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# Influence of landscape interventions on thermal comfort under time-varying building shadow; new Gwanghwamun square case, Seoul, South Korea

Yuha Han [a], Yongjun Jo [b], Eujin Julia Kim [c,*]

[a] *Research + Design Lab 517, Department of Environmental Landscape Architecture, Gangneung-Wonju National University, Gangneung, 25457, South Korea*
[b] *College of Architecture and Urban Planning, Hongik University, Seoul, 04066, South Korea/Design Development Department, CA Landscape Co., Ltd., Seoul, South Korea*
[c] *Department of Environmental Landscape Architecture, Gangneung-Wonju National University, Gangneung, 25457, South Korea*

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## ABSTRACT

This study investigated the cooling effects of landscape interventions and their relative magnitude under hybrid urban context including time-varying building shadow cast. The study focused on the practical design alternatives, rather than experimental scenarios. We conducted outdoor thermal comfort (OTC) simulation using ENVI-met, and spatial-temporal comparison analysis for three green space expansion interventions for new Gwanghwamun square, Seoul, South Korea. In addition, we statistically analyzed the relationship between TCR (tree coverage ratio), GCR (green coverage ratio), WCR (water coverage ratio) and PET (Physiological Equivalent Temperature). The correlation and regression coefficients of the relationships under different building density, building locations and shadow cast conditions were compared. As a result of three interventions comparison, the comfort zone increased almost two times, while the discomfort zone decreased to ≈70% of the current condition in the long-term alternative. As TCR increases 22%, PET decreases up to 2.6 °C in average. Tree coverage ratio showed significant importance among the landscape elements. The influence of trees was slightly different for different contexts; larger cooling effect was found in no building shadow cast and low-density buildings. However, the difference was not noticeable; the influence of trees is still effective under building shadow cast and high-density buildings. Moreover, for high tree density area (TCR>50%), temporal gap of thermal comfort between measured time that mainly caused by building shadow change was greatly reduced compared to low tree density area (TCR<5%), which suggest the important role of tree in providing consistent thermal comfort. This study provides scientific evidence for trees' cooling effect and its relative magnitude under diverse built contexts of N–S oriented urban canyon. This study also contributes to developing an inclusive thermal comfort evaluation method based on both temporal and spatial scales for the effective comparison of real-world design alternatives.

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* Corresponding author.
*E-mail addresses:* wldnrsla95@gmail.com (Y. Han), jojerem@gmail.com (Y. Jo), ejkim@gwnu.ac.kr (E.J. Kim).

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## 1. Introduction

Rapid urbanization and excessive urban development have led to increased urban heat and changed urban microclimate[1]. Recently, abnormal climate including extreme heat, have heavily influenced the health and real life of citizens. To respond to these tendencies, regional and macro scale climate studies based on long-term periods are necessary, however, complementary micro-level studies based on the human life cycle and experiential scale should be undertaken. In addition, based on the real-world condition, practical urban and landscape design responses and strategies that are suited for specific city and neighborhood location are significant.

Landscape design resilient and adapt to urban heat and thermal discomfort have become important[2]. When considering availability, human-scale impact, and project budget, the landscape design intervention can have a much more direct and immediate influence than built structure. Engaging urban green infrastructure (i.e., trees, herbs, green-roofs, vertical greenings, and water bodies) suggest a sustainable solution to urban heat discomfort[3–5]. In particular, strategic landscape design utilizing GI, if it is planned properly, can be a good measure to control the outdoor microclimate and enhance thermal comfort, therefore, study results should be well-interpreted and the information needs to be available for landscape architects to fully utilize those in planning and design process [6–9]. For effective thermal comfort evaluation and comparison of different types of design interventions, this study tests different ways to calculate the averaged thermal comfort values of each alternative, considering diverse temporal and spatial scales, and utilizing bottom-up analysis of equally subdivided sections. This study provides implications and meaningful influences on an on-going project and engaging in a practical landscape planning and design process.

While the major influences of urban form and structure (i.e., building density and height, street patterns, sky view factor) on thermal comfort have been emphasized in several studies[10–17], the influence of landscape elements that include vegetation, paving structure, and water installation has also been proved in much research.

