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Article *in* Urban Forestry & Urban Greening · January 2017

DOI: 10.1016/j.ufug.2016.12.005

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Urban Forestry & Urban Greening 21 (2017) 203–212

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

The influence of small green space type and structure at the street level on urban heat island mitigation

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A R T I C L E I N F O

Article history:
Received 1 April 2016
Received in revised form 8 December 2016
Accepted 9 December 2016
Available online 26 December 2016

Keywords:
Air temperature
Green space
Microclimate
Street trees
Urban heat island

A B S T R A C T

The purpose of this study was to determine the types and structures of small green spaces (SGs) that effectively reduce air temperature in urban blocks. Six highly developed blocks in Seoul, South Korea served as the research sites for this study. Air temperature was measured at the street level with mobile loggers on clear summer days from August to September in 2012. The measurements were repeated three times a day for three days. By analyzing the spatial characteristics, SGs within the six blocks were categorized into the four major types: polygonal, linear, single, and mixed. The result revealed that the polygonal and mixed types of SGs showed simple linear regression at a significant level ($p < 0.01$). It indicated that the blocks' urban heat island (UHI) mitigation (ΔT_{Rmn}) increased in a linear fashion when the area and volume of these two types of green spaces increased. The area and volume of a polygonal SG with mixed vegetation, over 300 m^2 and 2300 m^3, respectively, lowered the ΔT_{Rmn} by 1 °C; SG with an area and volume of larger than 650 m^2 and 5000 m^3, respectively, lowered the ΔT_{Rmn} by 2 °C. The results of this study will be useful to urban planners and designers for determine the types and structures of urban green spaces to optimize the cooling effect, as well as how such green spaces should be designed and distributed.

1. Introduction

Rapid urbanization has increased environmentally negative impacts with the high demand of land use change, particularly in developing countries. Urbanization in 2014 accounted for 54% of the total global population, up from 34% in 1960. Urban populations are expected to reach 81% by 2030 (UNFPA, 2007). This urbanization affects the urban climate, creating urban heat islands (UHIs) (Oke, 1987; Asimakopoulos et al., 2001). UHIs cause higher temperatures in urban centers than in surrounding suburban and rural areas (Peng et al., 2012; Wang et al., 2015); this effect has become one of the urban disasters such as floods, inundation, and landslides, and has taken an increased toll on human health (O'Loughlin et al., 2012; Zhou et al., 2014).

The presence of green spaces in urban areas can mitigate these negative impacts by creating cooling buffer zones; in such zones, urban areas shaded by green spaces are cooler than other areas heated by direct solar radiation (Kim et al., 2016; Oliveira et al., 2011). These cooling areas improve microclimatic conditions and human health (Georgi and Dimitriou, 2010). Green spaces are important to reduce urban air temperature maximum and variation (Norton et al., 2015). Previous studies based on onsite observations have focused on measurements of air temperature in order to quantify the degree of cooling effect of certain structures and types of green spaces. Those studies have dealt with urban parks (Cao et al., 2010), small parks (Bowler et al., 2010), gardens (Oliveira et al., 2011), green roofs (Klein and Coffman, 2015), vertical greenery (Tan et al., 2014), street trees (Oke, 1988) and pocket parks (Lau et al., 2012), according to the shape and distribution of the space.

In the existing body of literature, only a few studies have investigated the density (Oliveira et al., 2011; Lehmann et al., 2014 Lehmann et al., 2014), size (Dimoudi and Nikolopoulou, 2003; Georgi and Dimitriou, 2010), shape (Fintikakis et al., 2011; Feyisa et al., 2014), and ratio of green spaces (Alexandri and Jones, 2008; Lehmann et al., 2014; Saito et al., 1990; Sun, 2011). However, despite the expectation that small green spaces (SGs) provide high cooling effects and thus, make air temperatures drop (Feyisa et al., 2014), such an effect in urban areas has been under-explored in

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http://dx.doi.org/10.1016/j.ufug.2016.12.005
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comparison to well-documented UHI reducing effect of larger parks and urban forests (Oliveira et al., 2011).

The degree of cooling is affected by the type, structure, and size of green spaces (Spronken-Smith and Oke, 1999; Doick and Hutchings, 2013). For example, diverse types and compositions of green spaces in urban areas would have a stronger cooling effect than other green spaces comprised of simple structures have (Li et al., 2012, 2013). However, air temperature changes by SG type and structure are still challenging to measure at the street level in urban areas (Escobedo and Nowak, 2009; Manes et al., 2012) because the UHI mitigation effect of SGs can vary among different sites due to factors such as topography, traffic density, and other anthropogenic heat-release influences (Shashua-bar and Hoffman, 2000). In addition, although large urban forests and green spaces have been evaluated mainly as a cooling tool with remote sensing techniques used to measure land surface temperatures (Zhang et al., 2009; Cao et al., 2010; Connors et al., 2013; Wong and Lau, 2013; Asgarian et al., 2014), only a few studies have assessed the influence of the characteristics of SGs on air temperature changes at the street level.

Based on the existing gaps in the current literature, the objective of this study was to analyze the cooling effect of SGs at the street level, according to their types and structures. The results of this research will be useful for understanding the cooling effect of SGs on urban block units, which will facilitate the creation of more specific and effective master plans that incorporate SGs of the optimum size, distribution, and composition.

2. Material and methods

2.1. Study site

The City of Seoul (Seoul) (37°34′0″N, 126°58′4″E) is the capital of South Korea. Since 1960, Seoul has been quickly urbanized and become densely populated. Seoul's climate is characterized by hot and humid summers with high air temperatures that occasionally climb to over 35 °C. The annual average temperature, humidity, and rainfall are 12 °C, 64.4%, and 1,450.5 mm, respectively. The study sites for this research are located in the Jongno-gu and Jung-gu districts showing high built-up ratios; (15.4% of Jongno-gu, and 37.6% of Jung-gu) (see Fig. 1).

