Open space networks can guide urban renewal in a megacity

James H Thorne 1,*, Hyeeyeong Choe 1,2,4,*, Ryan M Boynton 1,3 and Dong Kun Lee 1

1 Department of Environmental Science and Policy, University of California, Davis, CA 95616, United States of America
2 Dept. of Ecological Landscape Architecture Design, Kangwon National University, Chuncheon 24341, Republic of Korea
3 Dept. of Landscape Architecture, College of Agriculture & Life Science, Seoul National University, Seoul 08826, Republic of Korea
4 Author to whom any correspondence should be addressed.

E-mail: hychoe@kangwon.ac.kr, jthorne@ucdavis.edu

Keywords: urban renewal, megacity, open space networks, connectivity, urban green area, street tree, urban park, redevelopment, Omniscape

Supplementary material for this article is available online

Abstract

As human populations move into cities they are increasingly isolated from the natural world, with associated negative impacts on health and well-being. However, as cities renew themselves through urban redevelopment and climate-adaptation, opportunities arise to improve people’s access to urban green areas that can be informed by modeling the network of urban open spaces. Recent research identified the need for multi-criteria indices of access to urban green spaces. Including open spaces such as empty lots, ground- and air-spaces surrounding buildings, and spaces associated with roads and other linear features can improve planning for urban greenspaces by identifying areas of opportunity for additional greening. Further, the gradient of interconnections among open spaces can be used to prioritize urban greening locations to build green networks. We modelled all open-space connections across 605 km² in Seoul, population 10.3 million, using Omniscape, a landscape connectivity model. We combined the resulting open-space connectivity map with distance-based indices for existing urban parks and street trees. Combining these criteria permits rank-prioritization of locations where new green spaces would most improve residents’ access. We found 2910 of 3375 (86.2%) locations where urban green spaces already exist within 300 m for city residents. Of the remaining 465 locations, 276 are in areas with the lowest-open space connections. For urban street trees, 44.3% of the 2588 km of the city’s major roads are already planted with street trees. Of the remainder, 210 km (8.1%) are located in the areas with the least connections to green spaces. Nine new urban parks would provide relief for the most highly-impacted areas, where the flow of open space is lowest and where no green spaces are available within 300 m. The integration of a spatial model typically used for conservation assessments with city planning provides useful additional context for building urban health.

1. Introduction

Over half the global human population live in cities and nearly 70% will do so by 2050 (United Nations 2013). This trend increases human need for open space in urban areas to offset the physical and psychological impacts of being disconnected from nature, a need amplified by the urban challenges of designing and preparing for climate change adaptation (Georgescu et al 2014) and mitigation (Childers et al 2015). As cities grow, examining the patterns of their open spaces holistically can inform the site selection of new green spaces, while ongoing urban redevelopment provides opportunities to create new useable green spaces and to strengthen the existing networks of open space (Rovai et al 2014). Open spaces in cities are often only thought of as parks or green spaces, which are widely recognized for their beneficial effects, even though they are declining in the majority of cities (Haaland and Konijnendijk van den Bosch 2015, James et al 2015). The benefits of urban green spaces include reduction of urban heat island effects (Zhang et al 2017, Yang et al 2017), reduction of runoff volume (Fintikakis et al 2011, Li et al 2017, Giacomoni and Joseph 2017), and stress relief (Thompson et al 2012). Green spaces may also be able to provide a network of suitable habitats for species movement (Aronson et al 2017).
However, urban open space is a broader category that includes all areas not occupied by urban structures. Urban open spaces include the air space above sidewalks and roads, undeveloped land, open water, and the landscaping and air space associated with various categories of buildings, in addition to urban parks and green spaces. In highly urbanized environments, these open or unoccupied spaces also offer some relief from congestion and in many cases could be planted to become green spaces for climate adaptation (Kim et al. 2018). Maps of open space in cities therefore represent current existing and potential future green infrastructure, and they can inform open-space preservation, enhance peoples’ access to and connections among open spaces, and be used to identify optimal locations for new green spaces and to guide construction and redevelopment processes. Such maps can also help identify urban ecological networks and their ecosystem services (Ahern 2013), which in turn can be used to inform nature-based strategies for improving city conditions and reducing climate change impacts (Hobbsie and Grimm 2020). This paper demonstrates how the connections and spatial patterns among urban open spaces can be used to select locations for new urban green spaces that improve residents’ equal access.

