Assessment of Urban Heat Island and Mitigation by Urban Green Coverage

Dong Chen, Xiaoming Wang, Yong Bing Khoo, Marcus Thatcher, Brenda B. Lin, Zhengen Ren, Chi-Hsiang Wang and Guy Barnett

Abstract Urban heat island (UHI) is a growing threat to human well-being and poses increasing pressure on urban utility infrastructure, especially during summer months. This study examined the UHI in Melbourne using remote sensing imagery from MODIS to derive land surface temperature (LST) for the summer of 2009. Then, the potential of urban green coverage in reducing extreme summer temperatures in Melbourne was investigated using an urban climate model for 2009 and for projected 2050 and 2090 future climates. Modeling results showed that the average summer daily maximum (ASDM) temperature differences between Melbourne CBD, suburbs and rural areas were in the range of 0.5–2.0 °C. It was also found that despite the projected climate warming in 2050 and 2090, the cooling benefit in terms of the reduction in the average summer daily maximum temperature due to various urban forms and vegetation schemes remains similar to that estimated for 2009. Thus, the cooling benefit due to various urban forms and green schemes in future climates can be reasonably projected based on the benefits identified with the present-day climate.

Keywords Urban heat island · Green coverage · Climate change · Urban climate model · Remote sensing · Land surface temperature

1 Introduction

The Australian landscape is becoming increasingly urbanized with around 85 % of Australians living in urban areas and 64 % in the eight capital cities (DSEWPaC 2011). Although the percentage of the urban population has only increased slightly from several decades ago, the total Australian population has doubled in the

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past 50 years. This rapid population growth has led to extensive urban and suburban development and an increase in the density of housing and other urban infrastructure.

The transformation from native landscape to engineered infrastructure leads to increased heat generation from anthropogenic activities and heat accumulation due to massive heat absorption and storage of radiative heat by roads, buildings and other urban infrastructure. This results in higher temperatures in urban areas in comparison with rural areas, a phenomenon known as the urban heat island (UHI) effect. High ambient temperatures and humidity affect the livability and sustainability of our cities, especially during the summer. The most recent heat wave event in Melbourne in January 2009 may have resulted in an estimated 374 excess deaths over what would normally be expected: a 62 % increase in total all-cause mortality and 8 fold increase in heat-related presentations to the emergency departments (DHS 2009).

Melbourne has a temperate climate with warm to hot summers, mild and sometimes balmy springs and autumns, and cool winters. In 2009, it had one of the hottest summers since the commencement of records from mid-1800. In January 2009, Melbourne experienced a record heat wave with three consecutive days over 43 °C. On 7th February 2009, it recorded the hottest day with its maximum temperature reaching 46.4 °C in CBD.

Urban summer heat accumulation is likely to be further exacerbated with global warming. Climate change projections for Australia suggest an increase in the number of warm nights and heat waves which can pose significant threats to human health (Alexander and Arbalster 2009). The dual pressures from the increasing UHI effect and climate change present enormous environmental challenges which require urgent collaborative efforts and measures from governments, industries and communities.

One strategy to mitigate the UHI effect is the “cool cities” concept (Luber and McGeehin 2008). The “cool cities” strategy reduces the urban heat island effect by promoting tree planting to shade buildings, to cool the ambient temperature through evapotranspiration of vegetation and using reflective roofs and paving surfaces to reduce the heat accumulation due to solar radiation. These “cool cities” strategies, at the same time, reduce the cooling energy consumption of residential and commercial buildings and thus reduce green house gas (GHG) emissions. In this study, the potential of urban vegetation in mitigating UHI in Melbourne was investigated by analyzing remote sensing imagery for the summer of 2009 and by using an urban climate model to predict urban temperature changes under various urban vegetation schemes for the 2009 climate and projected future climates in 2050 and 2090.

2 Assessment of UHI During the 2009 Summer in Melbourne

The assessment of UHI during the summer of 2009 in Melbourne used the MYD11A2 data product from Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua satellite, which captures images once every eight days at 1 km spatial resolution. The images were converted to rasters using U.S. Geological Survey (USGS's) MODIS Reprojection Tool.