To identify the UHI mitigation effect of SGs on microclimates and make this effect easy to apply in urban policies, plans, and designs, we selected six actual urban blocks as study sites from the two districts. The urban block is the smallest urban planning unit and comprised of various landcovers such as buildings, pavements, and green spaces. The six urban blocks selected were divided into three pairs (Block 1/Block 2, Block 3/Block 4, and Block 5/Block 6) (see Table 1); they had a homogeneous microclimatic urban structure, based on the local climate zone (LCZ) model (Stewart and Oke, 2012). This theoretical climatic model was developed and applied to explain the local climatic homogeneity to prove the relationship between the urban microclimatic characteristics and urban landcovers spatial characteristics such as disposition, purpose, and form of buildings within an urban block (Stewart et al., 2014; Stewart and Oke, 2012). The LCZ model helped to conceptualize our experimental method, which was based on each urban block pair having mutual urban settings with one distinct characteristic of the green spaces. This model ensured that the observations would be representative of the microclimate of the particular green space's structure and type (Runnalls and Oke, 2000). The selected blocks had identical microclimatic conditions with buildings ratios greater than 35%, whereas the SGs ratios ranged from 2.4% to 38% and the average heights of the buildings ranged from 30 m to 45 m (see Table 1).

2.2. Air temperature measurements

Air temperature measurements were performed based on mobile transect surveys at the street level in each block. The mobile transect survey is more economical, accessible, and safer than stationary measurements when a block-sized urban area with various urban settings is measured on a fine scale (Oke, 2006; Grimmond et al., 2010; Stewart, 2011). It produces multiple points across a single block, which record detailed temperature measurements of urban microclimatic factors, and do not require calibration when the measurement is conducted with slow travel speed such as walking (Aguilar et al., 2003; Sun, 2011). The type of air temperature measurement logger used in this research was the Testo 174H (Testo Inc, 2012, Germany), which can measure from −20 °C to +70 °C; its accuracy is ±0.5 °C, and resolution is 0.1 °C. The thermometer was an NTC sensor whose temperature response speed is under 1 s. We set the loggers to record every 1 min.

The air temperature was recorded in the summer, at daytime, for a total of twelve days (from August 9 through September 11, 2012) (see Table 2). The measurement thermometer was sensitive to wind and direct solar radiation; therefore, we shielded it with white plastic (Erell et al., 2003). The observations were assumed to represent the best synoptic meteorological conditions for each of the selected urban blocks.

Measurement points were 1.5 m above the ground. In addition, these selected points were set on mid-width of sidewalks, alleys, and pathways shaded by trees, buildings or exposed to sunshine (Bohnenstengel et al., 2011; Martin et al., 2000; Oke, 2004; Runnalls and Oke, 2006; Sun, 2011; Unger, 2004) (see Fig. 2). To collect reliable data from each single measurement point, we measured the air temperature repeatedly up to nine times through a mobile transect survey (Bowler et al., 2010; Grimmond et al., 2010). The survey routes were established to measure air temperature at the same time and for the same number of measurement points to determine the mutual synoptic conditions for paired blocks, based on LCZ (see Table 2) (Stewart and Oke, 2012). This method was effective in reducing errors in air temperature measurement by mutually setting the control conditions of the test to the pairs used in the mobile transect surveys (Oke, 2004; Bowler et al., 2010; Stewart, 2011).

2.3. Data analysis

In this study, linear regression analysis was used to determine the cooling effect of SGs and their significant types of patches and structures, for use in UHI mitigation planning and design. In previous studies, the structure and type of individual SGs were generalized with specific crown shapes (VanPelt and North, 1997; Lehmann et al., 2014), because these forms are effective in calculating tree characteristics (Georgi and Zafiriadis, 2006). The type and structure of an SG was expected to have an impact on its cooling effect (Hongbing et al., 2010; Napoli et al., 2016). It was unclear, however, what effects would result from various SG types and structures. Thus, we defined the type and structure of each SG through the use of aerial images and field surveys (Forman, 1995; Lehmann et al., 2014): a "polygonal type" of SG, which was shaped like a circle or regular polygon; a "linear type" of SG, which formed a line or bar planted with one or two rows; a "mixed type" of SG, with multilayered vegetation structures composed of tall trees, arbors, and shrubs; or a "single type" of SG, with a single layer of vegetation of only one species. Based on those four types, each SG was categorized in a combination of two types based on its form (polygonal or linear) and vegetation characteristics (single or mixed).

To calculate the volume and area of each SG, a method that included information about the tree height (H), crown radius (r), height of the tree canopy, and crown density was employed; the relevant data were collected through a field survey (Yui, 1969;

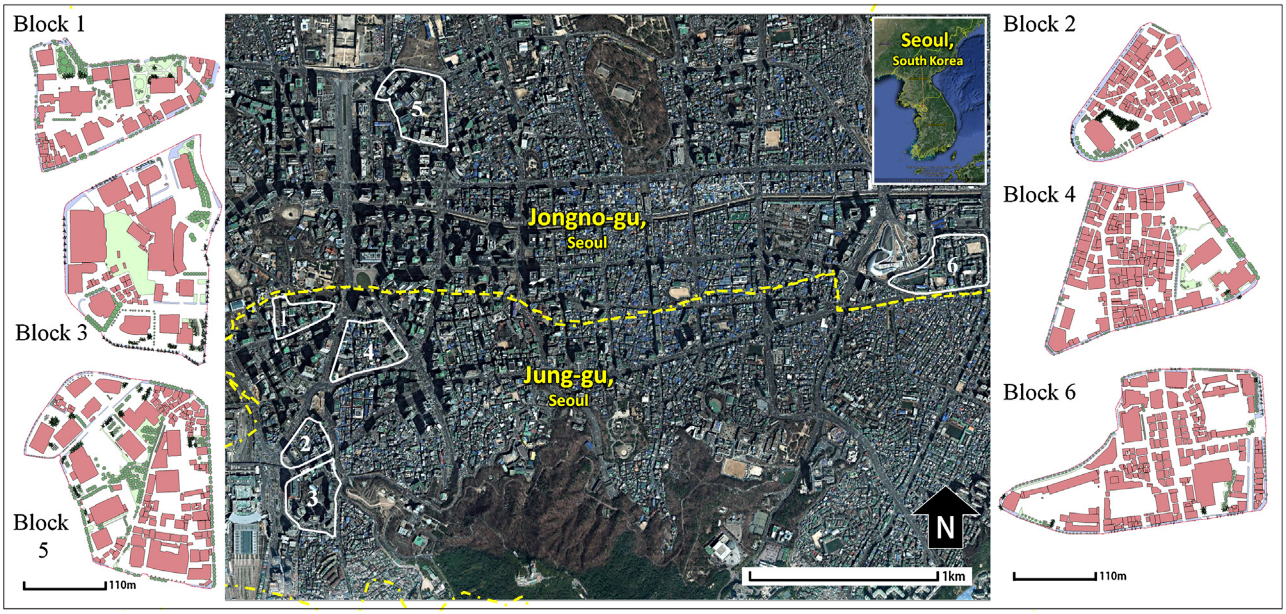

Fig. 1. The study site comprised of three pairs of urban blocks.

