalities have no UGS deficit using 300m and 800m as search radii respectively (Table 2). However, at regional level, with the 300m radius, the total UGS area deficit is 4396 ha and the population with a UGS deficit accounts for 55% of the total population. With the 800m radius, the total UGS area deficit is 2810 ha and the population with a UGS deficit accounts for 42% of the total population.



475

476 **Figure 4. Recreation service balance (per capita UGS supply-demand balance,** $Balance_{cap,i}$**) in Ile-de-France region for different distance thresholds** (m^2/cap).

477 Blank areas mean there is no population on the pixel.

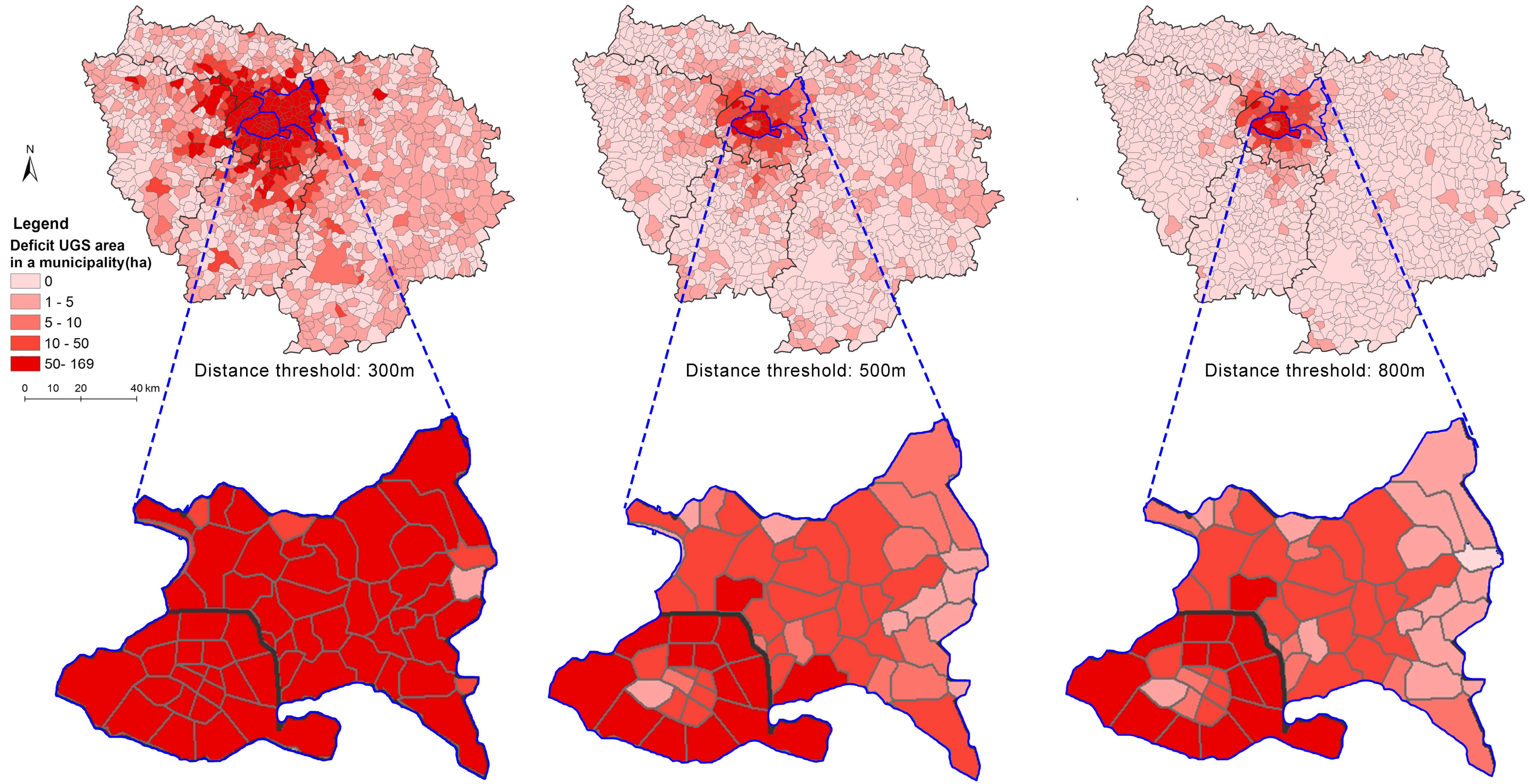


Figure 5. Recreation service deficit (*Def_{adm}*) in Ile-de-France region, for different distance thresholds. Policy target: 10 m^2 /capita