Figures 1 and 2 show the estimated daytime and night time land surface temperatures (LSTs) in Melbourne during the summer of 2009 derived using the averages of 12 daytime and 12 nighttime MYD11A2 images from December 2008 to February 2009. Day and night LSTs extracted from MYD11A2 images (2002–2011) at six locations in Victoria (Melbourne Airport, Werribee, Carrum Downs, Brighton, Aspendale, and Queenscliff) were compared with the average of eight days of measured maximum and minimum temperatures provided as part of the SILO climate data (Jeffrey et al. 2001). The results showed high levels of correlation ($R^2 > 0.70$) between the measured temperatures and those derived through remote sensing. In general, Melbourne and the surrounding urbanized areas experienced higher average LSTs compared with rural areas (about 20 °C and 10 °C for daytime and nighttime LSTs respectively) during this period. Figure 2 depicts the extent of higher nighttime LSTs to be clearly overlap with urbanized areas of Melbourne metropolitan areas as well as more densely populated town centers such as Geelong (to the south–west of Melbourne). Furthermore, areas near the coast had lower LSTs during the day but higher LSTs during the night as a result of evaporation, higher specific heat capacity and low solar absorptance of water relative to land-based areas. High nighttime LSTs were observed at the forest regions to the east, south west and west of Melbourne. Similar findings were reported by van Leeuwen et al. (2011) when they analysed LSTs in forest areas in Mato Grosso, Brazil. The high nighttime LSTs were believed to be due to nocturnal drainage of air from upper canopy layers and pooling of cold air at the forest floor keeps upper levels of the canopy relatively warm. On the other hand, high daytime LSTs to the west of Melbourne (Fig. 1) may be due to bare agricultural land and low soil moisture (as a result of

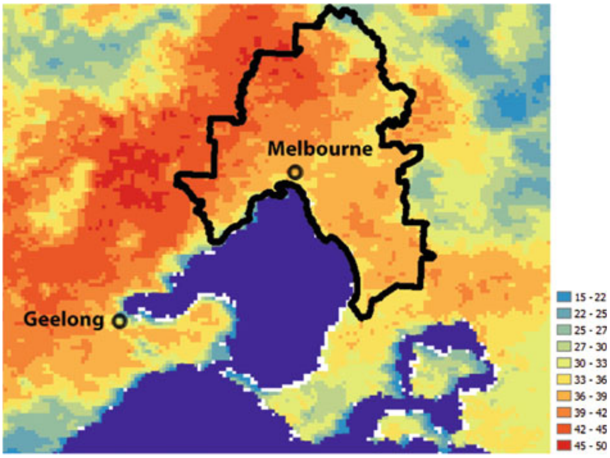


Fig. 1 Average daytime LST in degree celsius during the summer of 2009 at about 1600 h

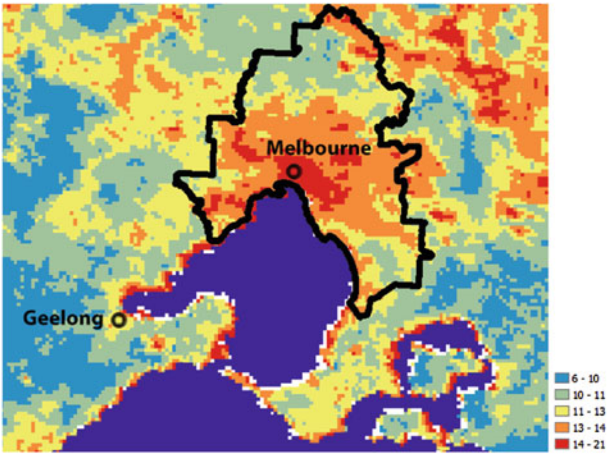


Fig. 2 Average night time LST in degree Celsius during the summer of 2009 at about 0300 h