We mapped the connections (or flow) among all open spaces in Seoul, the capital of the Republic of Korea. Seoul occupies 605 km$^2$ (figure 1(a)) and with an average population density of 16,728 people/km$^2$ within the city boundary (Seoul Metropolitan Government 2018). Seoul is transected by the Han River (figure 1(a)), a large river spanned by multiple bridges. The city nestles among several large mountain ridges that form natural breaks in the city’s built environment, and to which open spaces within the city can be related. To map the connections we used Omniscape (Mcrae et al. 2016), a spatial model that is a moving window version of Circuitscape (Mcrae et al. 2013). These models are often used to map various types of connectivity across landscapes, which can inform conservation planning efforts (Keeley et al. 2018). For example, they have been used in over 400 biological conservation-focused studies to simulate landscape connectivity for specific animals (corridors) or to assess genetic connectivity at landscape or population scales (review in Dickson et al. 2018). Omniscape has also been used to map climate analogs, by modeling potential movement of species from historical climate conditions found in their range and future areas predicted to have the same climate conditions (Littlefield et al. 2017). The Omniscape model uses circuit-theory to quantify the connections to a target grid cell from all others within a set distance (Mcrae et al. 2016). As the program progresses from one grid cell to the next, the relative connectivity of the entire landscape emerges. Although Omniscape is usually applied to natural landscapes, we used it to quantify the flow of open space from the natural forests along the perimeter through a wide range of open space conditions in Seoul’s built environment.

We classified the Omniscape model output, a map of connections among all open space in Seoul, into five levels of open space flow (Choe and Thorne 2019). We then used additional maps of the parks and street trees in the city in conjunction with the class of lowest open space flow to identify locations where new urban greening efforts, through redevelopment, would provide the greatest benefits to city residents.

2. Materials and methods

2.1. Omniscape model parameterization

The Omniscape model is applied in a geographic information system. It uses a rasterized inputs and requires that every grid cell be scored for two values: source and resistance (Mcrae et al. 2013, 2016). For this study, source values were an index of the relative amount of open space in each grid cell, while the resistance values were an index of the relative level of difficulty expected to traverse each grid cell. Omniscape uses a moving window that quantifies the level of connectivity between a target grid cell to all the grid cells within a set distance. It then proceeds to the next target grid cell and repeats, until all grid cells have been modeled. We used Omniscape methods for urban environments (Choe and Thorne 2019) to map the connectivity of all open spaces in Seoul.

We used a vector map produced by the Seoul Metropolitan Government (2015; hereafter the SMG map), containing 39,418 polygons with a mean polygon size of 1.54 ha (SD 4.77 ha). The SMG map details 69 types of landcover, a combination of types for areas such as natural forests and riparian zones and also human uses of land, including 11 categories of residential and five commercial and business classes (supplementary table 1[available at https://stacks.iop.org/ERL/15/094080/mmedia]). The residential and business class categories also provided data on the number of floors in buildings and the proportion of each class with pavement (examples figures 2 (a)–(f)). To create input maps for Omniscape, we converted the SMG map to a 30 m resolution raster format using the ‘Maximum area’ option in ArgGIS (ESRI 2015), that assigns the most prevalent value to each grid cell when the grids are overlaid with the polygons. This was done to create the raster input requirements for Omniscape. To mitigate for edge effects, input land-use data needs to extend beyond the boundary of study area (Mcrae et al. 2016). For the lands adjacent to but beyond Seoul we used a 2009 landcover map (South Korean Ministry of Environment 2016) that we also converted from vector to the 30 m raster format.

To assign source and resistance values to each of the 69 landcover classes we used polygons in the SMG map (e.g. Figure 2(g)) to identify locations, and
geo-located imagery from Google Earth and Google Streetview (Google Digital Globe 2018), field visits and website photos (supplementary figures 1–60). We estimated the proportion of open space associated with each of the 69 categories using up to five images as well as the level of paving and number of floors from the SMG map. Some classes such as airports had fewer than five occurrences.

For the source values input to Omniscape, we ranked each of the 69 types (supplementary table 1) from 0–10 with 0 containing essentially no open space, and 10 containing the most open space (e.g. Figure 2(h)). Because imagery for drought-tolerant natural forests (classes H5 & H6 in the biotope map) and for planted forests (H1 and H2) was limited, we used modified rankings from natural forests (H3 and H4). For the resistance scores, which represent the difficulty or ease of movement across the landcover type in each grid cell, we ranked each of the 69 types from 1–19, with 19 being the least traversible (e.g. figure 2(i); table S1). We included a higher number of resistance than source classes to extract more detail in the output map, and also because the SMG map provided enough contextual data to permit a greater range of values.