Table 1
Summary statistics of each block selected.

Spatial indicator	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6
Block area (m^2)	48,989	49,103	98,375	98,102	112,874	108,151
Building ratio (%)	37.3	41.7	35.1	44.6	36.8	35.6
SGs ratio (%)	14.5	2.4	38	6.4	19.5	9
Buildings height (m)	30	30	45	30	45	30

$\text{Building ratio}(\%) = \frac{\text{Gross area of buildings in a block}(m^2)}{\text{The area of a block}(m^2)}$

$\text{SG sratio}(\%) = \frac{\text{Total area of small green spaces in a block}(m^2)}{\text{The area of a block}(m^2)}$

Table 2
Information of air temperature measurement.

Repetition	Classification	Block 1 and Block 2	Block 3 and Block 4	Block 5 and Block 6
First	Date	Aug. 9th, 2012	Aug. 9th, 2012	Sep. 6th, 2012
	Time	14:00–14:58	12:46–13:52	15:28–17:22
	Iteration	Three times	Three times	Three times
	Weather	Calm	Calm	Calm
Second	Date	Aug. 16th, 2012	Aug. 16th, 2012	Sep. 7th, 2012
	Time	17:16–17:56	16:00–16:58	12:50–14:30
	Iteration	Three times	Three times	Four times
	Weather	Serenity	Serenity	Serenity
Third	Date	Aug. 27th, 2012	Aug. 27th, 2012	Sep. 11th, 2012
	Time	16:00–16:58	13:33–14:31	13:00–14:40
	Iteration	Three times	Three times	Four times
	Weather	Calm	Calm	Calm

Lehmann et al., 2014). However, in this abstraction, the volume of the treetop could be overestimated (Lehmann et al., 2014). Thus, a correction for the crown form was calculated to reflect a more complicated and realistic crown shape, using field survey information and Eq. (1) (Yui, 1969):

$$r = (r_1 + r_2)/2 \tag{1}$$

where r is the radius of the crown measured through the field survey (Lehmann et al., 2014; Yui, 1969), r_1 is the minor axis of the tree crown, and r_2 is the major axis of the tree crown.

The air temperature reduction effect of each SG was analyzed according to paired blocks, using a t-test and Eq. (2):

$$\Delta T_{Pi} = T_{Bc} - \mathrm{T_{Be}} \tag{2}$$

where P_i $(i = 1, 2, 3)$ is the pair (P) and its pair number ($_i$), T_{Bc} is the mean air temperature of each control block (B_c: B_2, B_4, B_6), T_{Be} is the mean air temperature of B_e for the experimental block, (e = 1, 3, 5), and ΔT is the air temperature difference between the two variables.

To evaluate the air temperature reduction effect of SGs according to volume and area, we calculated the volume (SG_V) and area (SG_A) of each SG using Eqs. (3) and (4) (Lehmann et al., 2014; Yui, 1969):