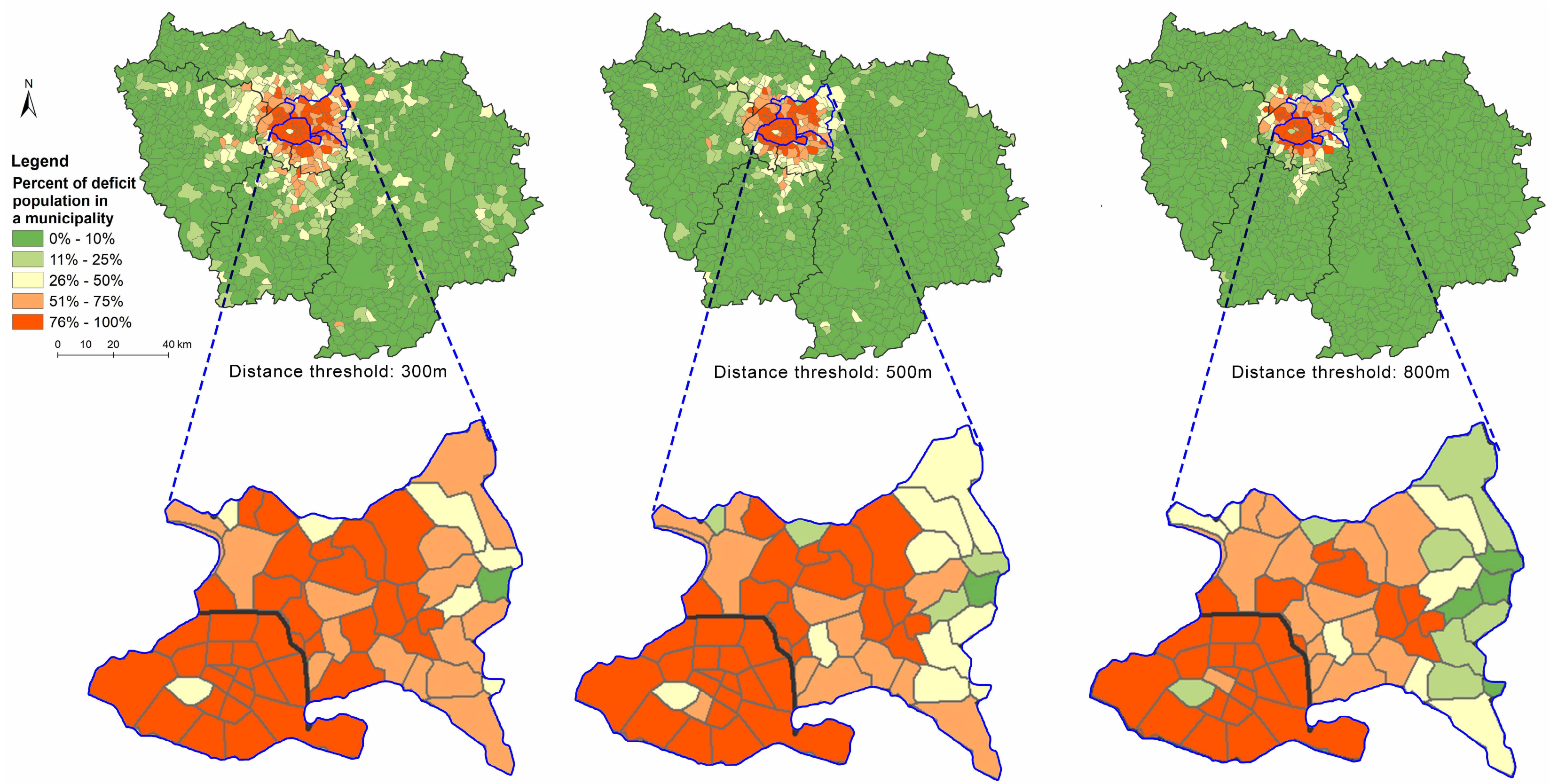


Figure 6. Percent of population below the policy target ($pop_{def,adm}$) in Ile-de-France region, for different distance thresholds. Policy target: 10 m^2 /capita.

Table 2. Number of municipalities associated with deficit UGS area and percent of deficit population using different distance thresholds

Deficit indicator and levels		No. of municipalities in relation to UGS deficit levels		
		300m	500m	800m
