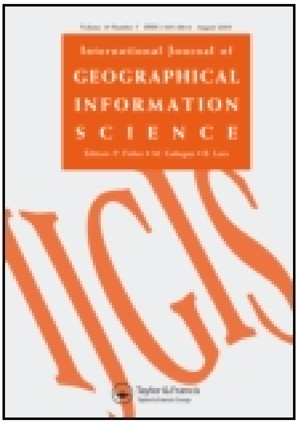

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Virtual city models for assessing environmental equity of access to sunlight: a case study of Kyoto, Japan

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Virtual city modelling is expected to play a central future role in the field of urban planning and design. Currently, most of the uses of this modelling method are related to the production of visualizations, but there is also a potential for developing novel methods of spatial analysis that focuses on vertical variations in, for example, building heights. One application concerns the assessment of access to sunlight. This is an essential consideration in urban planning, and there is considerable demand for geographical information systems which can provide efficient solar radiation analyses. Nevertheless, few studies have attempted to model variations in sunlight exposure over entire urban areas. This article illustrates an application of solar radiation analysis using a detailed virtual urban modelling for the case study of city of Kyoto, Japan. The research presents and implements a methodology to examine how sunlight access varies between different social groups in the city. The findings, which show evidence of inequity, illustrate the potential of virtual city models and their benefits are discussed along with the caveats of their application.

Keywords: virtual city; solar radiation; environmental equity; Japan

1. Introduction

In the 1990s, increased demand for digital information on the structure and design of cities, coupled with a greater availability of computing power, encouraged the development of novel digital urban modelling and representation techniques (Evans *et al*. 2005, Hudson-Smith 2008). In particular, advances in geographical information system (GIS) technologies and the improved availability of digital data allowed a new generation of three-dimensional (3D) virtual city models to be produced (Evans *et al*. 2005, Hudson-Smith 2008). Dodge *et al*. (1997) described a virtual city model as a 3D urban representation employing 3D-GIS/virtual reality techniques to depict realistic buildings and provide a wide range of services, functions, and information. The use of these virtual models is expected to play a central role in the field of urban planning and design in the coming decades.

In recent years much research and discussion have been undertaken to examine the uses of virtual city models in the field of urban planning. Most of the potential applications benefit from two key advantages of virtual city models: the potential to undertake 3D

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visualization and 3D spatial analyses that focus on vertical variations in building heights (Kurakula and Kuffer 2008). For example, Yano *et al*. (2007) demonstrated several uses of virtual city modelling (Virtual Kyoto model) for landscape management, including visualizing current and past city landscapes, simulating future landscapes and generating visibility maps employing viewshed analysis. Kolbe *et al*. (2005) also discussed several potential uses of virtual city modelling for hazard management, such as determining escape routes inside and outside of buildings and examining effects of floods on building storeys under a range of scenarios.

In this article, we examine how the application of virtual city models might contribute to the estimation of solar radiation in an urban context using a case study of environmental equity of access to sunlight. Conserving access to sunlight is regarded as an essential part of city planning, since sunshine is closely related to living standards (Kobayashi 1974). Laws relating to the conservation of access to sunlight exist in many countries. For instance, the Zoning Law of 1916 in New York was enacted to set height and set back restrictions for buildings in order to preserve sunlight exposure (Weiss 1992). The California Solar Rights Act of 1978 was enacted to protect installations of solar energy technology by restricting obstructions of access to sunlight caused by neighbouring buildings (Anders *et al*. 2010) Furthermore, there are various regulations which specify minimum recommended levels of sunshine duration for residential buildings in Asian, European and North American countries (Qian 1995). The availability of sunlight is also enshrined in culture, and thus there is a substantial demand for efficient and accurate calculation of solar radiation, with several methods being used (e.g., see Morello and Ratti 2009). Good access to sunlight is important for two principal reasons. First, there are known positive influences on general quality of life (Kobayashi 1974, Yoshimi *et al*. 1999) as the effects of heating, drying and lighting provided by sunlight have all been shown to be important determinants of well-being. Second, exposure to sunlight has positive effects on health (Kobayashi 1974, Yoshimi *et al*. 1999). For example, exposure to sunlight has been shown to be positively related to recovery from symptoms of depression (Beauchemin and Hays 1996, Benedetti *et al*. 2001) and negatively related to the degree of one's sense of being healthy (Sakabe and Yamazaki 1999).