The map for the areas beyond Seoul (South Korean Ministry of Environment 2016) consists of 23 landcover classes. We assigned these landcover classes to corresponding suitability and resistance scores based on the scores we developed for the more detailed map (supplementary table 1). The two map datasets were combined to form the study domain.

We excluded bridges over the main river that transects the city (the Han River). To remove these bridges from the land use map, we used the Shrink function (ESRI 2015), which replaces a specified number of cells with the value of the cell that is most frequent in the neighborhood. We shrunk bridges by one cell, replacing those values with the most frequent neighboring value, water.
Figure 2. Parameterizing the Omniscape Model. To parameterize the Omniscape model we first examined georeferenced locations described in Seoul Metropolitan Government (2015) landcover map using Google street view, field visits and online resources. The SMG map names 69 classes (table S1) such as 'residential buildings with 1–4 floors and <70% pavement' (a) or with >70% pavement (b); ‘5–10 story buildings with >70% pavement’ (c); roads (d); ‘planted areas <1 ha’ (e); and ‘natural forest dominated by native pine trees’ (f). A full set of images is provided in supplemental materials. We used these images along with the SMG map (sample area show in (g) with residential classes in tan, commercial in grey-to-black, and riverine in blue, and forest/planted area classes in green tones), to create the two input rasters for the model: source (h), an index of the level of open space, with green tones the most open and descending levels of open space in blues, yellow and browns; and resistance (i), an index of the relative ease or difficulty of movement across each grid cell. These two rasters were used by the model to generate a map showing the connectivity of open space (j). (Photo credit a, b, c: Image capture ©2019 Google; d: Hyeyeong Choe; e and f: James H Thorne).

2.2. Mapping the network of open space connections

After preparing the two input rasters, we ran Omniscape with a 3 km moving window, to trace the level of connectivity of each 30 m grid cell to all cells within 3 km (e.g. Figure 2(j)).

We summarized the continuous outputs into quintile classes of overall connectivity. The highest
quintile represents the areas with combined most open space and ease of movement. This classification has the effect creating contiguous areas with similar levels of open-space connectivity that can be used to assess different parts of the city.

2.3. Combining the open space network with spatial data for urban parks and street trees

After running Omniscape, we used the modeled outputs to find regions with high/low open spaces flows and accessibility, and combined the outputs with maps of Seoul’s urban parks and street trees. We used a 300 m distance to assess the accessibility of these green spaces for all city residents. This distance was chosen because many studies suggest that urban parks within 300–400 m of residents are accessed more and are associated with better health and well-being (e.g. Nielsen and Hansen 2007, Reklaitiene et al 2014, Triguero-Mas et al 2015).

2.3.1. Urban parks

People in areas with low- to no-open spaces benefit by the creation of new urban parks. The Create Fishnet command (ESRI 2015) creates a map of squares and their centroids across an area. We used the centroids from the fishnet command to map equally-spaced locations that would provide all residents in the city access to an urban park within 300 m, if every centroid was a green space (supplementary figure 61). The SMG map (2015) identifies Seoul’s urban parks. We removed the centroids that were inside of or within 300 m of existing parks. We classed the remaining points, those with no urban park within 300 m, by the five levels of open space connectivity.

2.3.2. Street trees

The redesign of transportation corridors to incorporate street trees (Mullaney et al 2015, Norton et al 2015) and better pedestrian walkability (Frank et al 2010) is already widely practiced in Seoul. We used maps of the city’s major roads (Ministry of the Interior and Safety) in Seoul and of the street trees (Seoul Metropolitan Government 2012). We stratified the major roads by the five levels of open space connectivity. We buffered the map representing individual street trees by 15 m to make polygons, and intersected the major roads with the street tree polygons to identify those lengths of roads that are treed and not treed in each of the five open-space connectivity classes. We identified the linear road length in kilometers in the highest urban density class, where planting to include street trees would provide the greatest relief to residents.

2.3.3. Priority ranking for new green space access

A recent review calls for a multi-criteria approach to assessing access to green spaces (Ekkel and de Vries 2017). To identify areas in greatest need of new green spaces in Seoul, we combined the low-flow zones from the open space network, with the locations of highest need for urban parks and/or street trees. We used the three sets of locations to rank-prioritize new urban green spaces.