Deficit UGS area (ha) in a municipality	0	505	886	1084
	0-5	639	291	128
	10	48	42	24
	10-50	90	64	50
	50-169	18	17	14
	Municipal mean	3.38	2.67	2.16
	Region total	4396	3475	2810
Percent of population under UGS deficit in a municipality	0%-10%	901	1073	1147
	11%-25%	155	62	36
	26%-50%	100	64	36
	51%-75%	75	41	30
	76%-100%	69	60	51
	Region total	55%	48%	42%

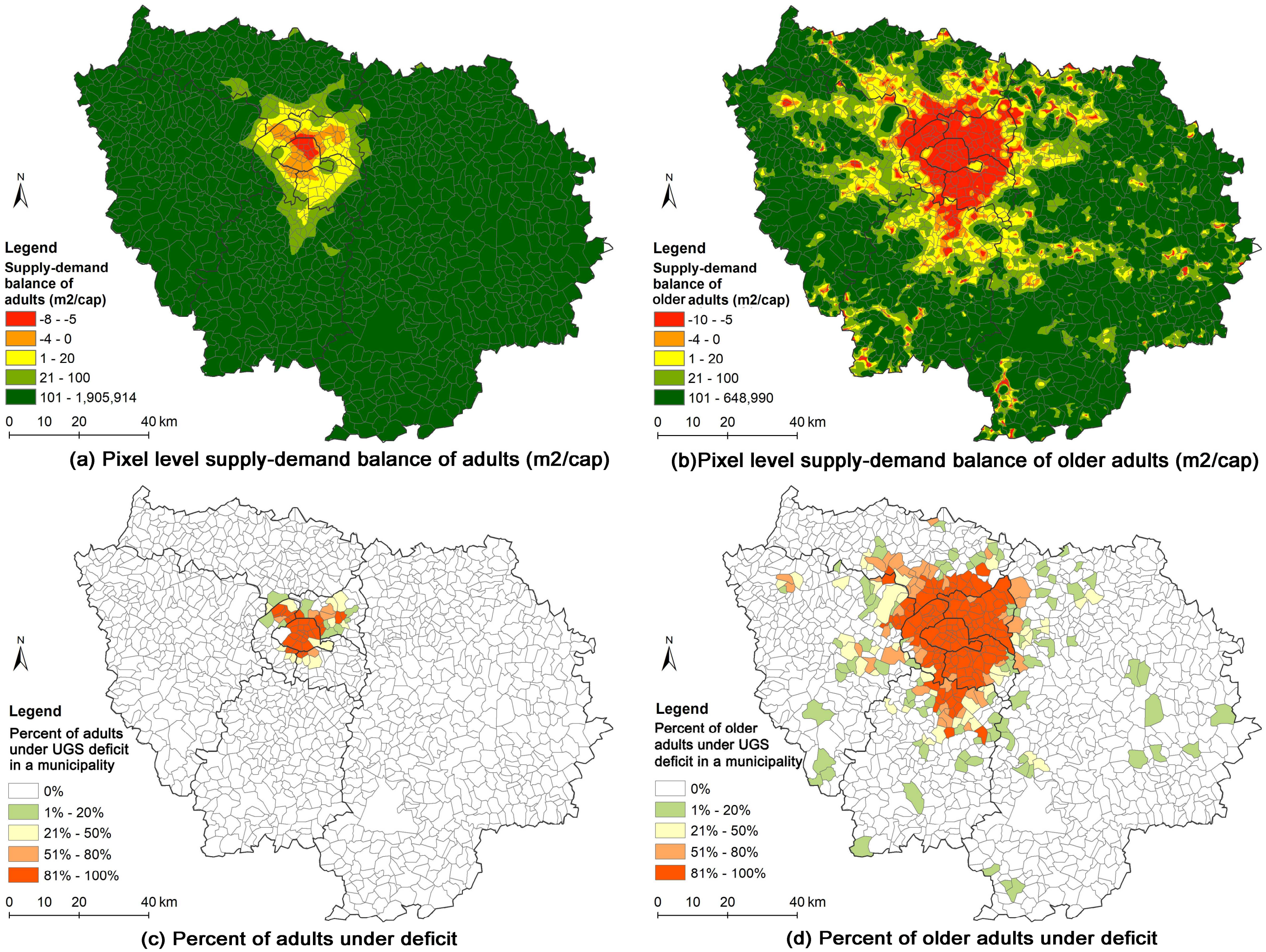
Note: Total population: 12.08 million. Total number of municipalities: 1300