As a consequence of positive benefits of sunlight, and given that the effects of shading mean that competition for the resource exists in the urban environment, it is useful to consider whether access to sunlight is equitably distributed in the population. Early environmental equity analyses focused primarily on environmental disamenities, such as the proximity to waste management plants or exposure to air pollution (e.g. Zimmerman 1993, Perlin *et al*. 1995). However, in recent years, access to positive amenities such as green spaces or hospitals also has a focus (e.g. Christie and Fone 2003, Jones *et al*. 2009). Jones *et al*. (2009) defined equity in access to such amenities as an equal opportunity standard among different socio-economic groups. In this work, we thus define equity of access to sunlight as the equal distribution of possible direct sunshine duration on buildings regardless of the socio-demographic characteristics of their residents.

Prior to the availability of virtual city models, several methods were used to assess the possible sunshine duration on buildings, including site visits, handwritten shadow diagrams and physical models that use light rays (Matsuura and Takahashi 2001). More recently Computer Aided Design (CAD)-based software packages have been developed, but they are generally only capable of considering a single structure of limited number of buildings in a small area, a limitation which reflects the fact that they have been designed for architects to calculate how a newly constructed or proposed building may interfere with another buildings' access to sunlight. In this work we make use of the 'Virtual Kyoto' model produced for the city of Kyoto, Japan. Japan is particularly appropriate for this case study because, during the 1960s and 1970s, high-rise buildings were constructed rapidly in Japanese cities with few controls or regulations, interfering with the access to sunlight of neighbouring residences. As a consequence newly introduced regulations set several construction standards on buildings, including height limitations. Civil law also states that if a newly constructed building interferes with a neighbour's access to sunlight and violates the standard maximum permissible level, the victim can sue for compensation or an injunction (Yoshimi *et al*. 1999).

In this article, we first present a methodology to estimate possible sunshine duration upon buildings in an urban context using the Kyoto virtual city model before applying it to examine environmental equity of access to sunlight in Kyoto.

2. Data and methodology

2.1. Study area

The case study city of Kyoto (Figure 1) is the seventh most populous in Japan, located at a latitude of 35° north and with a population close to 1.5 million. Formerly the imperial capital of Japan, it is now the capital of Kyoto Prefecture, as well as a major part of the Osaka-Kobe-Kyoto Metropolitan Area. Kyoto is located in a valley, part of the Yamashiro (or Kyoto) Basin. With over 2000 religious places, as well as palaces, gardens and early architecture intact, it is one of the best preserved cities in Japan.

2.2. Data – the 'Virtual Kyoto' model

Table 1 lists details of the data sets used in the analysis. The principal data source, the 'Virtual Kyoto' model, was developed by the GIS research team at the Ritsumeikan University in Kyoto. The production of the model is described in detail in Yano *et al*.

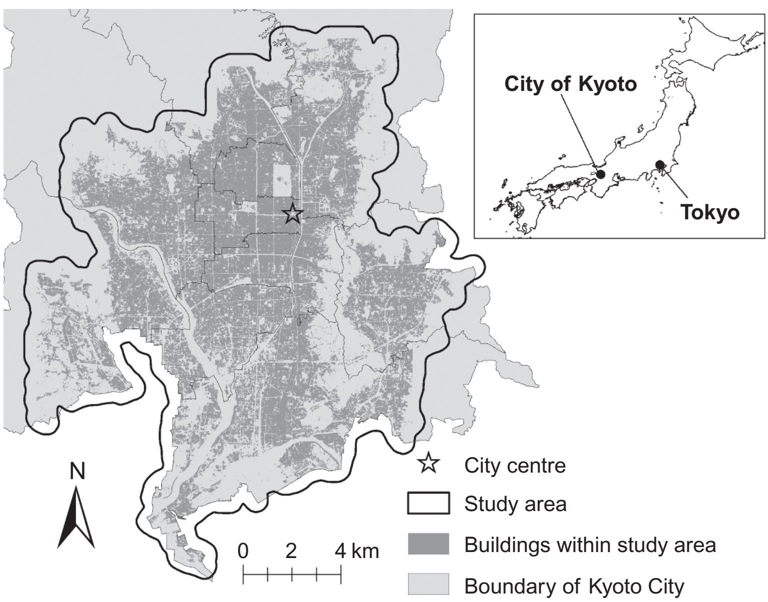

Figure 1. The study area in the city of Kyoto.