3. Results

Ridgelines interdigitate with densely urbanized sectors in Seoul (figure 1(a)). These ridges, which are predominantly in various types of forest, provide a backbone for open-space connectivity. Riverine features provide a second major source of open space. Connectivity is observably strong in waterways, visible as green lines in several parts of the city (figure 1(b)). For the quintile analysis, the 10 largest areas in the lowest connectivity quintile range in size from 4.2–22.6 km$^2$ (figure 3; table 1).

3.1. Urban parks

An array of points that provide 300 m access from anywhere in the city finds 3375 locations in Seoul where an urban park is indicated. Of those, 2910 locations are already in a park, over open water, or are within 300 m of an existing park, leaving 465 points that do not have park access. Of those, 276 (59.3%) are in the lowest open space connectivity class (figures 4(a), (b); table 2).

3.2. Street trees

There are 2588.4 km of major roads in Seoul, of which 44.2% are already planted with street trees. Of the remaining 1443 km, most (32.4%) are found in level 3 of open space connectivity. In the quintile with the
The ten largest areas with lowest connectivity for open space within Seoul (numbered grey areas, showing satellite image). The other colors represent the four other quintile classes of open space flow, with green being the most open and natural vegetation-dominated areas.

Figure 3. The ten largest areas with lowest connectivity for open space within Seoul (numbered grey areas, showing satellite image). The other colors represent the four other quintile classes of open space flow, with green being the most open and natural vegetation-dominated areas.

lowest open-space flow, 40.3% of the major roads are currently not-treed (table 3; figures 5(a), (b)).

The largest block of low-open space connectivity (table 1) has 112.4 km of major roads, of which 43.3 km do not have street trees, including parts of a 7.6 km transit route that bisects the area (figures 4(c), (d)).

3.3. Three-way criteria for priority ranking of new green space access

Combining the three metrics creates a spatial index of the level of open space connectivity and green space access that can be used to prioritize locations for new urban parks, street tree planting and enhancing open space flow (supplementary table 2).

Of the 46 locations that are beyond 300 m of an existing park or tree-planted avenue (figure 6(a)), nine locations are also in areas with the lowest open space connectivity (figure 6(b)). Another 85 locations are >300 m from an existing park, and between 100–300 m from street trees.

4. Discussion

City open spaces and their connections, including green spaces, are the context in which urban structures exist. The mapped differences between patterns of open space and green space can be used to identify urban renewal opportunities. This information is highly relevant to city governments, many of which are attempting to improve their green spaces for climate change adaptation (Bowler et al 2010, Hobbie and Grimm 2020), to improve the life of their inhabitants (Lee and Maheswaran 2010), and to restore ecological processes (Plastrik and Cleveland 2018). For planning purposes, the flow of connectivity among open spaces adds a dimension to distance-based measures of human need for and access to green spaces in cities (Ekkel and de Vries 2017). By identifying areas that could become green spaces, open space connectivity maps permit better context during city planning processes for the future built environment.

Seoul’s urban parks, including those along its water courses and mountain ridges, are very important to city residents: 54.4% of respondents to a survey stated that they visit the city’s parks more than once a week (Seoul Metropolitan Council 2015), and Bukhansan National Park, the large ridge on the north of the city, received 5.5 million predominantly Korean visitors in 2018 (Korea National Park Service 2020). The mapping of the open space connections in Seoul provides better context for its planners because it addresses the total city environment, and can be used to prioritize locations for creation of additional green spaces. We used the connectivity map to visualize how connectivity stretches across neighborhoods and districts, to identify the ten largest areas where decongestion is needed, and to prioritize nine locations where new urban parks or street trees would improve
conditions for the city’s residents with the poorest access to green spaces.

The open space network map can help Seoul’s 25 district-level governments evaluate human conditions in areas not dedicated primarily to green space, and can provide context suitable for use in multi-district planning exercises (Choe and Thorne 2019). Urban plans comprised of mapped open space networks and ecological infrastructure assessments can also help align urban growth and redevelopment strategies to promote multiple objectives such as ecological resilience and better human conditions (Lee and Choe 2011). Questions about where to place and how to build new parks or street tree alignments in neighborhoods identified using the open space network map can be evaluated using recently developed policy and planning optimization approaches (Yoon et al 2019, Park et al 2020) that permit comparisons.

