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Accessibility of green areas for local residents

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ABSTRACT

Green spaces play an important role in urban areas. We study the accessibility of green urban areas by combining open data sets about green with population size data. We develop a mathematical model to define the population density of a green area and calculate the available green space depending on the location. To this end, we do not only consider walking distance to and size of the green area, but also take into account the local population size. Our model quantifies how the available green space depends on the location in the city, such that heavily populated areas have a small amount of green available, even when closely located to a green area.

1. Introduction

Green spaces play an important role in urban areas for maintaining biodiversity, for climate control, the amelioration of air pollution and fire protection (Haaland and van den Bosch, 2015). For residents, green spaces are used for relaxation, sports and for recreation. Studies show a positive relationship between the availability of green areas and health and well-being of residents (Ostoić et al., 2017; Ma et al., 2018; Stewart et al., 2018). The evaluation of available urban green space has been studied from different perspectives, such as city planning, user appreciation, availability and accessibility, and its function in the urban context. These studies have given city planners and municipalities tools to manage urban green spaces in their cities, for instance to promote ecosystem services in cities or to stimulate physical activity (Gunderson et al., 2015; Wolch et al., 2014).

The classification and evaluation of urban green spaces uses commonly accepted indicators such as availability and accessibility (Gupta et al., 2012; Lee and Hong, 2013; Kabisch et al., 2016; Yao et al., 2014). Availability of green urban space is a quantification of green spaces in relation to land use, expressed in terms of, for instance, size (m2), relative to city size (%) or population size (m2/citizen). Accessibility is a quantification of green space availability to general or specified public groups in relation to distance. Accessibility to green urban spaces is an indication whether the spatial distribution of green spaces matches the demand of nearby citizens.

Many case studies on availability and accessibility of green space have been performed in all parts of the world (Fuller and Gaston, 2009; Kabisch and Haase, 2013; Kabisch et al., 2016; Xu et al., 2019; Yao et al., 2014; Khalil, 2014; Gupta et al., 2016) and new factors have been added to the quantification scores (such as frequency of park visits, in relation to personal factors such as having children or dogs (Jasper et al., 2010), and the length of the visits (Kaźmierczak, 2013).

The quality or attractiveness of a green areas is defined in relation to motivation factors for visits, such as services available in the green area, crowdedness, or size of the green area. Crowded areas have a lower attractiveness, and especially in heavily populated areas, the distance to a green area and size of the area may not be the only determining factor for local residents to visit. People mostly recreate in the closest green urban area (see Kabisch et al., 2016). In Van Herzele and Wiedemann (2003), the authors study the accessibility of urban green space in the city of Ghent, Belgium. This study dictates that every inhabitant has to have a green space of at least 10 m^2 within 800 m from home, and this area has to be multiplied by the number of inhabitants to have a total green area that is big enough to assure that every person has at least 10 m^2 "to him or herself". In Xu et al. (2019), the authors also refers to over-crowded parks as a dissatisfaction factor. They address the quality of a park by distance, size and capacity and formulate different capacity categories based on size (eg city level parks of size 20–100 ha, community level parks of size 2–20 ha and district-level parks of size less than 2 ha).

All previous models in urban green space analysis did not take into account the population size differences between neighborhoods of the cities, but only use the total population of the city in combination with distance to and size of the green areas. Scores for the accessibility (available m2 per citizen) of the green areas within walking distance may be too optimistic for highly populated neighborhoods, especially when we include restrictions such as minimum green space per person.

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The purpose of this study was to explore mathematical models for accessibility of green urban areas that include population volumes within the catchment area of each green area and that has norms for minimum available green space. Using real local population volumes data (on a grid level of 100 by 100 m), we show that there are significant differences in accessibility to green areas for neighborhoods within cities. Our study quantifies the differences that citizens experience in accessibility.

Our approach relates to the two-stage floating catchment area method (Luo and Wang, 2003), that has been widely applied in health care accessibility (Luo and Qi, 2009) and other fields. As our approach the model is based on a gravity method, and population volumes are taken into account.

For urban green space analysis formerly only local detailed data was collected for small and local experiments. Citywide differences between neighborhoods cannot be shown in this way. On the other hand city level data such as population size, is not detailed enough to study differences between neighborhoods. The use of big data is rapidly becoming available (CORINE and Urban Atlas data are provided free of charge by the European Environment Agency in a shape file format, useable by ArcView/ArcGIS (Urban Atlas, 2012; Copernicus, 2012), allowing for scaled experiments and global standardized data models (Xu et al., 2019). We used detailed open data sets on local population sizes from the Netherlands to validate our model for the City of Amsterdam.

The remainder of this paper is as follows: in section 2 we describe the mathematical framework for green area accessibility including population density in a city. The results are shown in section 3 for the city of Amsterdam, Berlin and Vienna. First we only consider a basic model for which no information about the number of inhabitants is known. For Amsterdam we compare the basic model with our model that includes local population data. In Section 4 we discuss the benefits of modelling population density in a city, together with scale and distance of the green areas, and future research directions are addressed.