$$SG_V = c\sum \pi r^2 (\mathrm{H} - \mathrm{h}) \tag{3}$$

$$SG_A = (1 - a)\sum \pi r^2 \tag{4}$$

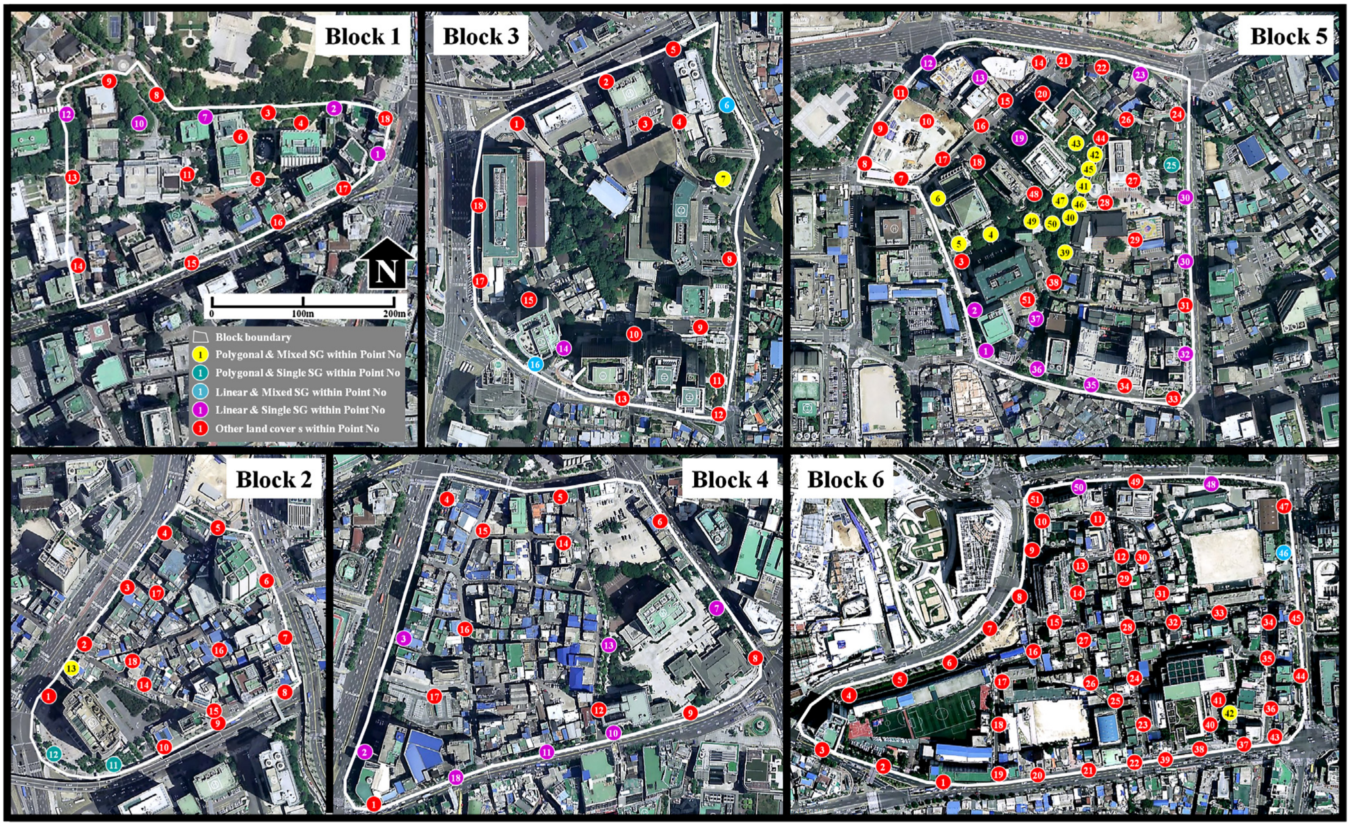

Fig. 2. Air temperature measurement points. All dots represent air temperature measurement points. Yellow dots identify measurement points within polygonal and mixed SGs, and green dots denote those within polygonal and single SGs. Cyan dots indicate measurement points within linear and mixed SGs, whereas purple dots represent those within linear and single SGs. Red dots signify measurement points that were not collected in SGs. The red dots include spaces that were exposed to solar radiation or shaded by buildings. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

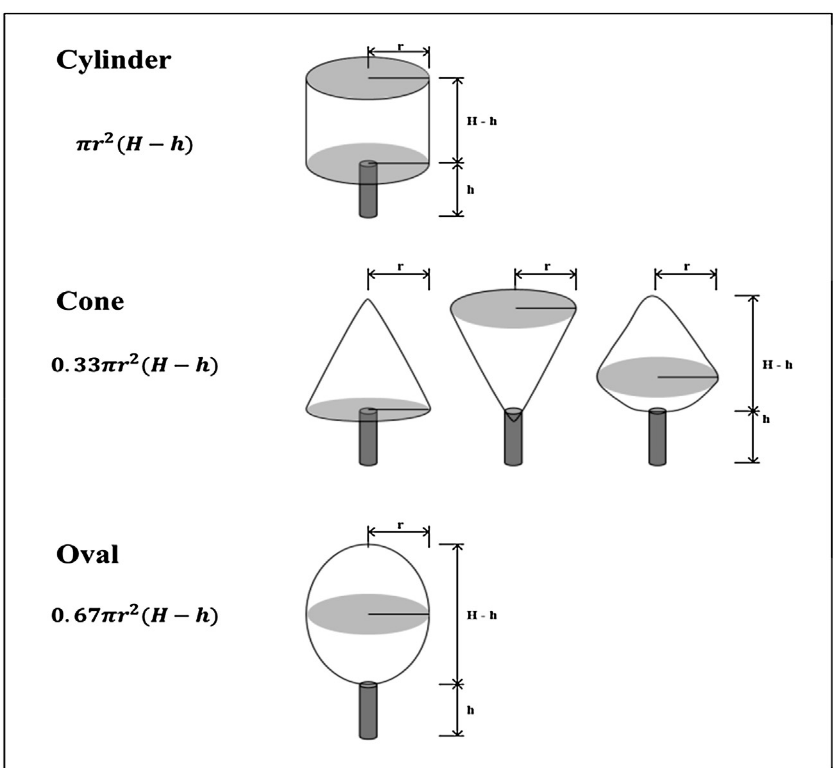

Fig. 3. Calculations for specific crown shapes (Yui, 1969; Lehmann et al., 2014).

where r is the crown radius of the tree or shrub, H is the height of the tree or shrub, h is the height from the ground to the lowest branch of the tree, a is ratio of duplication in the area occupied by the trees and shrubs, and c is the coefficient. Fig. 3 shows the types of c, such as oval (factor = 0.67) or cone (factor = 0.33), which are simple ratios, or cylinder (factor = 1).

The per-block effect (ΔT_{Rmn}) of SG type and structure on air temperature reduction was analyzed to produce a linear regression model; the model used Eq. (5) to show the degree of this effect:

$$\Delta T_{Rmn} = T_{Hm} - \mathrm{T}_{\mathrm{Gmn}} \quad (5)$$

where ΔT_{Rmn} is the difference between the highest air temperature in Block m (T_{Hm}) and the air temperature of G_{mn} (T_{Gmn}) in Block m, m is the block number (m = 1, 2, 3, 4, 5, 6), and n is the measurement point number (see Fig. 2).

Eight linear regression models were then established considering types and volumes of SGs. Four were based on ΔT_{Rmn} and the areas of the four types of SGs (polygonal, linear, single, and mixed). The remainder showed the relationships among ΔT_{Rmn} and the volumes of the four SG types.

3. Results

3.1. Air temperature differences (ΔT_{Pi}) between the control and experimental blocks

The maximum ΔT_{Pi} was 1.93 °C among the three pairs of experimental and control blocks, depending on the SG's area. In Pair 1, each block area was 50,000 m^2, and the green space ratio (green space area in the block/area of the block) of Block 1 (a B_e) was larger than that of Block 2 (a B_c). The ΔT_{P1} value was 0.27 °C (see Table 3). In Pair 2, the block area was approximately twice as large as that of Pair 1 (98,000 m^2). Block 3 (a B_e) had more green area than Block 4 (a B_c). The maximum value for ΔT_{P2} was 0.63 °C. In Pair 3, the block area was still larger (110,000 m^2) than that of Pair 2. The green space ratio of Block 5 (a B_e) was higher than that of Block 6 (a B_c). The ΔT_{P3} value was 1.93 °C.