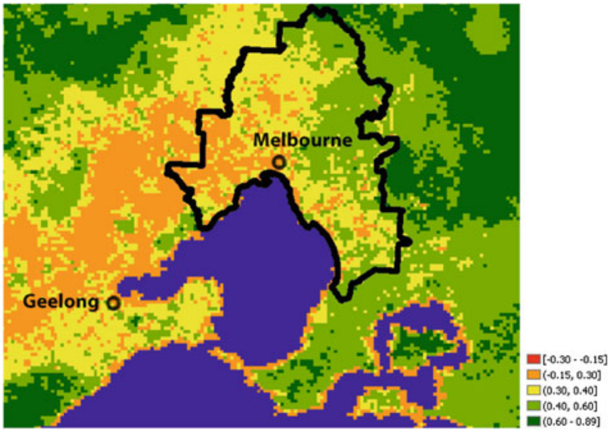
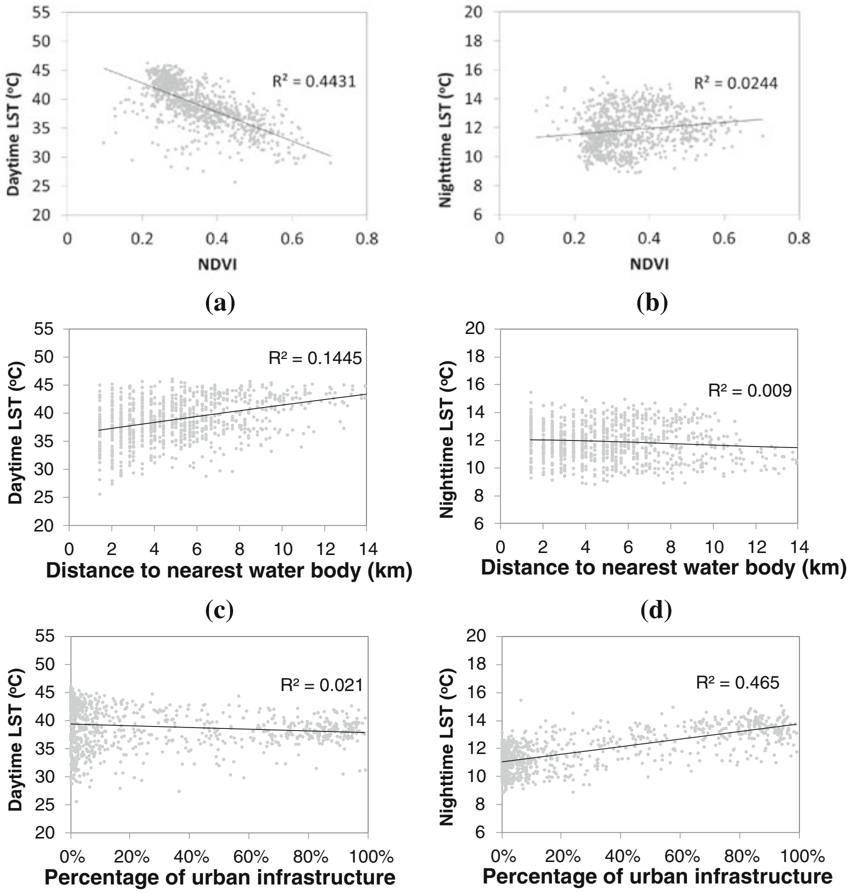


Fig. 3 Average NDVI during the summer of 2009

evapotranspiration) after a long drought period during the summer of 2009, indicated by low Normalized Difference Vegetation Index (NDVI) values in Fig. 3. NDVI is an estimate of the photosynthetically absorbed radiation over the land surfaces. High NDVI is an indication of abundance of live vegetation in the target area.

To further investigate the relationships between LSTs and the land use, information of NDVI and the distance to the nearest water body from 1,000 randomly selected grid cells (1 km × 1 km each) within the study region were extracted from the MYD11A2 data product. The percentage of urban infrastructure for each cell was also derived based on the Landsat TM 5 image taken on 6 November 2009 via Principal Component Analysis (Lillesand et al. 2008) and refined using Maximum Likelihood Classification (Lillesand et al. 2008).

Figure 4a and b show the relationships of average daytime and nighttime LSTs against NDVI. As shown in Fig. 4a, the average daytime LSTs can be significantly lower in areas where healthy vegetation is more abundant. On the other hand, vegetation appears to have relatively low impact on the average nighttime LSTs as shown in Fig. 4b. The trend is similar to what has been identified in other studies (Sun and Kafatos 2007). It can be considered as less evapotranspiration during the nighttime that would have cooled the land surface. Figure 4c and d show the relationships of average daytime and nighttime LSTs against the distance to the nearest water body. In general, average daytime LSTs are higher in areas that are further away from the nearest water body while there is no clear trend in average



(a) (b)

(c) (d)

(e) (f)

Fig. 4 Relationship between LSTs and land surfaces nighttime LSTs. Figure 4e and f show the relationships of average daytime and nighttime LSTs against the percentage of urban infrastructure. Increase in the percentage of urban infrastructure appears to be correlated with higher average nighttime LSTs. It is due to the significant thermal mass factor of the built environment. However, there is no clear trend in the average daytime LSTs.