2. Methods

The used methods, consist of several parts. First, we use data about green areas and cities to calculate walking distances to green space. With this data, we can calculate catchment areas of green areas and minimal walking distances. Second, we use data about the number of citizens in each cell of a grid of a city to construct a model that calculates the population density of green areas. Last, we use this model to calculate the available amount of green area (in square meters) for each cell in the grid. For this research, we use open data that is described in Section 2.2.

2.1. Mathematical models

Here we explain the model that is used to calculate population density and available green space.

First, we give the following definitions.

- The **catchment area** is defined as all grid cells within R meters walking distance of a green area polygon, with R having values of 1500, 1000, 500 or 300 m.
- The **enhanced catchment area** is defined as all grid cells within R meters walking distance of a polygon with population density below a threshold value Q.
- The **population density of a green area** is measured by the total population of the area, divided by the size of the area (population/m2). A parameter Q is used as a threshold of desired population density, with values of 0.05, 0.2 and 0.5.

2.1.1. Catchment model

We first introduce a basic model which can be used for all European cities: only green area polygon data and walking distances are considered. City boundaries are extracted and a grid (100 × 100 m) is made for each city. For each grid cell, we compute the walking distance to each green urban area. With this information, we are able to create catchment areas and calculate the minimal walking distance for each grid cell.

2.1.2. Enhanced catchment model

When additional data about the number of citizens in local areas is available, a more extensive model can be used to calculate the population density of each green area and the amount of available green space (in m2 per person). The population density is also used to determine the enhanced catchment areas of each green area.

Let.

G	set of all green areas
C	set of all grid cells
d_{ij}	distance (in m) from cell i to green area j, $i \in C, j \in G$
a_j	area (in m2) of green urban area j, $j \in G$
p_i	population of cell i, $i \in C$

To determine the total population using a green area, we use the following rules:

- Each person can visit multiple green areas but the visit preference is weighted over all areas in the city such that it counts for one in total. Weights are always non-negative.
- The weight of one person visiting a certain green area depends on the distance. The larger the distance, the smaller the weight.
- The weight of one person visiting a certain green area depends on its size. The larger the area of a green area the higher the weight.

The weight of a person living in cell i, potentially visiting green area j, $i \in C, j \in G$, is:

$$w_{ij} = w_j^a w_{ij}^d, \tag{1}$$

where w_j^a is the weight of green area j related to its size and w_{ij}^d is the weight related to the distance from a grid cell i to green area j. At the end of this section, we discuss several weight functions.

The population that is potentially visiting green area j, $j \in G$, is:

$$P_j = \sum_{i \in C} \frac{w_{ij}}{W_i} p_i, \tag{2}$$

where W_i ensures that each person only counts for one. Note that P_j does not give the actual number of inhabitants that are visiting area j, but the potential number of inhabitants that can visit P_j.

$$W_i = \sum_{j \in G} w_{ij} \tag{3}$$

The population density of green area j, $j \in G$,is:

$$PD_j = \frac{P_j}{a_j}. \tag{4}$$

The population density gives for each green area the number of estimated visiting citizens per m2. Therefore, this can be seen as a measure of how busy a green area potentially can be. This measure can be used to calculate the enhanced catchment areas in which Q is the overall maximum population density that one is willing to accept for each green area.

Finally, we are also interested in the available green space and how this relates to the location in the city. Therefore, we use the population density and weight functions on size and distance to calculate the available green space (in m2) for each grid cell i, $i \in C$, A_i as follows.

$$A_i = \sum_{j \in G} \frac{\frac{w_{ij}}{W_i}}{PD_j}. \tag{5}$$

While the population density is a measure of the attractiveness of a green area related to the size and number of inhabitants nearby, the available green space for each grid cell can be seen as a measure of the accessibility to green areas from this grid cell.

We explore the results for a threshold population density Q and a maximum walking distance R. To do so, consider the set of all green spaces and all grid cells of a city. For each green area j we determine the population density PD_j and for each grid cell i we determine the available green space A_i. Then for each grid cell only the green spaces within a walking distance of R and only the green spaces with a population density less than Q are considered. We determine.

1. The available green space (m^2) per grid cell, and on average the available green space in a city;
2. The fraction of the city area that is within the catchment area of R meters of a green area;
3. The fraction of the city area that is within R meters of a green area that has a population density below Q.
4. The fraction of the population that is served by a green area within R meters and that has a population density below Q.

2.1.3. Modelling the weight functions

We use decay functions to determine the weights w_j^a and w_{ij}^d. As stated, the weight functions satisfy the following conditions: (1) the larger a_j the larger w_j^a; (2) the larger d_{ij}, the smaller w_{ij}^d; (3) $w_j^a, w_{ij}^d \geq 0$.