Table 1. Details of data sets used in the environmental equity analysis.

Name	Type	Contents	Publisher	Year
MAPCUBE (Building shape)	Polygon	Building shape and height (scale: 1/2500)	Increment P, Co.CAD Centre, Co.PASCO, Co.	2000
MAPCUBE (Elevation)	Point	Elevation of land (horizontal resolution: 2.5 m) (vertical accuracy: ±15 cm)		
Z-Map Town II (building shape)	Polygon	Use of each building (scale: 1/2500)	Zenrin Co., Ltd.	2000
Digital Map 50 m Grid (elevation)	Point	Elevation of land (horizontal resolution: 50 m) (vertical accuracy: ±7.5 m)	Geographical Survey Institute	1986
Census record (tabulation for small areas)	Attribute	Population characteristics at each small census area	Japan Ministry of Internal Affairs and Communications	2000

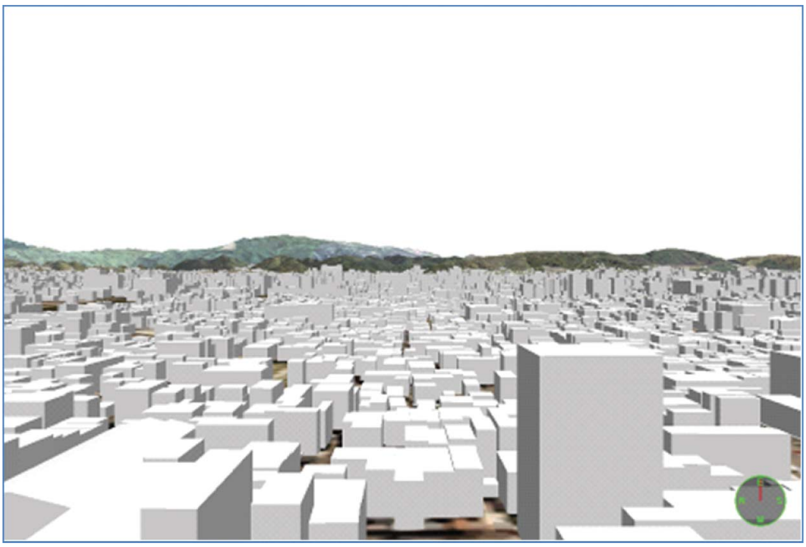

Figure 2. Building shape polygons from MAPCUBE.

(2007) and is hence only briefly recounted here. Two different commercially available building shape polygons, MAPCUBE and Z-Map Town II, were predominantly used to generate the building model. The former is composed of prismatic –3D structure models which use building footprint data and air-borne laser profiler data to measure height values at an interval of 2.5 m (Yano *et al*. 2008) (Figure 2). Z-Map Town II contains varied items of information including the use of each structure, for example, commercial or residential. In order to generate these attributes, the company ZENRIN undertook house-to-house surveys within Kyoto city.

The polygons from MAPCUBE had detailed and accurate building shapes, whereas those from Z-Map Town II had crude building boundaries since the boundaries equate to lots rather than the buildings themselves. Building centroids from Z-Map Town II were thus overlaid on the polygons of MAPCUBE to generate the accurate building shape data

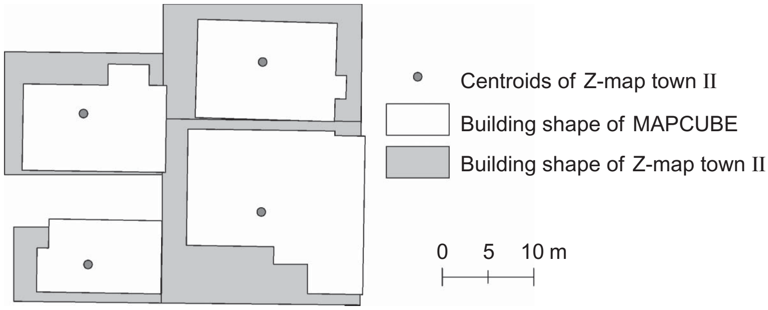

Figure 3. The method used to combine the two building data sets.

as shown in Figure 3. The output contained information on both the height and the use of each structure (see Yano 2006).