The assessment for the summer of 2009 in Melbourne shows that healthy vegetation coverage can be an effective measure for reducing UHI. Therefore, the following investigation will specifically focus on the improvement of urban climate via vegetation by proper urban planning.

3 Mitigating UHI by Urban Green Coverage

As shown above, healthy vegetation coverage can significantly reduce daytime LSTs, which can in turn result in lower maximum local ambient air temperature, though it could also be affected by urban forms and other environment parameters. Maximum local ambient air temperature is the major index for summer heat stress and is closely related to the peak electricity usage due to the requirement of air conditioning. To further quantify the potential of urban vegetation in mitigating UHI, a recently developed urban climate model (UCM-TAPM) (Thatcher and Hurley 2012) was used to investigate the impact of urban vegetation on ambient air temperature. The UCM-TAPM is a PC-based prognostic meteorological model which couples an urban canopy model based on the Town Energy Budget (TEB) model with a meso-scale climate model TAPM (Hurley et al. 2005) developed in CSIRO.

The UCM-TAPM uses fundamental prognostic equations for the conservation and continuity of momentum, turbulence, heat and moisture to simulate winds, potential temperature and specific humidity. It includes physical parameterisations for cloud microphysics (water vapour, cloud water, cloud ice, rain and snow) and radiation. The UCM includes an efficient big-leaf model to represent in-canyon vegetation in the predominately suburban component of Australian cities. The meteorological component of the model is nested within synoptic-scale analyses/forecasts that drive the model at the boundaries of the outer grid. The model employs a multiple one-way nesting procedure to dynamically downscale meteorological reanalyses, typically in steps of 30, 10, 3 and 1 km. In the UCM-TAPM, a 1 × 1 km grid tile of the land surface, for example, can be assigned one of 39 surface types that include a wide range of natural and built surface types (e.g. snow, water body, forest, shrub land, grassland, pasture, littoral, CBD, urban, and industrial). The characteristics of the surface types such as the average building height, building height to street canopy width ratio, vegetation coverage, leave area index, surface Albedos etc. can be adjusted for specific urban conditions. The UCM-TAPM model has demonstrated good capability in urban scale climate modelling for Australian cities (Thatcher and Hurley 2012).

Simulations were carried out for 2009 using UCM-TAPM with reanalysis climate data downscaled from National Centre for Environmental Prediction (NCEP) by replacing the Melbourne CBD areas with various urban and vegetation schemes as listed in Table 1. The vegetation and building coverage ratios of the generic urban type in Table 1 were based on measurements by Coutts et al. (2007). In Table 1, the summer maximum temperature is the predicted average summer daily maximum temperature (ASDM temperature) over December, January and February. In calculating the ASDM temperature reduction, the existing CBD is taken as the reference urban form.

Considering the ASDM temperature, the following can be found in Table 1:

1. Suburban areas are around 0.5 °C cooler than the CBD;
2. Leafy suburban areas may be around 0.7 °C cooler than the CBD;
3. Parkland (such as grassland, shrub-land and sparse forest) or rural areas are around 1.5–2 °C cooler than the CBD;
4. Doubling the CBD vegetation coverage may reduce the ASDM temperature by 0.3 °C;
5. 50 % green roof coverage of the CBD area may result in 0.4 °C ASDM temperature reduction;
6. ASDM temperature reduction of around 0.7 °C may be achievable by doubling the CBD vegetation coverage and 50 % green roof coverage in the CBD area.