In Lee and Hong (Lee and Hong, 2013), the authors use the decay function the determine the spatial weight, proportional to the distance: "The higher the decay, the lower the tendency to travel even a slightly longer distance; thus more people would be willing to travel a short distance." Giles-Corti and Donovan (2002) say that although the use is inversely related to the distance, the decay also depends upon the attractiveness of the destination as well as the nature of the trip (in our case size of a green area). While in Lee and Hong (Lee and Hong, 2013) the decay parameter of the distance also depends on the size of the green area, we introduce two weights with a separate decay for size and for distance and multiply these weights.

The weight function with decay is based on a gravity model (Hansen, 1959). Hansen states that the accessibility at a certain point (grid cell) to another point (green area) is proportional to the attractiveness of the green area and inversely proportional to the distance between the grid cell and green area. We consider the size of the green area as an indication for the attractiveness.

The following functions are used:

$$w_j^a = a_j^{\beta^a}, \tag{6}$$

$$w_{ij}^d = d_{ij}^{-\beta^d}, \tag{7}$$

$$\beta^a, \beta^d \geq 0, \tag{8}$$

where β^a and β^d indicate the importance of the distance and area of the green space. In general holds: the higher β^d, the lower the tendency to travel a longer distance, but also, the higher β^a, the higher the tendency to travel to a larger green area.

In the result section, Section 3, we experiment with different parameters of the decay functions and compare this with a naive approach, where both β^a and β^d equals 1 (Giles-Corti and Donovan, 2002). states that a decay parameter of 1.91 should be used for parks, we will also experiment with this value for β^d.

2.2. Data

We used multiple open data sets about green urban areas, population size and walking distances.

2.2.1. Urban Atlas

For this research, we use the Urban Atlas data set from 2012. The Urban Atlas service offers a high-resolution land use map of urban areas within Europe (Urban Atlas, 2012). From this data set, we use the categories 'Green urban areas' and 'Forests'. Only areas with a minimum mapping unit of 0.25 ha are considered. The green areas are given as polygons. To avoid that single green areas are split into multiple area (due to crossing road), we combine polygons that are within 25 m of each other.

Green urban areas are defined as follows: "Public green areas for predominantly recreational use such as gardens, zoos, parks, castle parks and cemeteries. Suburban natural areas that have become and are managed as urban parks. Forests or green areas extending from the surroundings into urban areas are mapped as green urban areas when at least two sides are bordered by urban areas and structures, and traces of recreational use are visible." (Copernicus, 2012).

2.2.2. CBS data

The green areas are denoted by polygons and these polygons are plotted on a 100 × 100 m grid of the urban area. To calculate the population density, we use a data set that is made publicly available by CBS, the national statistical office of the Netherlands (CBS in uw Buurt, 2017). This data set gives for each grid cell of 100 × 100 m the number of citizens (rounded to five).

2.2.3. OpenStreetMaps

The distance to a green area is measured by calculating the actual walking distance from the center of a grid cell to the nearest edge of the polygon of the green area. To this end, we use APIs that are made available by OpenStreetMaps (Project OSRM, 2020). Moreover, we use OpenStreetMaps to find the boundaries of a city (Nominatim, 2020).

3. Results

As described in the previous section, we consider two models. The results are given in this section.

3.1. General result for different European cities

In this section, we give general results different European cities: Amsterdam, Vienna and Berlin. We only consider the basic model for which no information about the number of inhabitants is known.

In Table 1, we give some general results about the cities and the green area. This shows that Amsterdam has less green available per person and, although Berlin is twice as big, Vienna and Berlin are comparable in available green space.

Since Amsterdam has a smaller percentage of green space available, this city is expected to have a longer distance to the closest green area and the fraction of the city that is contained in the catchment areas is expected to be smaller. Tables 2 and 3 confirm this conjecture.

For urban areas the difference between walking and Euclidean distance can be decisive in the attractiveness of green areas for local residents. In general, the Euclidean distance can be calculated a lot faster than the actual walking distance. However, since Tables 2 and 3 show that the Euclidean distance can differ significantly from the actual walking distance, we chose to present results only consider the actual

Table 1
Statistics on green area and number of citizens per city. Total green area, percentage of green area and green area per capita.

City	Total green area (km2)	% of green area	Green area per capita (m2)
Amsterdam	16.79	7.65%	19.22
Vienna	112.75	27.17%	58.42
Berlin	225.62	25.32%	60.19

Table 2
Average distance to the closest green area over all grid cells. The results considering Euclidean distance (ED) and actual walking distance (WD) are compared.

City	Avg distance (WD)	Avg distance (ED)
Amsterdam	1051.45	649.75
Vienna	310.56	175.74
Berlin	338.40	197.12

Table 3
Fraction of the total city area that is contained within the catchment area of a green space, given the maximum walking distance *R*. Euclidean distance (ED) and actual walking distance (WD).