2.3. Analytical methods

All the GIS analyses were undertaken in ArcGIS 9.3 (ESRI Inc., Redlands, CA) and all statistical analyses were done using SPSS 16.0 (SPSS Inc., Chicago, Illinois). For the calculation of possible sunshine duration, two types of data were required in addition to the Virtual Kyoto model: a Digital Surface Model (DSM) and positional data on calculation points for sunshine duration (ESRI 2008).

To generate the DSM used in this analysis, we first created a Digital Elevation Model using the 'MAPCUBE (elevation)' and 'Digital Map 50 m Grid (elevation)' data sets. Both types of data are point based recording the elevation of the land surface at equally spaced intervals. The former covers the urbanized parts of the city, while the latter covers the surrounding mountain areas. These two sets of points were merged and converted into a raster layer at a 1 m horizontal resolution. Next, the building data outlined above were converted into a 1 m raster grid, with each raster cell recording the height of the building it fell within. These values were then added to the Digital Elevation Model to generate a 1 m resolution DSM of Kyoto city.

Since the focus of this research was on the relationship between population characteristics and access to sunlight, only residential buildings were chosen to determine the positions of calculation points for possible sunshine duration. First, each building polygon was split into sidelines, and south, east, west and north facing walls were selected. The midpoint of each wall was then identified and was used to determine the calculation points (Figure 4). Because of the 1 m raster resolution used, there was a possibility that some points would fall inside a building boundary. To avoid this, each was moved 1 m away from the building polygon boundary.

The heights at which possible sunshine duration was measured were computed in one of three ways. For building boundaries that were not contiguous with a neighbouring property, the height was set to be half of the height of the property. In cases where the boundary was shared with a neighbouring structure which was lower than half its height, the offset was set to be the difference between the neighbouring building height and the midpoint of the building. Where a neighbouring contiguous property was higher it was assumed that a calculation point had no exposure to direct solar radiation.

For each property, three sunlight-related metrics were computed: a binary measurement of whether or not any direct solar radiation was exposed on any of the calculation points in

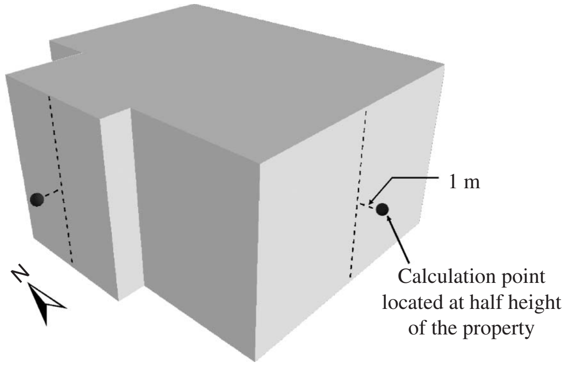

Figure 4. The location of calculation points on buildings.

each property, the average value of possible sunshine duration across all calculation points of each property and the value of sunlight duration at the point which received the longest possible sunshine duration. This maximum value was considered in addition to the average as the main living area of the property will have often windows along this boundary, and hence this metric captures the most typical sunlight exposure for occupants. All these metrics were computed for a single date, that of the winter solstice (21 December). This was chosen as it is the day for which the effects of any shading present would be expected to be greatest in the northern hemisphere.

The calculation of possible sunshine duration was undertaken using the ArcGIS Points Solar Radiation Tool. First, an upward-looking hemispherical viewshed (view of the whole sky from the ground up) for each calculation point was generated in the DSM (ESRI 2007). This is a raster-based representation of the whole sky, where each pixel identifies whether each corresponding sky location is visible or not when viewed from the calculation point. Next a sun map was generated for each point. This is a raster-based representation of the sun track at the latitude of the calculation point. The viewshed was then overlaid on the sun map to identify which parts of the sun track were obstructed. By counting the unobstructed length of the sun map, the possible sunshine duration for the calculation point was calculated (see Figure 5). Other input parameters were set to be the same values as those shown to be optimal by Fu and Rich (1999); the number of directions on the viewshed was 64; the resolution for viewshed and sun map was 512 $\times$ 512 pixels and the temporal resolution of the sun map was 0.1 h.