Figure 4. Additional locations in the city that would provide every location in the city access to a park or green space within 300 m. The level of open space connectivity is shown in 5 colors (a). Existing urban parks are shown in green, rivers in blue (b).
Table 3. The linear kilometers of major roads in Seoul stratified by the five classes of open space connectivity. Street tree maps permit the assessment of the level of linear greening along roads within the city and by open space connectivity class.

| Open-space flow | Total Roads | Roads with | Street without | Open-space connectivity class | Percent of all treeless roads found in each open space connectivity class |
|-----------------|-------------|------------|----------------|-------------------------------|---------------------------------------------------------------------|
| Low             | 522.6       | 312.2      | 210.4          | 1                             | 14.60%                                                              |
|                 | 746.5       | 391.7      | 354.8          | 2                             | 24.60%                                                              |
|                 | 789.1       | 321.1      | 468.1          | 3                             | 32.40%                                                              |
|                 | 435.9       | 109.9      | 326.1          | 4                             | 22.60%                                                              |
| High            | 94.2        | 10.5       | 83.7           | 5                             | 5.80%                                                               |
| Total           | 2588.4      | 1145.4     | 1443.1         |                               |                                                                     |

Figure 5. The major roads and street trees in Seoul are shown over a background of open space connectivity classes (a) and over existing parks and green spaces (b). Planting treeless road extents (c) that transect the low open space block could provide access to green space for people living along either side of the road. As an example of how open space connectivity and road data can be used together, the city's largest block of low connectivity is shown with black roads being those without street trees (d) (Photo credit c: Image capture ©2019 Google).

of the performance and costs of different scenarios.

Housing and population density are frequently used metrics to describe city conditions, but they need to be connected across larger extents to understand the city-wide effects of urban density and open-space flow. For example, urban heat island effects are negatively correlated with green spaces (Estoque et al 2017), and open space networks can be used to prioritize locations for urban heat island reduction. The guidelines for such plantings can be obtained from local studies modeling mean radiant temperature reductions possible with the addition of trees (e.g. Park et al 2018) or with a combination of heat mitigation actions (Park et al 2020). The Omniscape open space network can...
identify areas with similar characteristics, permitting the scaling up of modeling exercises such as the Park et al (2018, 2020) studies, to identify similar areas across the entire city. The network can also be used to help with trans-neighborhood passage by identifying where strong open space connectivity will encourage movement from one area to another.

Roads and other linear features have the potential to be used to increase the strength of the open space network and to improve access to urban green areas. Each of the 10 highest-density urban areas (figure 3) have roads that could be retrofitted to improve open-space flow (e.g. the black roads in figure 5(d)). Particularly if the linear features being retrofitted transect a highly dense area, they would contribute to reducing

Figure 6. The 46 locations most in need of additional green space, those that are >300 m from an existing park and >300 m from a road with street trees (a), portrayed over the five classes of open space connectivity. There are nine locations of the 46 that are in the lowest open space connectivity class, including the six shown here (b) in western Seoul.
uninterrupted high-density urban environments. In Seoul, cutting across these impacted areas by planting street trees could increase accessibility to urban green spaces for approximately 13,382 residents per project kilometer. With regards to new parks, their creation may in some cases raise concern from local residents about displacement. However, from a city planning perspective, with time horizons of 10–30 years, recognition of locations that need new parks can allow planners to take advantage of opportunities to obtain empty lots or buildings that come up for sale.

Regarding the broader landscape, Seoul’s open space connectivity map identifies links to areas beyond the urban periphery, which could permit open space in Seoul to be integrated into regional contexts (Liu et al. 2015), such as plans for sustainable regional infrastructure (Thacker et al. 2019). Integrating the Omniscape model outputs for Seoul with national conservation and climate change studies (Choe et al. 2017, 2018, Choe and Thorne 2017), or Korean peninsula wide connectivity models (Kang et al. 2019) could help national conservation and climate adaptation planning. Regarding our model’s outputs, two lines of further research could prove useful. First, to model the connectivity of Seoul for specific species groups and compare with the open space model presented here. This would address the suitability of our structure-specific model to inform ecological restoration in the city. Second, to model all of South Korea for connectivity based on its natural habitats, and to analyze how natural flow relates to the flow of open space in Seoul and other cities.