4.4.2 Recreational UGS supply-demand balance among different age groups

There is a striking difference between the supply-demand balance between adults and older adults (Figures 4 and 5). The total number of older adults with a UGS deficit is 1,610,208 and number of adults with a deficit is 2,523,292. Adults with less than 10 m^2 UGS per capita are concentrated in a few inner-city municipalities, while the deficit among older adults is more widespread. For both adults and older adults, a higher percentage of people with a deficit are observed in and directly around Paris.

4.4.3 Supply-demand balance in future scenarios

Scenario 1 (500ha additional UGS) reduced the UGS deficit by 360ha, accounting for 8% of total UGS area deficit. This scenario elevated 270,639 people's UGS access over the 10m^2 UGS per capita policy target, alleviating 4.1% of total deficit population. Scenario 2 (2800ha additional UGS) reduced the UGS area deficit by 1582ha, accounting for 36% of the total UGS area deficit (Figure 8 a,c). This scenario reduced the number of people under UGS deficit by 1,381,591 accounting for 21% of the deficit population (Figure 8 b,d). Among the reduced deficit population, the majority were in the lowest income quantiles (64% and 80% respectively for Scenario 1 and 2) (Table 3).



503
504 **Figure 7. (a-b) Supply-demand balance , and (c-d) percent of population under UGS deficit, for different age groups.** *Policy target: 10 m^2/capita*