Morris et al. (2001) reported an average UHI effect of around 1.3 °C for Melbourne summers between 1972 and 1991. Simulation studies by Coutts et al. (2008) also showed that the daytime UHI is between 1 and 2 °C. By

Table 1 Predicted ASDM temperature in 2009 with various vegetation schemes

Urban type	Vegetation coverage (%)	Green roof (%)	Building coverage (%)	Irrigation	ASDM temp (°C)	ASDM temp reduction (°C)
Forest (low sparse)	100	0	0	No	25.7	−2.1
Shrub-land	100	0	0	No	25.8	−1.9
Grassland	100	0	0	No	26.1	−1.7
Urban (leafy)	49	0	40	Yes	27.1	−0.7
Urban (generic)	38	0	45	Yes	27.3	−0.5
CBD (reference)	15	0	65	Yes	27.8	0
CBD (with 1/3 vegetation)	5	0	65	Yes	27.9	0.2
CBD (Double vegetation)	33	0	58	Yes	27.5	−0.3
CBD (50 % green roof)	15	50	65	Yes	27.4	−0.4
CBD (double vegetation +50 % green roof)	33	50	62	Yes	27.1	−0.7

reviewing a number of observation studies, Bowler et al. (2010) summarised that, on average, an urban park would be around 1 °C cooler than a surrounding non-green site, while 2.3 °C cooler was reported when compared with a town or city further away. Therefore, a difference of 0.5–2 °C in the ASDM temperatures between Melbourne CBD, suburbs, and rural areas is reasonable.

In modeling the benefit of vegetation under future Melbourne climate scenarios, the current Melbourne metropolitan boundary was assumed to be maintained in the next several decades. Future Melbourne climate was projected based on the A2 scenario using a coupled atmosphere–ocean general circulation model (AOGCM), GFDL2.1 (IPCC 2000). The IPCC suggested that due to the varying sets of strengths and weaknesses of various AOGCMs, no single model can be considered the best. Therefore, it is necessary to use multiple models to take into account the uncertainties of models in impact assessment. At the time of this study, the only climate model available for UCM-TAPM was GFDL2.1. Considering that the current study focuses on the relative impact of vegetation on local climate, the selection of a particular climate model may not significantly affect the modeling results.

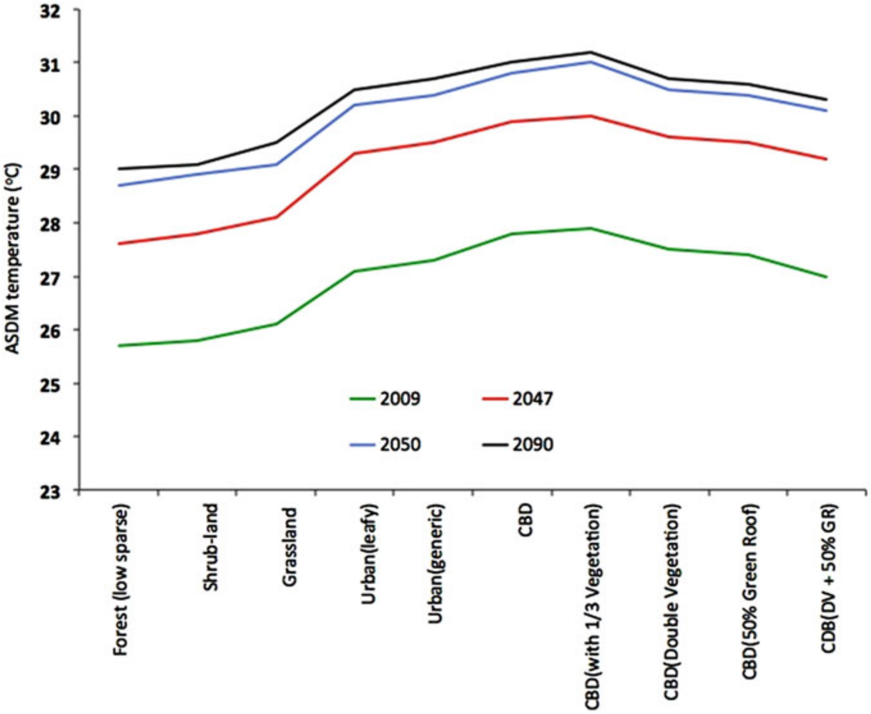


Fig. 5 Predicted ASDM temperatures in 2009, 2047, 2050 and 2090 for different urban forms and vegetation schemes in Melbourne