The generation of the sunlight metrics for each calculation point was found to be particularly computationally intensive. When the input DSM covered the whole of the study area, the computing power provided by a multi-core PC proved insufficient for the routines to run to completion in ArcGIS. Consequently, the DSM was split into small parts centred on each calculation point. Test simulations suggested that approximately 30 s was required to extract the DSM and calculate the possible sunshine duration for each calculation point. As there were over 330,000 residential properties in the study area, the process would take over 110 days to complete. These computational considerations meant that stratified random sampling was used to compute the sunlight metrics for a sub-sample. The strata were selected using two measures: one capturing affluence and the other the physical structure of properties. From the 2000 Japanese Census, the percentage of professional/technical workers and managers and the percentage of detached houses in small census areas were obtained. All properties were assigned to one of 25 groups based on the combined quintiles

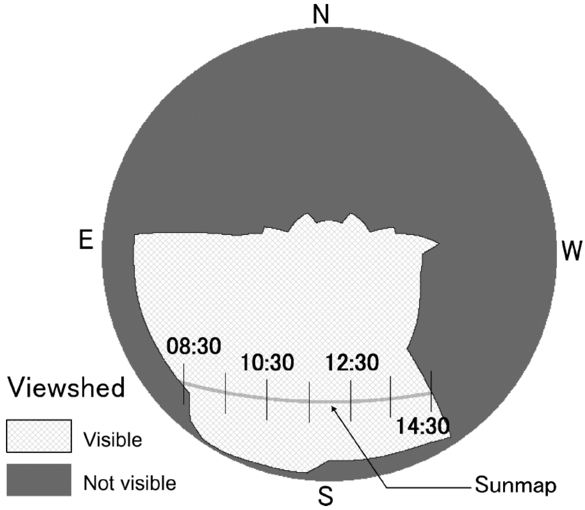

Figure 5. The calculation of sunshine duration on a sample calculation point on the winter solstice 2000.

of each of the two variables within which they fell. An equally sized random sample of properties was then selected from within each quintile to provide a sample of 5400 properties, around 2% of the total number present.

The socio-demographic characteristics of the population of Kyoto used in the equity analysis were also extracted from the 2000 Japanese Census at the small census area level. Age group is a frequently used indicator in equity analysis (e.g. Brainard *et al*. 2002, Mitchell and Dorling 2003) because it is an important determinant of each person's vulnerability and life patterns (Liu 2001). In particular, an older population may be more susceptible to environmental disamenities due to poorer health status and decreased mobility and social activity (Sexton *et al*. 1993). For the purpose of our age group analysis we thus focused on pensioners (over 65 years old). The Japanese Census does not record incomes but does hold information on occupation and educational level, both of which can proxy the affluence level of each small census area. For this analysis we computed the percentage of professional and technical workers and managers (high affluence) in each census area and the percentage of residents with either a degree or a postgraduate qualification (graduates).

The relationship between the measures of access to sunlight and each of the social indicators was investigated by classifying census areas into quartiles based on each indicator and examining how the three sunlight measures varied across the quartiles. We also undertook a sensitivity analysis using a sample of 1000 randomly selected calculation points to examine how possible sunshine duration was influenced by both the distance around each building within which other buildings were considered and the horizontal resolution for the DSM. For the former we repeated our calculations using a 1 m DSM resolution for different distances of 50 m, 100 m and 500 m. For the latter, three DSM cell sizes (0.5 m, 1 m and 2 m) were examined using a maximum distance of 100 m.

3. Results

Figure 6 maps the spatial distribution of average sunshine duration (a) and quartiles of the socio-demographic indicators within the city. The unshaded areas in the figure are