3.2. Relationship between the highest air temperature and linear/polygonal type

As shown in Table 4, the relationship between the ΔT_{Rmn} value and an SG's polygonal type was significant in the linear regression model; Eq. (6) and Eq. (7) indicated that a block's cooling effect increased as the SG_A and SG_V of the polygonal type increased. However, the ΔT_{Rmn} value and the linear type of SGs did not show significant relationship in the final model. The area and the ΔT_{Rmn} value of each polygonal green space ranged from 500 m^2 to 2500 m^2 and 0.72 °C to 4.10 °C, respectively (see Fig. 4). The polygonal SG_V ranged from 1300 m^3 to 10,000 m^3, as shown in Fig. 5, which indicates that the $\Delta \mathrm{T}_{\mathrm{Rmn}}$ value increased as the volume of a polygonal SG increased.

3.3. Relationship between air temperature and single/mixed type

Table 5 shows the results of the linear regression analysis of ΔT_{Rmn} with the area and volume of two types of SGs: a single and mixed type. The regression model for the mixed type of SG showed a significant relationship, whereas the model for the single type of SG was not significant. This result indicates that mixed SGs' cooling effect on a block increased significantly as its area increased. However, for the single SG, the linear regression model did not explain its cooling effect on a block via its area and volume.

Fig. 6 shows the linear regression model, Eq. (12) for the mixed type of SG_A, which ranged from 100 m^2 to 2000 m^2. The graph represents that the 1500 m^2 mixed type of SG_A had the highest cooling effect, dropping the air temperature by 3.5 °C. According to Eq. (13) of the model (see Table 5), to reduce an urban block's air temperature by 1.0 °C, a mixed type of SG_V needs to be approximately 2081 m^3.

Fig. 7 shows that as the volume of mixed SGs increased, the ΔT_{Rmn} values increased. This type of SG has a mixed and multilayered vegetation structure composed of tall trees, arbors, and shrubs, whereas single SGs consist of tall trees or arbors only.

4. Discussion and conclusions

This research focused on analyzing the cooling effect of SGs at the street level. We categorized SGs in diverse structures and types, as derived from a field survey. Then, four specific SG types (linear/polygonal or single/mixed) were determined based on the vegetation structures and shapes of individual SGs. The results showed that the degree of cooling effect on an urban block was consistent with the SG's size and morphological characteristics (Spronken-Smith and Oke, 1998; Upmanis et al., 1998; Healey, 2006; Forman, 2008; Petralli et al., 2014; Monteiro et al., 2016). This research identified significant relationships among the cooling effect on a block and an SG's type and structure at the street level, which means that SGs could play a significant part in cooling down an urban block's UHI, as larger urban forests do for neighborhoods and whole cities. According to our findings, when an SG's area ratio affected a block's temperature, the cooling effect ranged from 0.27 °C to 1.93 °C. This result supports previous studies reporting that the cooling effect was a maximum of 0.5 °C–1.3 °C when the green space area ranged from 20% to 40% (Giridharan et al., 2008; Moriyama et al., 2009; Yang et al., 2015). Our results indicate that the degree of cooling will increase when the larger proportion of green spaces exist in urban areas, which is a consistent result from previous research (Forman, 2008; Healey, 2006; Petralli et al., 2014).

With regards to the relationship between ΔT_{Rmn} and the linear/polygonal types, the polygonal type of SGs showed a higher level of significance than the linear type in reducing air temperature. This is because the polygonal SG type tends to be clustered. A configuration of the polygonal shape of SGs has an important role in delaying cooling air's diffusion (Spronken-Smith and Oke, 1999; Cao et al., 2010). Meanwhile, linear SGs were generally located on the block boundaries with narrow widths, which could contribute to increasing vulnerability to heat invasion. Moreover, linear SGs had generally a single-layer structure which was primarily composed of identical species of tall trees, without small trees and shrubs, to allow heat flow to easily pass through. Thus, the air temperature near the linear SGs does not drop significantly, even though they can offer tree-shaded spaces. For these reasons, in this study the polygonal type of SGs showed a more effective cooling effect than the linear type.

The mixed type of SG_A and SG_V showed significant in the final linear regression models. Mixed SGs can effectively block heat inflow and easily make cooling zones with multilayered structures composed of tall trees and understory plantings such as grasses, bushes, and small trees (Lehmann et al., 2014). More specifically, SGs with increased tree volumes block solar radiation between the tops of the trees and the ground and absorb heat reflected from surfaces (Oke, 1988; Taha et al., 1991), while their evaporation volume increases the latent heat flux and lowers the temperature through wind ventilation (Bonan, 2002; Bowler et al., 2010; Ferguson et al., 1973; Stewart, 2011; Zhang et al., 1999). According to our findings, mixed-type SGs with areas of 1500 m^2 showed the highest cooling effect, dropping the air temperature by 3.5 °C. Previous studies have also found a significant positive correlation between increased green space and increased cooling effect. They