The input file ‘source’ represents the relative proportion of open space at 30 m resolution for the entire city, including urban green spaces and other categories. Omniscape’s output permitted the visualization of the strength of connections from one location to the next, based on the open space in each grid cell, the estimated difficulty to move across the cell, and the level of connection to all other cells within 3 kilometers. These structural characteristics of open space flow are similar to those in other studies. For example, a study of green space connectivity in Hong Kong found lower connectivity in older neighborhoods (Tian et al. 2017). We suggest that these densely urbanized areas, in Seoul circa the 1980’s (Han et al. 2019), are priority candidates for long-term planning of new parks or street tree plantings, to provide relief to people in these areas and to increase the value of homes through the improved access (Park et al. 2017). Among Seoul’s more recently constructed areas, we found that larger residential buildings typically provided more space around their bases, which could contribute positively to human wellbeing (supplementary figures 1–11). A concern for skyscraper-sized buildings is their exposure to wind shear (Gu and Quan 2004) at upper levels. Our mapping of open space between buildings combined with dominant wind patterns could also be used in planning applications to promote greater flow of wind through dense urban areas, which might provide some relief from air pollution and heat (Du and Mak 2018).

5. Conclusions

We found that Omniscape, a landscape-modeling tool typically used for conservation planning of natural landscapes, was suitable for identifying the connections among all open spaces in Seoul, and that it efficiently mapped the urban open space connectivity network across a large area. The map provides context for urban renewal processes including the greening of linear features and the placement of new parks. It can also inform objectives such as retention of existing parks and zoning restrictions to maintain areas with high open-space flow from being developed. Because Omniscape has relatively low levels of parameterization, connectivity maps of urban open spaces can be replicated for other large cities. Applying this approach to other cities would require maps of sufficient detail to identify a variety of landcover types, and the use of field validation or imagery to classify their relative levels of open space.

Acknowledgments

The authors thank Dr Brad McRae and Dr Carrie Schloss at The Nature Conservancy for use of their codes. We also thank two anonymous referees for constructive comments on the initial manuscript. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2019R1G1A1005770).

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: http://urban.seoul.go.kr/4DUPIS/sub7/sub7_7_4.jsp; https://data.seoul.go.kr/dataList/OA-1325/S/1/ datasetView.do.

ORCID iDs

James H Thorne @ https://orcid.org/0000-0002-9130-9921
Hyeeyong Choe @ https://orcid.org/0000-0003-2130-1622

References

Ahern J 2013 Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design Landscape Ecol. 28 1203–12
Aronson M F J, Lepczyk C A, Evans K L, Goddard M A, Lerman S B, Maclvor S, Nilon C H and Vargo T 2017 Biodiversity in the city: key challenges for urban green space management Frontiers Ecol. Environ. 15 189–96
Seoul Metropolitan Government 2012 *Seoul street trees inventory* https://data.seoul.go.kr/dataList/OA-1325/S1/datasetView.do

South Korean Ministry of Environment 2016 Development of Land Cover Map [7th] and Improvement of National Environmental Map System Request data at http://egis.me.go.kr/req/intro.do

Thacker S, Adshead D, Fay M, Hallegatte S, Harvey M, Meller H, O’Regan N, Rosenberg J, Watkins G and Hall J W 2019 Infrastructure for sustainable development *Nat. Sustain.* 2 3240331

Thompson C W, Roe J, Aspinall P, Mitchell R, Clow A and Miller D 2012 More green space is linked to less stress in deprived communities: evidence from salivary cortisol patterns *Landscape Urban Plann.* 105 221–9

Tian Y, Liu Y, Jim C Y and Song H 2017 Assessing structural connectivity of urban green spaces in metropolitan Hong Kong *Sustainability* 9 653

Triguero-Mas M, Dadvand P, Cirach M, Martinez D, Medina A, Mompart A, Basagaña X, Gražulevičienė R and Nieuwenhuijsen M J 2015 Natural outdoor environments and mental and physical health: relationships and mechanisms *Environ. Int.* 77 35–41

United Nations (UN) 2013 *Sustainable development changes. world economic and social survey 2013* (Department of Economic and Social Affairs, United Nations) http://www.un.org/en/development/desa/policy/wess/wess_current/wess2013/WESS2013.pdf

Yang C, He X, Wang R, Yan F, Yu L, Bu K, Yang J, Chang I and Zhang S 2017 The effect of urban green spaces on the urban thermal environment and its seasonal variations *Forests* 8 1–19

Yoon E J, Thorne J H, Park C, Lee D K, Kim K S, Yoon H, Seo C, Lim C, Kim H and Song Y 2019 Modeling land use adaptations to mitigate climate change impacts on disaster rice yield and species richness using multi-objective genetic algorithms *Environ. Res. Lett.* 14 024001

Zhang Y, Murray A T and Turner B L 2017 Optimizing green space locations to reduce daytime and nighttime urban heat island effects in Phoenix, Arizona *Landscape Urban Plann.* 165 162–71