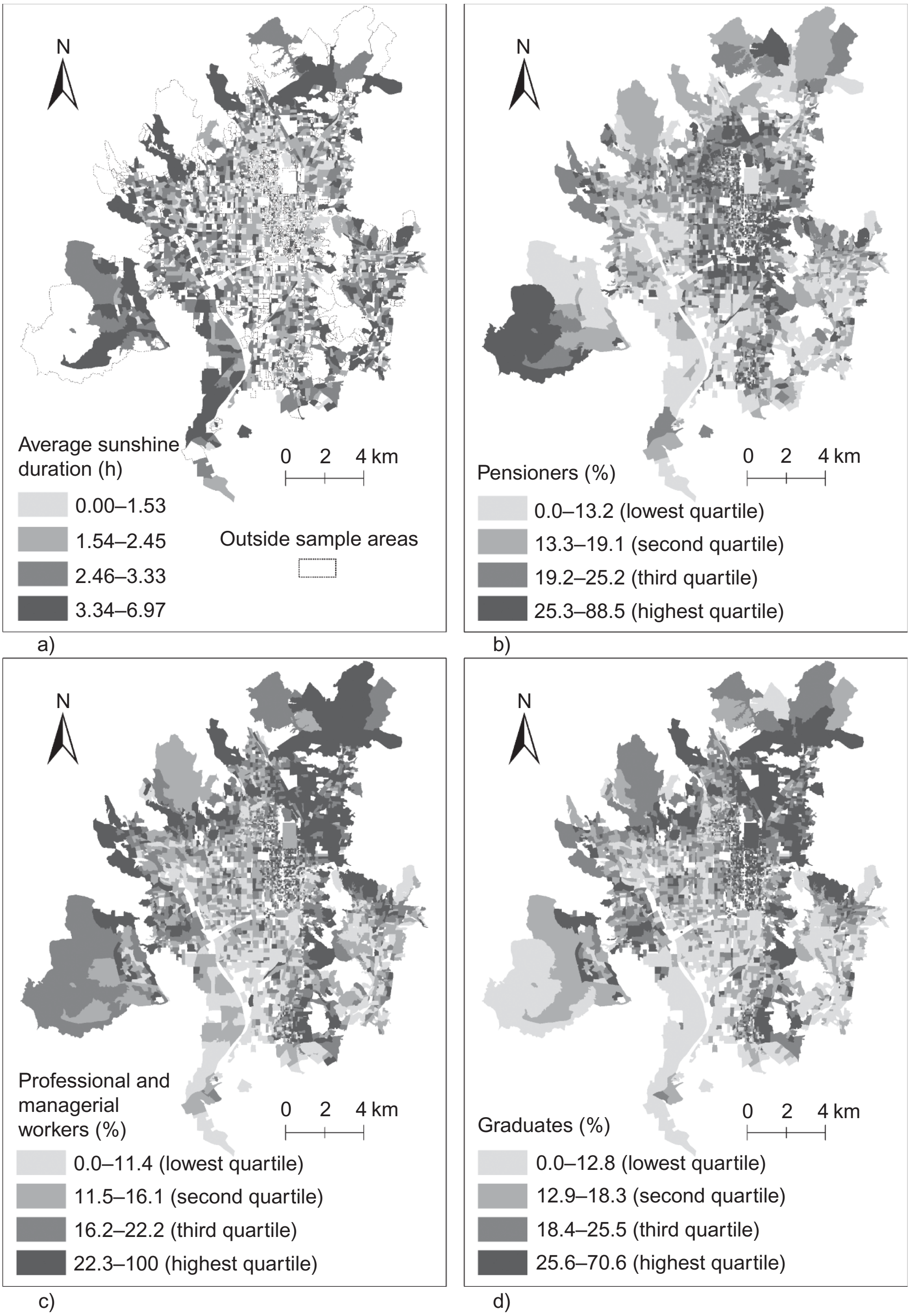

Figure 6. The spatial distribution of access to sunlight and social indicators: (a) average sunshine duration (h); (b) pensioners (%); (c) professional and managerial workers (%) and (d) graduates (%).

Table 2. Results of equity analyses: odds ratios of receiving sunlight, distribution of average sunshine duration (h) and distribution of maximum sunshine duration (h); direction of trend (+, positive and –, negative) is also reported.

	Pensioners (%)		Professional and managerial workers (%)		Graduates (%)	
Odds ratio of receiving sunlight	OR	95% CI	OR	95% CI	OR	95% CI
Lowest quartile	1		0.53	0.36–0.80	0.78	0.52–1.16
Second quartile	0.79	0.50–1.24	0.62	0.41–0.93	0.67	0.46–0.99
Third quartile	0.58	0.37–0.88	0.68	0.45–1.03	0.80	0.53–1.19
Highest quartile	0.36	0.24–0.54	1		1	
Test for trend	– **		+ **		+ NS	
Distribution of average possible sunshine duration (h)	Mean	95% CI	Mean	95% CI	Mean	95% CI
Lowest quartile	2.81	2.73–2.88	2.34	2.26–2.42	2.46	2.38–2.53
Second quartile	2.54	2.46–2.62	2.46	2.38–2.54	2.39	2.31–2.47
Third quartile	2.38	2.30–2.45	2.50	2.42–2.58	2.47	2.39–2.54
Highest quartile	2.03	1.95–2.10	2.45	2.37–2.53	2.44	2.36–2.52
Test for trend	– **		+ *		+ NS	
Distribution of maximum possible sunshine duration (h)	Mean	95% CI	Mean	95% CI	Mean	95% CI
Lowest quartile	5.98	5.85–6.11	5.22	5.08–5.36	5.41	5.28–5.54
Second quartile	5.61	5.48–5.74	5.40	5.26–5.53	5.27	5.14–5.41
Third quartile	5.29	5.15–5.42	5.50	5.37–5.63	5.46	5.33–5.60
Highest quartile	4.68	4.55–4.82	5.45	5.32–5.59	5.42	5.28–5.56
Test for trend	– **		+ **		+ NS	