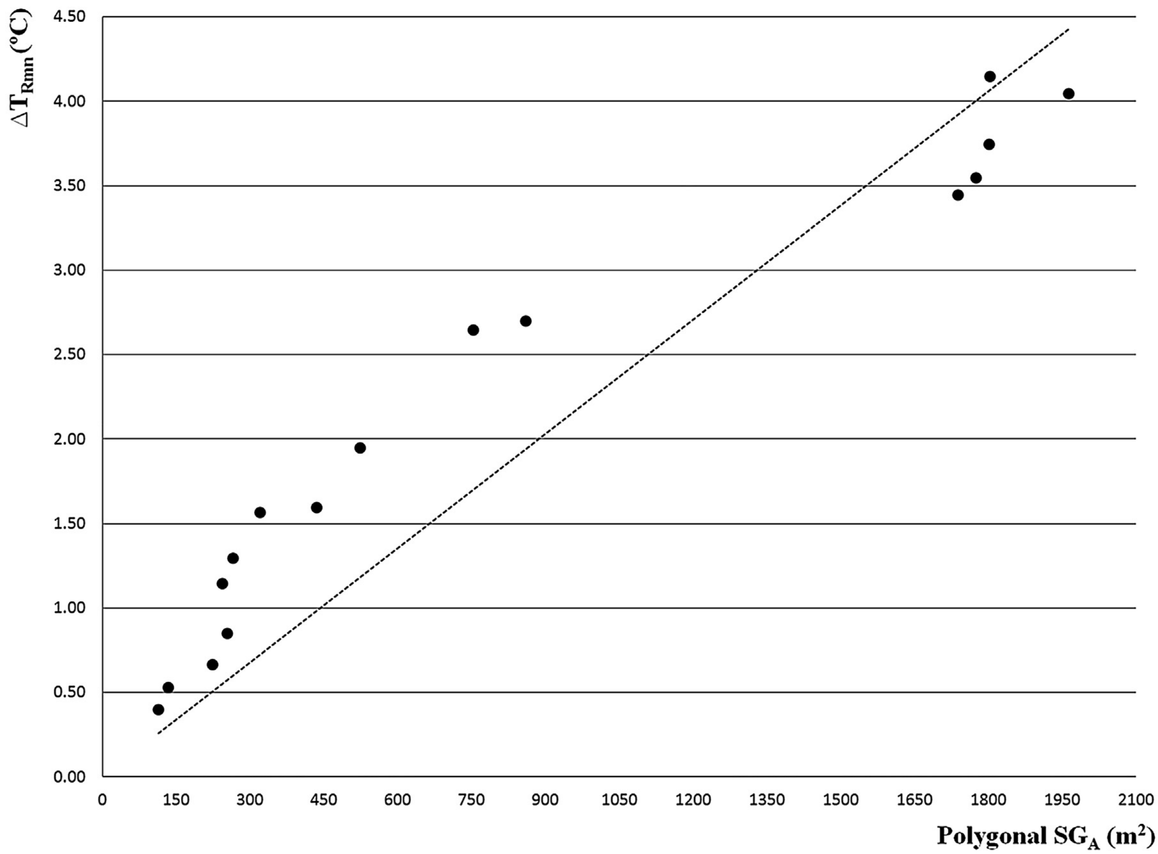

Fig. 4. The relationship between urban heat island reduction and polygonal SG_A.

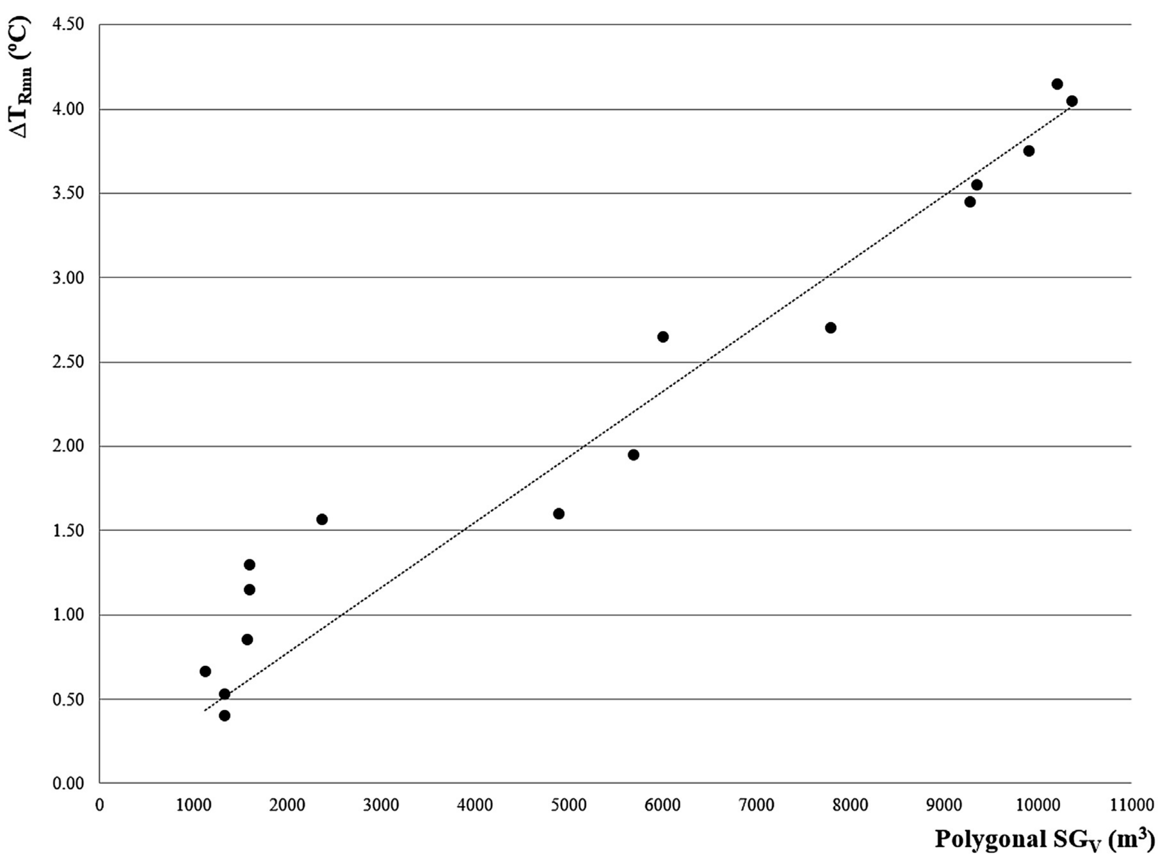

Fig. 5. The relationship between urban heat island reduction and polygonal SG_V.