City	*R*	Fraction area (WD)	Fraction area (ED)
Amsterdam	1500m	0.78	0.88
	750m	0.64	0.76
	500m	0.53	0.66
	300m	0.40	0.52
Vienna	1500m	0.98	1.00
	750m	0.89	0.97
	500m	0.79	0.92
	300m	0.63	0.81
Berlin	1500m	0.99	1.00
	750m	0.89	0.97
	500m	0.75	0.91
	300m	0.56	0.76

walking distance in the remainder of this chapter.

In Fig. 1, the minimal distance to the closest green area for each grid cell is visualized. For Amsterdam we see that the walking distances in the North East and some parts of the North West parts of the city are longer. The North West is the harbor of Amsterdam, the North East part is a suburb with large green areas outside the city boundary, but very few green space within the city boundary. For Vienna and Berlin there are also well identifiable parts of the city with longer distance to green areas.

The population within the catchment areas cannot be calculated without data on local resident numbers. In Section 3.3 we include this data for the city of Amsterdam.

3.2. Results with population density: The Amsterdam case

In this section, we evaluate the models considering the population density for the city of Amsterdam. We use data with the population size of each grid cell. For comparison, we applied the same model to the situation where the total city population is equally divided over the grid cells.

3.2.1. Sensitivity of distance and area parameters

To study the impact of different weight functions on the available green space per grid cell, we performed a sensitivity analysis on the parameters β^d and β^a. The value of both parameters are varied between 0.25 and 3. We calculated different statistics on the amount of available green space per grid cell $A_i, i \in C$ for these parameters. The results can be found in the appendix, Tables 8–11 A selection of these results is displayed in Tables 4 and 5. In Table 4, the amount of available green space is considered for all cells, while in Table 5 only populated cells are taken into account.

In general, Table 4 shows that the results are strongly influenced by changing the distance parameters. A higher value of β^d (people are less willing to travel a slightly longer distance) also results in a wider range of available green space per grid cell. However, this effect is a lot smaller when only populated areas are taken into account, see Table 5. This indicated that large values of β^d mainly result in extremely high amounts of available green space for cells that are not populated. The median seems to be less sensitive for fluctuations in the parameters.

The results are less influenced by changes of the area parameter. However, higher values of β^a also result in a wider range of available green space per grid cell, especially in combination with a high value of β^d.

A similar result is shown in Fig. 2, where the amount of available green space is displayed geographically. Higher values of β^d and β^a result in a wider spread of the amount of available green space, but the location of areas with a relatively low or high amount of available green space remain similar.

3.2.2. Impact of considering local population size

The remainder of the results considers a selection of weight functions: naive (decay with $\beta^a = 1, \beta^d = 1$) and decay with $\beta^a = 1, \beta^d = 1.91$ (in line with (Giles-Corti and Donovan, 2002)).

To study the impact of the local population size, we compare the results with real population size with the case where the total population of Amsterdam is equally divided over all grid cells. When the population size is equally distributed over all grid cells in Amsterdam, the mean available green space is $19.93m^2$.

We visualize the amount of green space per grid cell (A_i, $i \in C$) in Fig. 3. The visualization shows that the equally divided population size data underestimates the amount of green space available in suburbs, and overestimates in the city center. Intuitively this is clear from fact that in the suburbs the population size differs from the average population size: there are areas with fewer residents (the harbor in the North West) and areas with more residents (other areas). In the city center there is fewer green space available due to competition of the green areas for the residents in the center.

Table 6 gives the fraction of the population and the area that are within the enhanced catchment area for different values of *R* and *Q*. This can be compared with Table 7, where population size is equally divided over the grid cells.

Comparing the results of Table 6 with the Amsterdam results from Table 3, it can be concluded that the fraction of the total population and area within R meters of a green area will be smaller when population density is considered. However, a value of $Q = 0.5$ does not have a lot of impact, since most green areas have a population density smaller than 0.5.