Notes: Lowest quartile = least aged/most deprived quartile group; highest quartile = most aged/least deprived quartile group; OR = odds ratio; 95% CI = 95% confidential interval; $^{**}P < 0.01$; $^{*}P < 0.05$; NS: no statistical significance.

those that fell outside the sampling framework for this analysis, and hence no measures of sunlight duration were available for them.

The first rows in Table 2 show the odds of receiving any direct solar radiation at a particular point on the building on the winter solstice according to quartiles of each social indicator. In total, 4.2% of the entire sample was modelled as having no access to sunlight on the winter solstice in Kyoto. The trends in odds across quartiles of retired populations suggest that properties in communities with older residents are considerably less likely to receive any direct solar radiation. There is also a statistically significant increase in the odds of properties having access to sunlight with an increasing percentage of the population working in professional or managerial jobs. A weaker trend, not statistically significant, is also apparent with the percentage of the population educated to degree standard or above.

Table 2 also shows the mean values of possible average and maximum sunshine duration across quartiles of the social indicators. For retired populations there is again clear evidence of inequities; both average and maximum values of possible sunshine duration

Table 3. Estimated sunshine duration (h) at each calculation point in the sensitivity analysis.

	Maximum distance			DSM horizontal resolution		
Duration	50 m	100 m	500 m	0.5 m	1 m	2 m
Mean	3.29	3.23	3.23	3.25	3.23	3.21
25 percentile	0	0	0	0	0	0
50 percentile	2.87	2.79	2.79	2.8	2.79	2.74
75 percentile	5.52	5.44	5.44	5.48	5.44	5.43
Minimum	0	0	0	0	0	0
Maximum	9.63	9.63	9.63	9.63	9.63	9.63

show statistically significant declines with an increasing percentage of pensioners. Both average and maximum values are also related to affluence levels measured according to employment type, with lower values in census areas with fewer residents employed in professional and managerial occupations. No trend was apparent for education.

Table 3 shows the results of the sensitivity analysis. The outcomes for the computation of possible sunshine duration for the 100 m and 500 m buffers were completely identical to two decimal places, with that for the 50 m buffer being very similar. This suggests, in Kyoto at least, a 50 m radius is sufficient. The effects of all three DSM resolutions are also almost identical. This suggests that smaller cell sizes increase computational overheads but does not affect results, and thus a 2 m resolution is sufficiently small for this purpose. Because the sensitivity analysis did not reveal large differences in computed values, the equity analysis was not repeated for each of the sensitivity parameters tested.

4. Discussion and conclusion

This research was undertaken to illustrate how a virtual city model may be applied in the field of environmental equity analysis. Using the case study of Kyoto city, the distribution of access to sunlight among different social groups was estimated revealing evidence of inequity in access to sunlight, particularly by aged population. Therefore, we have illustrated one way by which virtual city models can be used to model complex environmental phenomena that require a consideration of three dimensions.