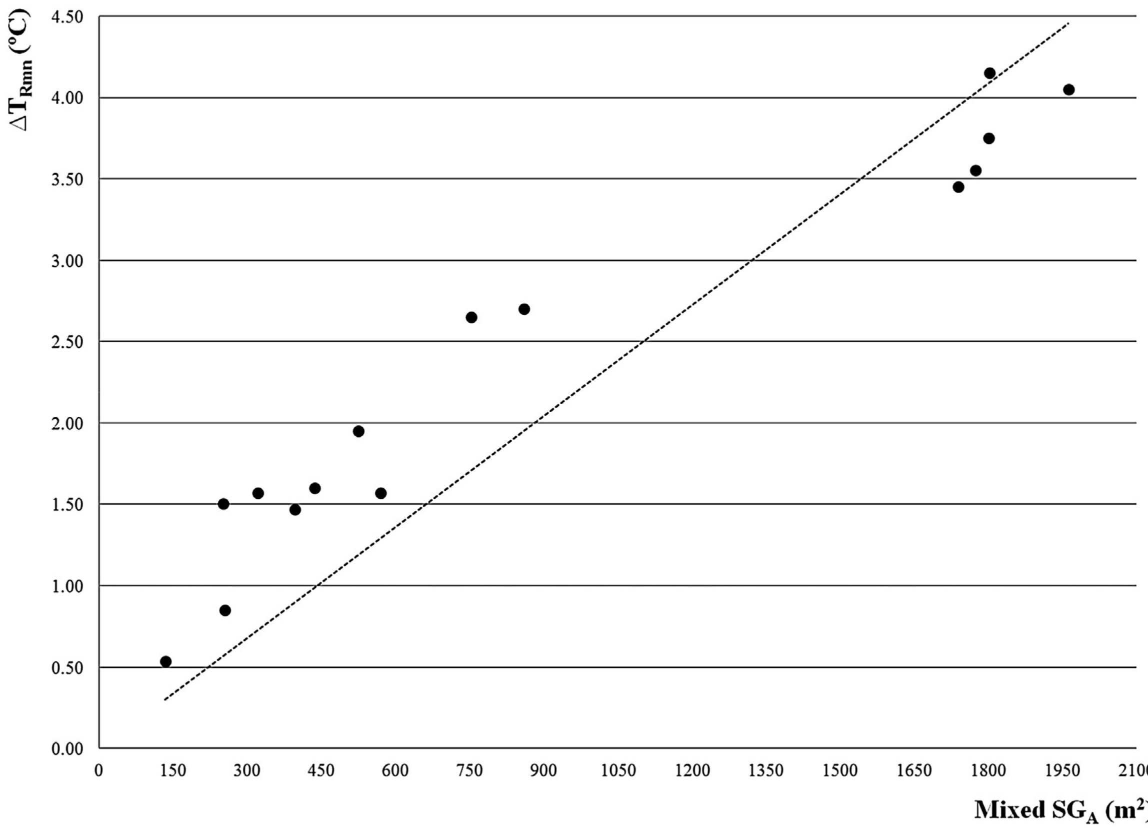

Fig. 6. The relationship between urban heat island reduction and mixed SG_A.

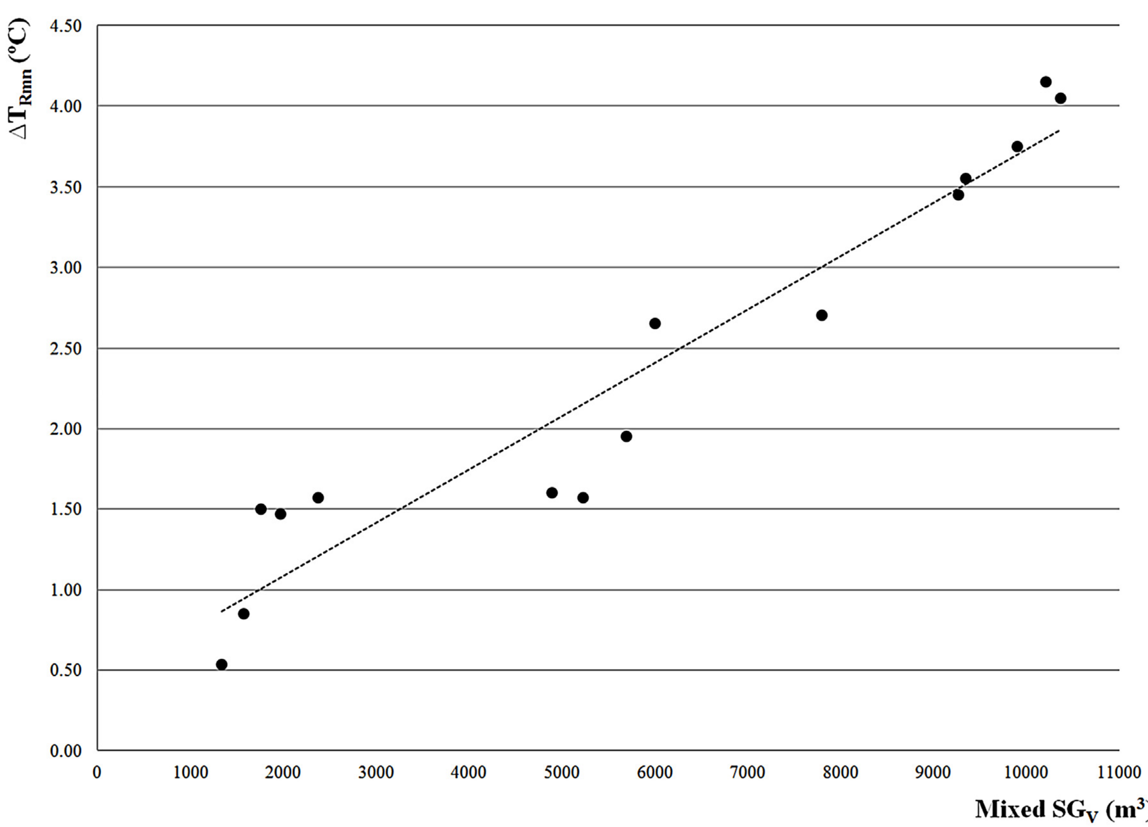

Fig. 7. The relationship between urban heat island reduction and mixed SG_V.

Table 3
T_{Pi} and paired samples *t*-tests experimental and control blocks.

P_i	B_e or B_c	Block Name	Paired Samples Statistics			Paired Differences			t	df
			$T_{BE(BC)}$ (°C)	Std. Dev.	Std. Error Mean	T_{Pi} (°C)	Std. Dev.	Std. Error Mean		
P_1	B_e	Block 1	32.73 (T_{B1})	3.06	1.77	0.27	0.83	0.48	−0.55	2
	B_c	Block 2	33.00 (T_{B2})	2.47	1.42					
P_2	B_e	Block 3	32.63 (T_{B3})	1.45	0.84	0.63	0.98	0.56	−1.11	2
	B_c	Block 4	33.26 (T_{B4})	2.41	1.39					
P_3	B_e	Block 5	29.26 (T_{B5})	1.36	0.78	1.93*	0.25	0.14	−13.30	2
	B_c	Block 6	31.20 (T_{B6})	1.38	0.80					

$T_{Pi} = T_{Bc} - T_{Be}$ (i = 1,2,3, c = 2,4,6, e = 1,3,5).
* Significance $p < 0.05$.