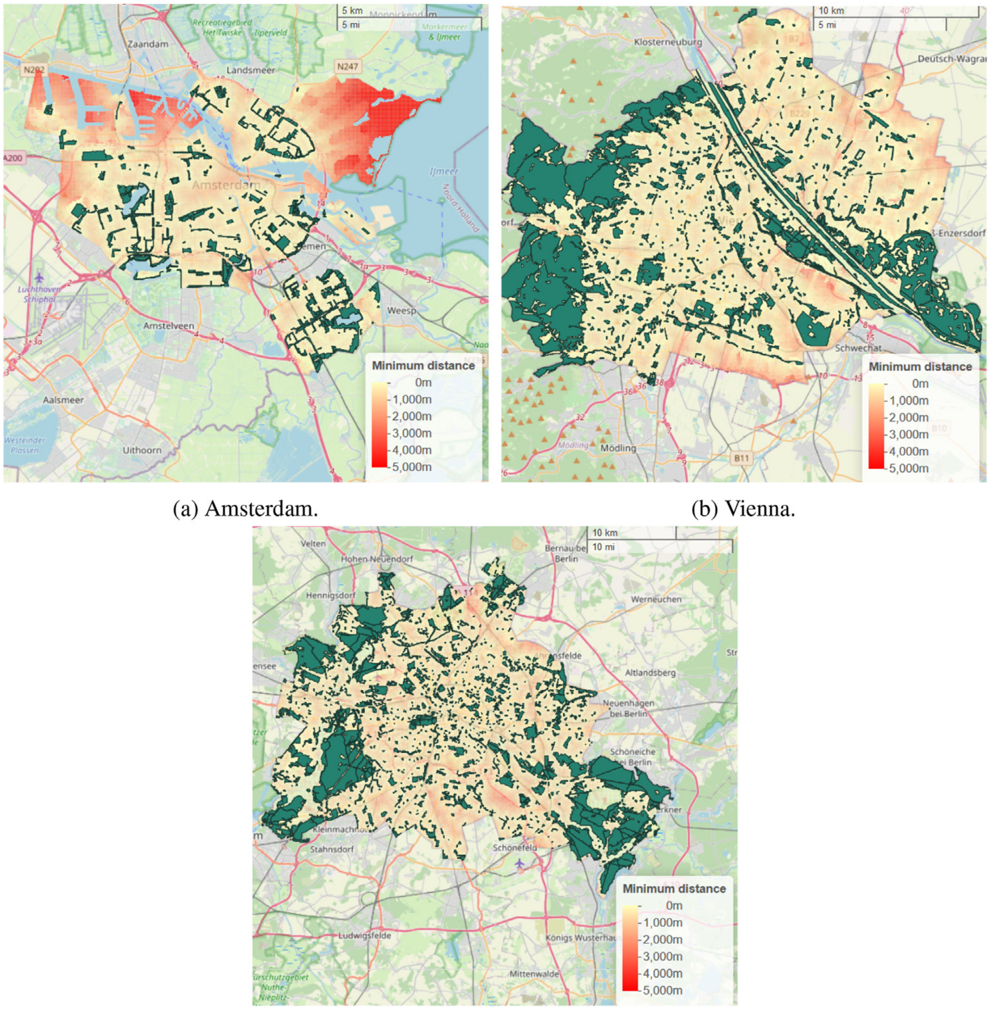
The comparison of Tables 6 and 7 show that the model with equally divided population is underestimating the fraction of the population that lives nearby green urban area. This can be explained since only few people live in the areas that are further away from green areas than 1500 m and this is not taken into account when the populations size is equally divided over all grid cells.

4. Discussion/conclusions

With a availability of urban data sets a data driven approach can enhance the understanding of accessibility of green urban areas. Previous accessibility models record the available green space (in m^2) averaged over the entire city, or the city population fraction that has a green area within a threshold (walking) distance. Clearly there will be differences between parts of the city, especially within large metropole areas such as Berlin. Specifying the “greenness” of a city can be ambiguous, depending on the relative measurement scale.

The findings in this study clearly show that adding the population density in the vicinity of urban green areas further specifies accessibility of the green areas. Neither the total population size of a city, nor available green space city wide is a dominant factor for accessibility of local urban green areas. Population size data is needed with local detail, to address the phenomenon that residents are more likely to go to green areas within walking distance.

Our model depends on two geographical units, the green areas and grid cells in the city, and on two variables to determine the accessibility: population density for each green area and available green space (in m^2) for each grid cell. The new data that is modelled is the actual population



(a) Amsterdam. (b) Vienna. (c) Berlin.

Fig. 1. Minimum walking distance to green urban area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 4
Selection sensitivity analysis results. Summary statistics for the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, all grid cells are considered.