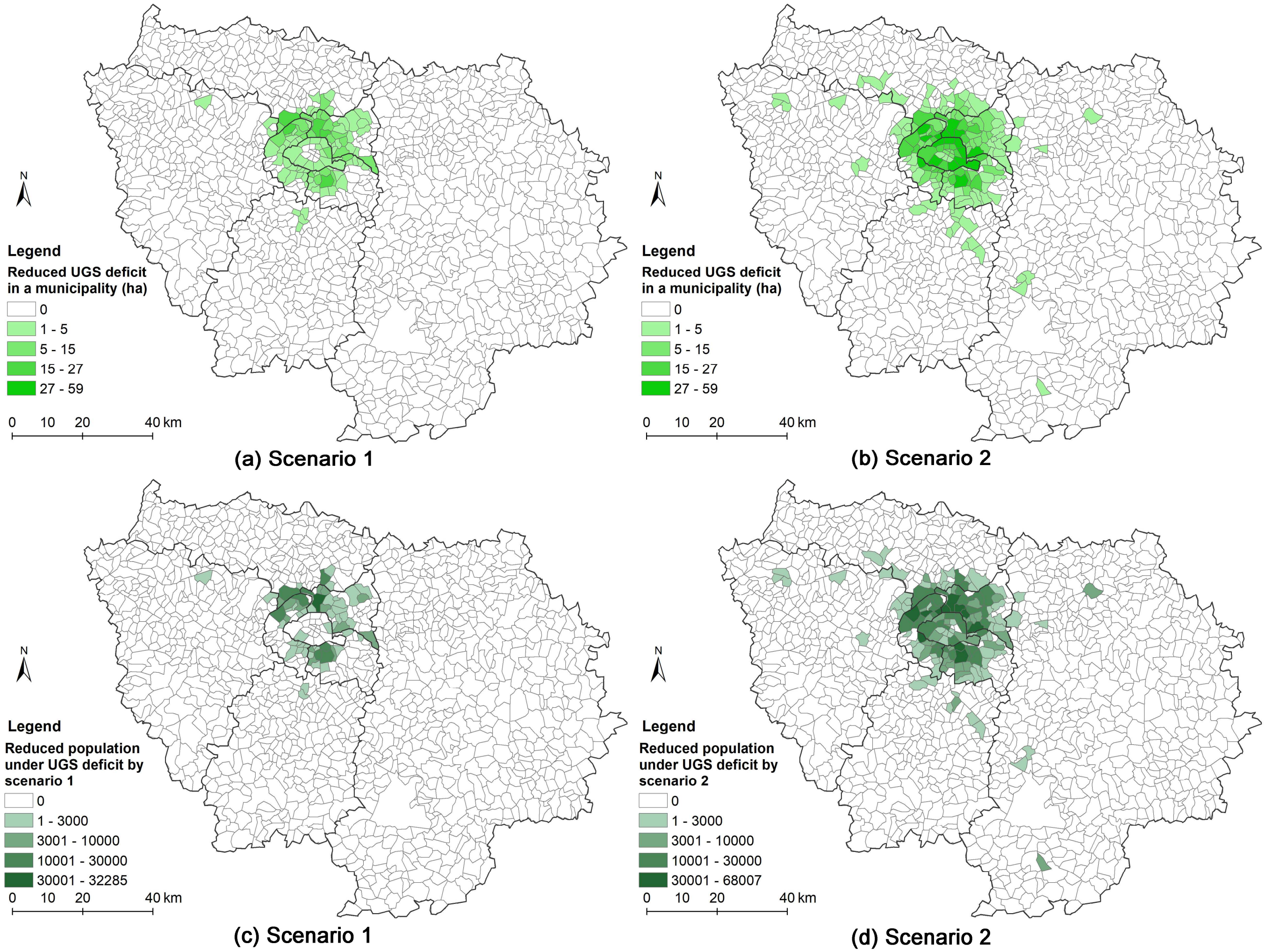


Figure 8. Reduced UGS deficit (top row) and population deficit (bottom row) in scenario 1 (maps a, c) and scenario 2 (maps b, d)

Table 3. Percent of reduced deficit population in each income quantile by two scenarios

Income quantile	Percent of reduced deficit population in each income quantile	
	Scenario 1	Scenario 2
Lowest 25%	55.5%	40.5%
50%	25.2%	24.0%
75%	13.7%	16.7%
Highest 100%	5.6%	18.8%

5 Discussion

5.1 Recreation service in Ile-de-France

Although UGS accounts for 31% of land surface area in the Ile-de-France region, 55% of population have less UGS than the desired target. An additional 4396 ha is required to meet the policy target for every inhabitant indicating that the master plan and Plan Vert objectives are not ambitious enough with regard to this service. Recreational UGS deficit showed a clear concentric pattern: high deficit areas are located in a few high-density municipalities in and around the city center, while high surplus areas are located in peripheric area, making the development of UGS in these deficient municipalities even more difficult (Liotta et al. 2020). This is not unusual, especially in large cities such as Paris, Guangzhou (Liu et al. 2020), or cities with historic central neighborhoods such as Amsterdam (Paulin et al. 2020).