Table 4
Simple linear regression results of ΔT_{Rmn} by SG_A and SG_V for the polygonal or linear types.

Type	Linear regression model		N	Adjusted R^2	Std. Error
Polygonal	$Y = 0.002^{**} X_1 + 0.679$	Eq. (6)	16	0.926**	0.359
	$Y = 0.000347^{**} X_2 + 0.316$	Eq. (7)	16	0.950**	0.295
Linear	$Y = 0.001 X_3 + 1.627$	Eq. (8)	29	0.051	0.974
	$Y = 0.000117 X_4 + 1.745$	Eq. (9)	29	0.051	0.975

Y: ΔT_{Rmn} (°C), which is the difference between the highest air temperature of a block (T_{Hm}) and the air temperature of a SG (T_{Gmn}); X_1: Area (m^2) of the polygonal SG; X_2: Volume (m^3) of the polygonal SG; X_3: Area (m^2) of the linear SG; X_4: Volume (m^3) of the linear SG; Std. Error: Standard error of the estimate of the linear regression model.
** The significance is 0.000 ($p < 0.01$).

Table 5
Simple linear regression results for ΔT_{Rmn} by SG_A and SG_V in single and mixed types.

Type	Linear regression model		N	Adjusted R^2	Std. Error
Single	$Y = 0.001 X_5 + 1.455$	Eq. (10)	30	0.091	1.007
	$Y = 0.000146 X_6 + 1.610$	Eq. (11)	30	0.076	1.016
Mixed	$Y = 0.002^{**} X_7 + 0.854^{**}$	Eq. (12)	15	0.925**	0.327
	$Y = 0.000331^{**} X_8 + 0.423$	Eq. (13)	15	0.912**	0.354

Y: ΔT_{Rmn} (°C), which is the difference between the highest air temperature of a block (T_{Hm}) and the air temperature of a SG (T_{Gmn}); X_5: Area (m^2) of the single SG; X_6: Volume (m^3) of the single SG; X_7: Area (m^2) of the mixed SG; X_8: Volume (m^3) of the mixed SG; Std. Error: Standard error of the estimate of the linear regression model.
** The significance is 0.000 ($p < 0.01$).

have documented that the amount of green space is strongly related to reducing air temperature. When the amount of green space has been increased from 14,700 m^2 to 3,240,000 m^2, the air temperature has been dropped by 0.51 °C to 8.96 °C (Hamada and Ohta, 2010; Lee et al., 2009; Lehmann et al., 2014; Maimaitiyiming et al., 2014; Ng et al., 2012; Wong and Yu, 2005). In addition, our results demonstrated that even small green spaces of less than 200 m^2 with a mixed polygonal type had a significant cooling effect on urban blocks, reducing ΔT_{Rmn} up to 1 °C. This finding supports that the configuration of green space plays a more important role in influencing the degree of cooling effect (Li et al., 2012; Lehmann et al., 2014).

According to our findings, polygonal as well as mixed SG of 10,000 m^3 has a significant cooling effect on urban blocks covering 50,000 m^2 to 110,000 m^2. The results shown in the final regression models for the SG_V values of the polygonal and mixed types were as significant as those of the SG_A values of the same types. This was a consequence of the increased tree density improves cooling through evaporation (Kettridge et al., 2013). This provides a critical UHI mitigation approach that urban planners or policy makers should consider with regards to SG areas and volumes and their association with cooling (Rafiee et al., 2016).

This study has several limitations. First, the selection and the number of study sites should be addressed. Even though we selected urban blocks representing very similar settings to compare pairs, this study was not an experimental study enabling to fully control all variables which could affect each study site. The results from the comparison of pairs of blocks would have been more reliable if the selected blocks had more mutually microclimatic conditions, such as being geographically close to one another or having more identical block areas, building heights, or building areas on single blocks. In addition, future research should collect a larger amount of data measurement points with more numbers of study sites to improve general validity. The method of this study was also limited based on how transect measurements were conducted within a single block. Although we properly maintained the air temperature measurement device and repeated the measurements up to nine times to enhance reliability, heating sources surrounding the measurement instrument may influence the values of our final data sets.

Despite those limitations, this research contributes to filling the gap of the existing body of literature. The objective of our research was to analyze the SGs' cooling effects at the street level in urban blocks based on their types and structures. At the street level, air temperature measurements were conducted based on mobile transect survey of the SGs on each block. The outcomes of this study extend those of most previous research, which has historically been focused on a broad scale and analyzed big green spaces' cooling effects on a city. The main results of this study are: 1) in the paired blocks, a block that had more SGs (19% and more) showed lower average air temperatures, up to approximately 1 °C lower than the other block had less SGs; 2) polygonal and mixed types of SGs' areas and volumes increased the UHI mitigation effect by up to approximately 4 °C, as they increased according to significant linear regression models; 3) in particular, SGs of less than 500 m^2 and 2000 m^3 represented a reduction in UHI of up to 1 °C; and 4) the 1500 m^2 mixed type of SGs had the highest cooling effect by reducing the air temperature by 3.5 °C.

The outcomes of this research will help urban planners and policymakers, especially those who work among in cities struggling with UHI due to the large amount of solar-radiated paved areas. According to our findings, denser and multilayered with polygonal shaped SGs can positively contribute to reducing UHI. In addition, even small green area can bring a positive benefit to increase the cooling effects in urban blocks. The findings of this study will contribute to urban planning and design by helping stakeholders choose the most appropriate types and structures of green spaces required to optimize cooling, as well as inform them regarding how these green spaces should be designed and distributed.

Acknowledgements

This research was supported by a grant (16AUDP-B102406-02) from Architecture and Urban Development Research Program (AUDP) funded by Ministry of Land, Infrastructure and Transport of Korean government. We appreciate Dr. Byoung E Yang, Dr. Chong Hwa Park, and Dr. Hideki Takebayashi for their valuable insights to develop this research.

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