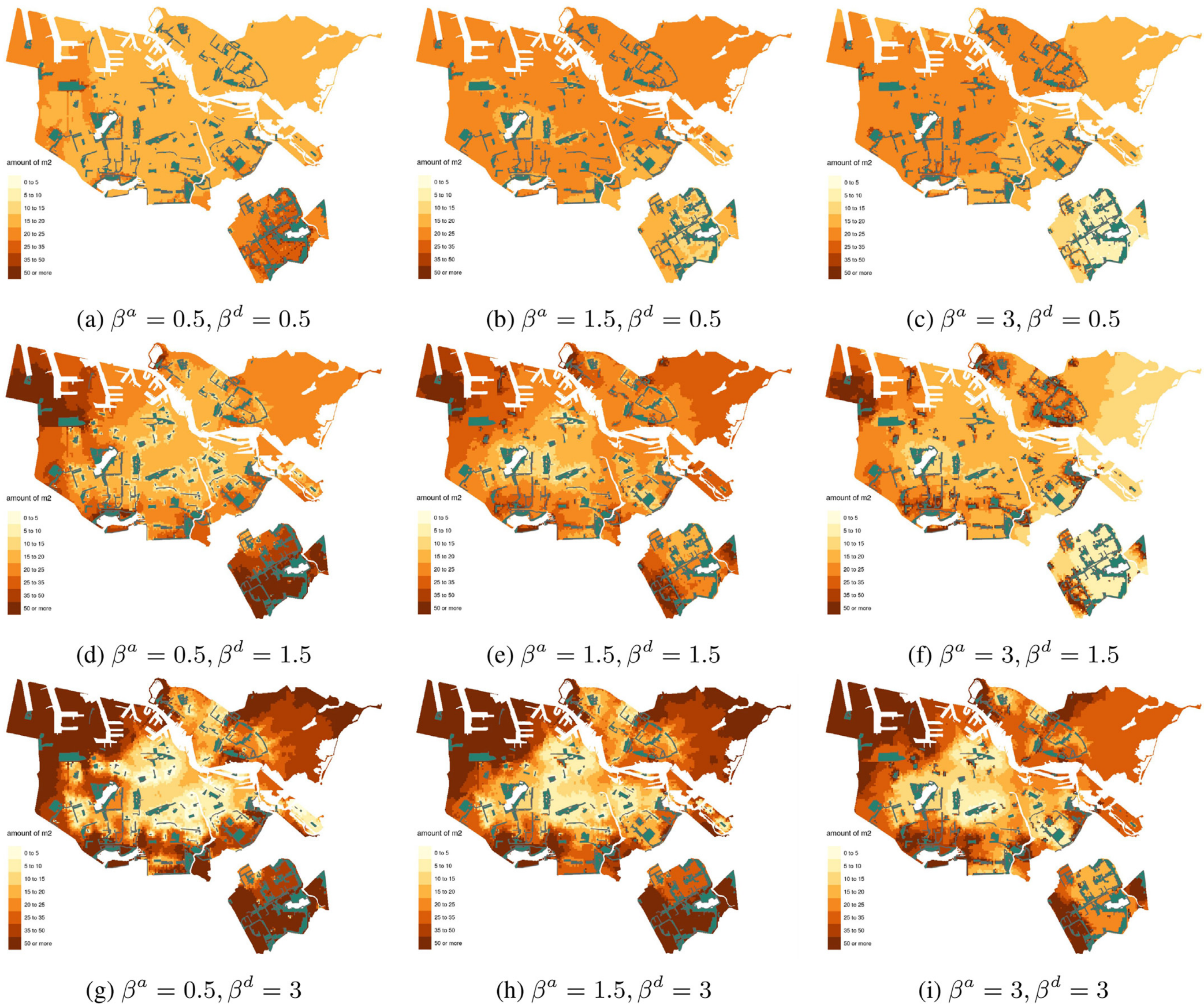
Parameters	Median	Mean	Standard deviation
$\beta^a = 0.5, \beta^d = 0.5$	19.32	20.75	5.01
$\beta^a = 0.5, \beta^d = 1.5$	23.14	29.84	21.86
$\beta^a = 0.5, \beta^d = 3$	38.06	156.55	415.94
$\beta^a = 1.5, \beta^d = 1.5$	24.47	29.63	28.04
$\beta^a = 1.5, \beta^d = 3$	17.29	94.36	766.08
$\beta^a = 3, \beta^d = 3$	29.21	1993.35	68125.95

Table 5
Selection sensitivity analysis results. Summary statistics for the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, only populated grid cells are considered.

Parameters	Median	Mean	Standard deviation
$\beta^a = 0.5, \beta^d = 0.5$	18.89	20.22	4.57
$\beta^a = 0.5, \beta^d = 1.5$	18.29	21.59	11.53
$\beta^a = 0.5, \beta^d = 3$	16.83	27.34	53.05
$\beta^a = 1.5, \beta^d = 1.5$	20.73	21.25	7.41
$\beta^a = 1.5, \beta^d = 3$	18.68	26.51	49.14
$\beta^a = 3, \beta^d = 3$	19.07	28.88	109.26

of each grid cell in a city, which is multiplied with the weights for distance and size of each green area to calculate the population density of a green area. This data is quite general and widely available, in contrast to data on local areas that needs to be collected. In comparison to the Enhanced Two-Step Floating Catchment Area (E2SFCA) application for health care (Luo and Wang, 2003; Luo and Qi, 2009) where the number of physicians is a linear function, we consider a nonlinear function with the size of the green space (a decay function). The sensitivity study shows that the travel distance tendencies to green areas with or without taking the population sizes of the local area into account significantly differ.