When including dwellers' preferences and use in the model, an important finding emerges. The spatial difference in deficit in UGS between the general adult population and older adults (Figure 7) is important and can be explained by the fact that elder people are less likely to travel long distances to reach a UGS (represented by a stronger distance decay than younger people), even though they are generally the most frequent visitors (Bateman et al. 2003). This has been observed in Ile-de-France through the revealed preference analysis conducted in this study (Supplementary information Table S4) and through the stated preferences obtained from a choice experiment (Ta et al. 2020). This suggests that older adults are disproportionately affected by the UGS deficit in Paris, having less opportunities to access UGS. Given the benefits of UGS for the ageing population, this finding could be used to promote UGS areas that respond to specific needs of this population group. In Ta et al. (2020), conducting a choice experiment study in the region, this population showed a clear preference for the walking transport mode on short distances (~1000 m), having access to UGS with trees no matter the size of the UGS. Thus for this population what matters is not a minimum surface of UGS but an easy access to wooded areas.

Although the 10m^2/cap target is not very high compared with policy standards from other cities (Badiu et al. 2016), scenario analyses showed that in a densely populated city like Paris, achieving this goal is difficult due to the lack of available vacant land. In Ile de France, we found that most convertible land was located in areas with UGS surplus, and usually far from Paris. Conversely, in highly deficit areas there were not enough land to build UGS. Although converting business and commercial land (Scenario 2) would be costly, our results shows that it would be effective in changing the UGS supply-demand balance. This transformation is possible in urban renewal programs where old infrastrucutre, industrial or residential land can be converted. Building UGS in these area can bring significant accessbile recreation opportunity to people along side other ES which should be considered to justify the cost (Song et al. 2019). Other options would involve retrofitting buildings with rooftop parks, greening courtyards and school yards, or altering street scapes to create greenways along roads, which would create additional greenspace for people to recreate (Manso et al. 2021).

Our scenario analyses also illustrate the importance of the accessibility criteria to identify priority areas for UGS investment. We used the Plan Vert to target our UGS implementation, where the municipalities were identified based on the criteria of access to greenspace as well as "attenuating or aggravating factors" such as the presence of other vegetation type (e.g., agricultural areas) or future urban densification plans. Targeting these municipalities while allowing UGS creation only in a few land use categories, meant that the amount of UGS added to the area (500 and 2800 ha, respectively, for each scenario) is less than the reduction in deficit (360 and 1582 ha, respectively). Although this study was conducted for illustrative purposes only, additional iterations with stakeholders could reveal more optimal scenarios based on commonly agreed UGS supply criteria (e.g., distance to UGS, type of UGS considered, and type of conversion allowed to increase UGS supply, etc.).

5.2 Strengths of the geospatial tool

Here we have presented and applied a UGS supply-demand assessment model that facilitates urban planning through a multi-scale approach. In previous models, recreation service is often measured by population with access to UGS within a certain distance (Geneletti et al. 2022, Cortinovis and Geneletti, 2018b, Sikorska et al.