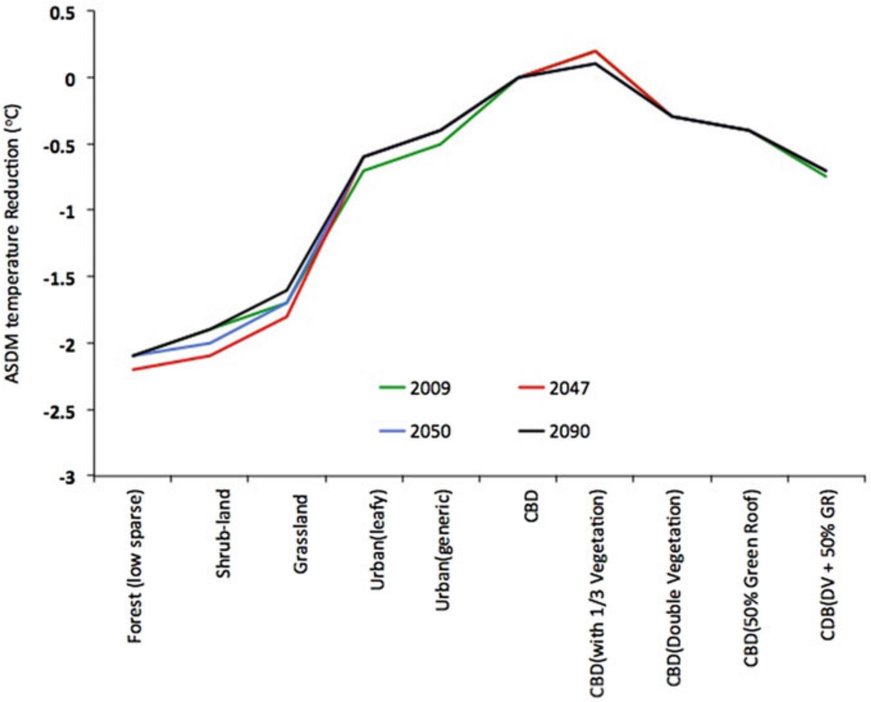


Fig. 6 Predicted reductions in the ASDM temperature in 2009, 2047, 2050 and 2090 for different urban forms and vegetation schemes in Melbourne

Simulations were carried out for years 2047, 2050 and 2090 by replacing Melbourne CBD areas with the urban and vegetation schemes detailed in Table 1. The predicted ASDM temperatures and the reductions in the ASDM temperatures relative to the CBD urban form in Table 1 for the year of 2009, 2047, 2050 and 2090 are compared in Figs. 5 and 6, respectively. Usually ten year simulations would be performed to estimate the climatology and the vegetation impact centered on 2050 and 2090. In this study, single simulation years such as 2047, 2050 and 2090 were used as random samples of the predicted future climates to demonstrate the cooling potentials by various vegetation schemes under global warming.

From Figs. 5 and 6, it was found that although Melbourne is projected to be warmer in 2050 and 2090, the relative impacts on the ASDM temperature due to various urban forms and vegetation schemes in any particular future year are projected to be similar to those in 2009. This is reasonable considering that the relative cooling effect of vegetation is mainly determined by vegetation types, shading and evapotranspiration. Since the current study assumes that the vegetation does not dry out with irrigation, the variation in rainfall, humidity, solar radiation and wind speed etc. for different years in the future may have some, but not significant, effect on the evapotranspiration rate and thus the cooling effect from vegetation. During this study, reanalysis and GFDL2.1 projected climate data were used for 2009 and future Melbourne climate respectively. The similar relative impact on the ASDM temperature due to various urban forms and vegetation schemes suggests that the selection of a particular climate model may not significantly affect the modeling results. Further modeling study is required to confirm this finding.

4 Conclusions

Analysis of remote sensing imagery in Melbourne in the summer of 2009 showed that healthy vegetation can significantly reduce daytime land surface temperatures, which can in turn result in lower maximum local ambient air temperature. The potentials of urban green coverage in reducing extreme summer temperatures in Melbourne were further investigated using an urban climate model for 2009 and for projected 2050 and 2090 future climates. Modeling results showed that the cooling benefit of various urban forms and vegetation schemes may be in the range from 0.3 °C by doubling the CBD vegetation coverage to around 2 °C with large parklands. It was also found that although Melbourne is projected to be warmer in 2050 and 2090, the relative cooling benefit of urban vegetation will not change significantly. Thus, the cooling benefit due to various urban forms and green schemes in future climates can be reasonably projected based on the benefits identified with the present-day climate.

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