For a given grid cell we see that calculating the available green space variable (in m^2) by considering only green spaces with a maximum population densities of Q and within the vicinity of R meters walking distance gives an accurate representation of locally available green space, rather than average green space for all citizens. The model provides a spatial specification of the green space availability within a city. This specifies the variability of the fraction of the city population that is served by a green area. For the city of Amsterdam, we show that 90% (naive) or 87% (decay) of the population is within 750 m of a green space with

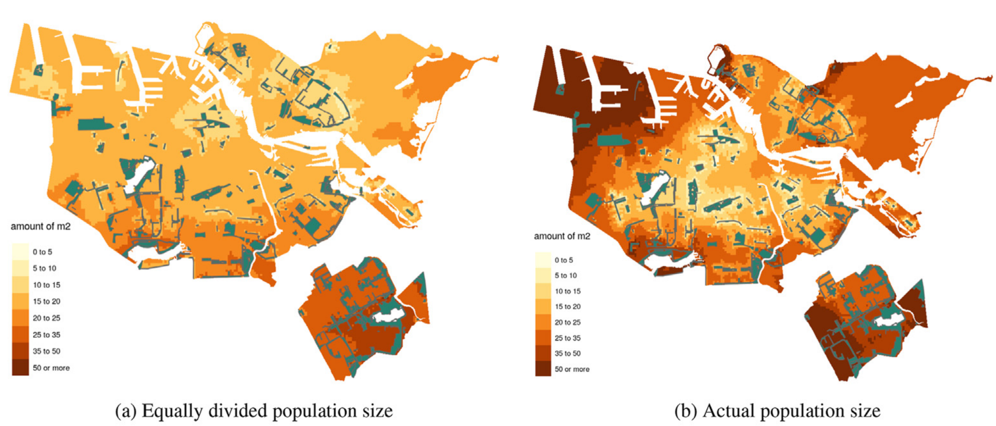


(a) $\beta^a = 0.5, \beta^d = 0.5$ (b) $\beta^a = 1.5, \beta^d = 0.5$ (c) $\beta^a = 3, \beta^d = 0.5$

(d) $\beta^a = 0.5, \beta^d = 1.5$ (e) $\beta^a = 1.5, \beta^d = 1.5$ (f) $\beta^a = 3, \beta^d = 1.5$

(g) $\beta^a = 0.5, \beta^d = 3$ (h) $\beta^a = 1.5, \beta^d = 3$ (i) $\beta^a = 3, \beta^d = 3$

Fig. 2. The amount of available green space (m2) for all grid cells in Amsterdam, considering different distance and area parameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



(a) Equally divided population size (b) Actual population size

Fig. 3. Amount of squared meters available per grid cell, for weight functions with parameters.$\beta^a = 1, \beta^d = 1.91$

Table 6
Amsterdam. Fraction of the total area and population that is served within the enhanced catchment area, given the maximum walking distance R and maximum population density Q. Naive: $\beta^a = 1, \beta^d = 1$; Decay: $\beta^a = 1, \beta^d = 1.91$.

		Fraction population		Fraction area	
R	Q	naive	decay	naive	decay
1500m	0.5	1.00	1.00	0.78	0.78
750m	0.5	0.90	0.90	0.64	0.64
500m	0.5	0.75	0.75	0.53	0.53
300m	0.5	0.51	0.51	0.40	0.40
1500	0.2	1.00	1.00	0.78	0.78
750	0.2	0.90	0.87	0.64	0.63
500	0.2	0.76	0.69	0.53	0.52
300	0.2	0.51	0.46	0.40	0.39
1500	0.05	0.54	0.53	0.58	0.57
750	0.05	0.30	0.29	0.37	0.37
500	0.05	0.20	0.20	0.29	0.28
300	0.05	0.13	0.14	0.21	0.21

Table 7
Amsterdam with population equally divided over all grid cells. Fraction of the total area and population that is served within the enhanced catchment area, given the maximum walking distance R and maximum population density Q. Different weight functions are used: Naive: decay with $\beta^a = 1, \beta^d = 1$; Decay: $\beta^a = 1, \beta^d = 1.91$.

		Fraction population		Fraction area	
R	Q	naive	decay	naive	decay
1500	0.5	0.78	0.78	0.78	0.78
750	0.5	0.64	0.64	0.64	0.64
500	0.5	0.53	0.53	0.53	0.53
300	0.5	0.40	0.40	0.40	0.40
1500	0.2	0.78	0.78	0.78	0.78
750	0.2	0.64	0.64	0.64	0.64
500	0.2	0.53	0.53	0.53	0.53
300	0.2	0.40	0.40	0.40	0.40
1500	0.05	0.52	0.40	0.52	0.40
750	0.05	0.34	0.30	0.34	0.30
500	0.05	0.26	0.24	0.26	0.24
300	0.05	0.19	0.19	0.19	0.19

more than $5m^2$ per person, and that people in the inner city area are within the 10% (naive) or 13% (decay) of the people not served by green areas.

The model was applied to the city of Amsterdam, with a comparison to Berlin and Vienna. According to Urban Atlas data, Berlin has the largest population in Europe, and Vienna has the largest green area within city limits within Europe. Both cities have on average approximately $60m2$ green space per person available, where Amsterdam is recorded to have only $19m2$ per person. However, our results show that this score depends on location in the city. Areas with a small population or close to green urban areas have much more green available while heavily populated areas within the city center have much less green space available. The general accessibility scores can denote the differences between cities, but for local planners the differences between neighborhoods should be incorporated for city planning.