2020). Thus, these models obfuscate the differences between a crowded residence community that has access to a small UGS and an uncrowded residence community that has access to a large UGS. Our model takes these situations into account by measuring the recreation service using UGS area per inhabitant. Also, previous models typically assign weights to UGS quality indicators and produce a dimensionless composite indicator to represent recreation opportunity (Cortinovis and Geneletti, 2018, Stessens et al. 2017). Our model assigns different search radii and decay functions to different types of UGS and represents the corresponding recreation service using indicators with clear biophysical meaning (i.e., area of different types of UGS per person) which is easier for model users to understand. Our tool calculates the recreational supply-demand balance at the pixel and administrative levels. Pixel level supply-demand balance information can identify areas with highest deficiencies—where new UGS will most effectively mitigate a UGS deficit for recreation. The analysis at the administrative level supports a multifaceted analysis of UGS supply and demand by estimating the population under UGS deficit or surplus, differentiating between socio-demographic profiles. This information helps moving beyond "standards-based" approaches (Wilkerson et al. 2018), and allows model users to iterate and test different UGS planning scenarios. The model is currently available in an online visualization platform that facilitates comparing the impacts of different planning scenarios (Supplementary Information B). The advanced options of the model allows non-specialists to integrate information on citizen's preferences and use, and to easily map the demand according to different distance decays and probabilities of visit. This is, to our knowledge, the first online tool enabling these functions. The integration into InVEST as an open source model will allow users to run multiple ecosystem service models for a single study region (Sharp et al. 2020).

The Ile-de-France case study demonstrated how the model works with widely available data (land cover, population, and a policy target for UGS availability) to provide policy-relevant informations to urban planners. The flexible data requirement is an important feature, making the model applicable in cities with less data availability. Land cover and population data are available globally with inceasingly high resolution (GHSL 2019, Urban Atlas 2018, Worldpop 2017). Therefore, the model can be particularly relevant in rapidly developing cities in the global South where UGS analyses have not been conducted routinely (Rigolon et al. 2018). The model can provide results sensitive to socio-demographic composition and allow to identify the beneficiaries of UGS investment. For example, in our case study we found that the scenario developed according to Plan Vert and SDRIF master plan predominantly benefitted people (IRIS) with the lowest median available income. The model also allows to implement more sophisticated assessment based on recreational surveys to consider individuals' preferences, widely hererogeneous regarding recreational activities.

5.3 Limitations and potential improvements

Despite its strengths, the tool may be not be appropriate for all recreational activities. For example, since the model provides a static picture of UGS and population locations, its usefulness is limited for activities such as running or cycling, where UGS users can cover long distances. Future improvements to the model could include different accessibility indicators for UGS and include road and pedestrian networks to better represent the idea of the "cognitive distance" for users to reach UGS (Montello 1991).

Another limitation of the model is that it expresses results in area per inhabitant and does not output economic or health and well-being indicators (although it can include preferences as an input). Future work could expand the indicators to facilitate economic valuation, at different scales. Revealed preferences as hedonic prices or stated preferences such as choice experiments approaches have been extensively used in urban areas to estimate the willingnesses to pay of dwellers for each visits (Choumert and Salanie 2008, Tu et al. 2016). As we also have expressed the "willingness to travel" of people in the Poisson regression (based in the travel cost technique intuitions), or in a choice experiment (Ta et al. 2020), our indicator of preference (distance or time) could be transformed into a monetary indicator for individuals. However their implementation typically varies with socio-economic and demographic context, making a standard approach and a standard evaluation difficult to implement in the tool.

6 Conclusion

We have developed a tool that supports the assessment of recreational supply and demand in urban environments. The tool's main strengths are: (i) spatially explicit assessment of recreational UGS supply and demand based on commonly available data (land cover, population rasters); (ii) disaggregation of results by population group or UGS type; (iii) compatibility with simple quantitative and qualitative planning strategies (e.g., UGS per inhabitant standard, survey of population UGS preferences); and (iv) rapid and easily-accessible online implementation and visualization platform that facilitates comparison and communication of impacts of different UGS planning scenarios. A case study in Paris demonstrated the application of the tool to address questions such as: 1) Where is the policy target of 10 m^2/cap met? (2) Which population groups are disproportionally affected by UGS deficits? (3) How do UGS implementation scenarios change the UGS deficits? We showed how older adults may be differently affected by UGS deficits, and how the criteria for UGS accessibility impacts policy recommendations in practice. This type of analysis helps nuance the assessment of UGS by providing more information on the beneficiaries of UGS implementation scenarios, thereby improving the integration of the UGS recreation service in ecosystem-based approaches to urban planning.

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