Although this work has illustrated the potential of the technologies, it has also revealed a number of limitations. In particular, the accuracy of the methodology will be dependent upon the quality of the data available. While the Virtual Kyoto model we employed provided accurate building representations, it did not include information on vegetation. Particularly for lower buildings, shading from trees might be significant, although it may be the benefits of living in an environment with such greenery will compensate for any loss of sunlight (Gao and Asami 2001, Gao and Asami 2007). The issue of non-representation of certain features has been discussed by Fu and Rich (1999). An additional limitation was that we did not have information on the location of windows in the buildings, and hence we used assumed points for our calculations. The output of our analysis is based on direct radiation only, while collected solar energy and diffuse plus reflected radiation can make a significant contribution in latitudes such as those where Kyoto is situated. Furthermore, our estimates of sunlight exposure were based on cumulative radiation received throughout the day, while the effects of sunlight during the middle of the day can differ from that during the early morning or late afternoon due to the angle of the sun and different luminance levels

(Morello and Ratti 2009). Kyoto is a city which is surrounded by mountains, but considerations relating to computational overheads meant that we were not able to include them in our analysis. Nevertheless, it is likely that the effect of the mountains on our measures of cumulative sunlight exposure throughout the day would be minimal.

A further limitation of this work was that we were only able to consider sunlight exposure on the outside walls of each property rather than sunlight entering the rooms. This will be affected by the characteristics of the windows, including their location, material and proximity to eaves (Tanaka *et al*. 2006). In the absence of such information we assumed the calculation points are representative of the actual location of the windows, although window locations could be used in our methodology if information was available. Another point to note is that the height limitation policy in Kyoto is relatively strict compared with other cities due to the city's long history and popularity as a tourist attraction (see Kyoto City Council 2007). Hence, the residences in Kyoto are more likely to have superior access to sunlight than those in other cities. Despite this, our research found that there were still inequities in access to sunlight in Kyoto. In other urban areas any disparities may be more considerable, although this is as yet untested.

We recommend several possible future directions for GIS-based solar radiation analyses. One aspect not considered here is the energy-saving potential of solar radiation. Heating buildings using solar gain can make some contribution towards greenhouse gas emissions reduction strategies, and we therefore suggest that future work may consider this potential (e.g. see Morello and Ratti 2009). Furthermore, GIS-based methodologies have recently been developed that illustrate the potential of mapping technologies to assess the viability of photovoltaic installations (see Wiginton *et al*. 2010) and clearly this work could be an important input into this process. Second, in this work we undertook some relatively simple sensitivity analysis to test for the effect of search distance and cell resolution and, while we found our findings to be relatively insensitive to parameterization within the range we tested, further work using probabilistic distributions should be undertaken to examine the effects of error and uncertainty in the DSM used (e.g. Wu *et al*. 2008). Other software packages (e.g. Geographic Resources Analysis Support Systems (GRASS) (Neteler and Mitasova 2008)/CADs) (e.g. A&A Shadow produced by A&A Co., Ltd., Tokyo, Japan) are available to estimate solar radiation (for example see Gao and Asami 2001), yet they all use different computational algorithms. The effect of algorithm choice on results obtained is not known and further work should be undertaken to test this.

Our findings suggest that increased efforts for enforcing those policies that do exist may be required. Pastor *et al.* (2001) suggest two drivers that act to generate environmental inequity: an unequal distribution of political power and the effect of unregulated market mechanisms. Based on this it is possible to suggest policy responses to the observed inequities. Environmental disamenities such as unwanted shading might be disproportionately sited in disadvantaged communities due to the presence of political inequities between different social groups, especially where disadvantaged communities have limited political power to resist them. While Japanese civil law guarantees the right to access sunshine to a satisfactory level, it is known that deprived population groups often have a limited ability to overcome the construction of new buildings in their neighbourhood since they rarely possess the resources to challenge any actions leading to the inequities (Miyake 1971). Re-examining zoning and height limitation legislation so it explicitly promotes equal access to sunlight may hence be one policy response (Pastor *et al*. 2001). Market dynamics could also result in the observed inequities as the land prices in environmentally disadvantaged areas are often relatively low leading to the in-migration of more vulnerable population groups. Several policies to help remedy problem have been suggested, including income redistribution programmes, initiatives to help socially disadvantaged individuals to secure equal opportunities to rent or purchase housing and the careful placement of low-income housing (Been 1994).

Although our focus was on the duration of sunshine inside properties, the provision of opportunities to enjoy sunshine outdoors may act as a partial solution to observed inequities. Miyake (1971) suggested that constructing new parks in communities that suffer from disproportionate amounts of shading may be beneficial, especially as the important role of parks in recreational walking is well known (Giles-Corti *et al*. 2005). Such benefits may be particularly important for the elderly, and we suggest that the process of planning for park provision might better take account of the distribution of access to sunlight among the populations that the parks are designed to serve.

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