Other possible extensions to the model involve the motivation to visit a local green area. The reason to visit a green area may depend on the services provided in the green area, such as sport facilities, dog areas, playgrounds for children and so on. Some studies (Stewart et al., 2018; Wu et al., 2018; Li et al., 2015) observe green area use, through location tracking (mobile devices, camera detection) or surveys and relate these to facilities. When the data is available about the services in green areas, the model can easily be adjusted to consider subsets of the green areas with the desired services.

Declaration of competing interest

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

Appendix

Table 8
Sensitivity analysis for different values of β^d (rows) and β^a (columns). Mean and standard deviation (between brackets) of the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, all grid cells are considered.

β^d / β^a	0.25	0.5	1	1.5	2	3
0.25	20.21 (2.49)	20.14 (1.79)	20.00 (0.14)	19.88 (1.29)	19.77 (2.15)	19.63 (3.03)
0.5	21.14 (8.74)	20.75 (5.01)	20.33 (0.96)	20.12 (2.37)	19.96 (3.93)	19.85 (6.23)
1	24.28 (15.65)	23.28 (10.06)	22.61 (5.47)	22.83 (9.82)	24.25 (24.82)	33.38 (118.26)
1.5	31.44 (28.67)	29.84 (21.86)	28.66 (17.09)	29.63 (28.04)	34.74 (79.22)	94.36 (766.08)
1.91	44.45 (56.33)	41.88 (47.14)	39.86 (41.70)	42.01 (63.62)	53.65 (220.03)	205.24 (2782.94)
2	48.67 (66.24)	45.82 (56.25)	43.60 (50.69)	46.13 (75.47)	60.00 (266.77)	239.41 (3378.49)
3	165.48 (453.22)	156.55 (415.40)	154.94 (409.62)	173.84 (567.51)	241.54 (1646.98)	1993.35 (68125.95)

Table 9
Sensitivity analysis for different values of β^d (rows) and β^a (columns). Median of the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, all grid cells are considered.

β^d / β^a	0.25	0.5	1	1.5	2	3
0.25	19.52	19.65	20.00	20.28	20.47	20.61
0.5	18.66	19.32	20.28	20.48	20.50	20.30
1	18.94	20.15	21.67	21.54	19.95	17.78
1.5	21.54	23.14	24.82	24.47	22.28	17.79

(continued on next column)

Table 9 (*continued*)

β^d / β^a	0.25	0.5	1	1.5	2	3
1.91	25.71	27.34	28.39	27.70	26.10	19.67
2	26.79	28.47	29.12	28.42	26.78	20.19
3	39.75	38.06	36.24	34.37	34.13	29.21

Table 10
Sensitivity analysis for different values of β^d (rows) and β^a (columns). Mean and standard deviation (between brackets) of the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, only populated grid cells are considered.

β^d / β^a	0.25	0.5	1	1.5	2	3
0.25	20.07 (2.43)	20.03 (1.75)	19.95 (0.12)	19.87 (1.35)	19.82 (2.27)	19.75 (3.19)
0.5	20.36 (7.75)	20.22 (4.57)	20.02 (0.68)	19.91 (2.29)	19.85 (3.80)	19.81 (5.71)
1	21.01 (11.32)	20.72 (7.87)	20.41 (3.16)	20.48 (4.85)	20.87 (12.06)	21.88 (31.52)
1.5	21.93 (14.53)	21.59 (11.53)	21.20 (7.12)	21.25 (7.41)	21.83 (17.71)	24.55 (73.90)
1.91	23.11 (20.10)	22.73 (16.92)	22.24 (12.35)	22.18 (11.93)	22.70 (22.69)	25.42 (82.67)
2	23.43 (21.87)	23.03 (18.58)	22.52 (13.91)	22.43 (13.41)	22.93 (24.19)	25.58 (84.02)
3	27.89 (58.88)	27.34 (53.05)	26.73 (48.25)	26.51 (49.14)	26.85 (59.86)	28.88 (109.26)

Table 11
Sensitivity analysis for different values of β^d (rows) and β^a (columns). Median of the amount of available green space (m2) per grid cell in Amsterdam using local population size data. For these results, only populated grid cells are considered.

β^d / β^a	0.25	0.5	1	1.5	2	3
0.25	19.35	19.49	19.93	20.29	20.64	20.87
0.5	18.33	18.89	19.98	20.36	20.54	20.72
1	17.67	18.46	20.21	20.30	19.46	17.78
1.5	17.51	18.29	20.01	20.73	20.11	17.00
1.91	17.22	18.06	19.70	21.13	20.70	17.36
2	17.14	18.00	19.58	20.97	20.66	17.67
3	15.53	16.83	17.91	18.68	19.30	19.07

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