Urban landscape, such as trees, parks, and water bodies, are found to change the incident solar radiation, air temperature, relative humidity, and wind flow, contributing a comfortable outdoor thermal environment for pedestrians[18–21]. In general, trees are proved toreduce the transmission of solar (shortwave) radiation[22] and lowers the air and surface temperatures through shading and transpiration in the urban canyon [23]. Regarding tree types, compared to groundcover and shrub, trees were estimated as the most effective medium for heat mitigation[24]; Chatzidimitriou and Yannas 2015). In addition, planting location and pattern, tree configuration parameters were also found to be significant factors (Abdi and Zarehaghi 2020; [25]. Other landscape elements, such as high albedo paving material and water space, were also found to mitigate urban heat stress (Chatzidimitriou and Yannas 2015; [26]. For example, water fountain and pond had a cooling effect in open area allowing air ventilation; however, they were not effective in the high-density area, or during nighttime[27–29]. For surface material, for both surface and globe temperatures, grass surfaces were significantly cooler than hard pavements, the same as shaded surface compared to exposed surface (Chatzidimitriou and Yannas, 2015). Although high albedo paving and building materials have been measured to have lower surface temperature, the globe and air temperatures were estimated higher due to the reflected radiation (Chatzidimitriou and Yannas, 2015, [30].

Although trees and other landscape elements has heat mitigating effect in general, they are the most versatile element and the degree of their influences varies depending on the surrounding built conditionorientation, andtime of day [22,31–34]. For sky view factor (SVF), in general, lower SVF leads to a decrease in air temperature by providing a building shading effect [10,13,17], thus, adding trees in high SVF area was found to be more effective. Most of all, the effectiveness of trees and water has been questioned under deep urban canyon and high urban density area due to blocked ventilation[28,32,35]. However, most recently, even in high-density condition, larger tree volumes as well as dense multi-layered plantings were found to lead to greater thermal comfort due to evapotranspiration and long-wave radiation blocking[36]. The understanding about two shading types of building and tree, and the contextual understanding for cooling effect of plants are important[37]. More complexity happens for street orientation. The maximum effect of planting trees was measured clearly in E—W streets with low-aspect ratios, the worst solar exposure scenario[11]. However, for N–S streets is complex to determine because the east and west sides are shaded by buildings in the morning and afternoon, respectively[12].

In sum, the efficacy of landscape elements at improving thermal comfort varies the morphological condition of the site, and the interpretation of results is complicated under the real-world condition because of the mix of built structure and landscape elements. In particular, for the shaded high-density area, the effects of landscape elements including trees and water space on pedestrian thermal environments are controversial. While the impact of trees is largely expected, clear evidence is lacking for the contextual differences, for instance, the relative magnitude under different building shadow cast, in particular, time-varying shadow cast in N–S urban canyon.

Therefore, this study focuses on how the changes of landscape elements affect the outdoor thermal condition, especially under the extensive and simultaneous influence of urban built structure with the case of the N–S orientation street and public space, where there is radical change of building shadow cast during the day. Gwanghwamun square, a representative square in the city of Seoul, has good scale and condition to investigate the practical, hybrid urban condition of a mix of buildings, roads, pedestrians, green space, plantings, paving, and street furniture that are important spatial factors for microclimate control. The site is located in the central district which is heavily visited and that is facing a major change of green space expansion.

## 2. Methodology

### 2.1. Study area

The study site is located in the central business district surrounded by various heights of buildings and roads where different aspect ratios are found, and the measured Sky View Factor (SVF) ranges (0.37 – 0.85) (Fig. 1)[38]. There is a wide-open space in front of Gwanghwamun Gate on the north side, and high-rise buildings are located on the south side. The paved square has a N–S oriented linear shape, and the dimensions of the study boundary are approximately 610 m × 80 m (length × width), including a central square, sidewalks, roadways, green space, water fountain, and street trees. Green expansion of linear public square in N–S oriented urban canyon Gwanghwamun square renovation project in Seoul, South Korea.

Gwanghwamun square has been recognized as a symbolic center of politics and administration in the City of Seoul, and diverse types of activities, events, and assemblies are held there throughout the year. During the Joseon Dynasty, major national events took place in this front square of the palace. In the Japanese colonial era, Gwanghwamun was relocated to the East area of Gyeongbokgung Palace, and the Japanese General Government building was constructed. In 1995, the building was demolished, based on a historical restoration project. Finally, the new Public Square was open in 2009, and Gwanghwamun gate was restored in 2010. Currently, a new Gwanghwamun square design and construction is completed in Aug 2022.

As public health and pedestrian environment becomes important, design alternatives of new Gwanghwamun square were investigate based on road reduction and green space extension. In 2019, Seoul city government held an international design competition for a new Gwanghwamun with the principles of a square to the West, bounded on the Eastern side by vehicular lanes, and road lanes reduction. As a competition result, the “Deep surface” idea was selected, in which the design team proposed a pedestrian-oriented and connected place, underground daily program development, various levels of plantings, and a specially designed paving area. After the selection, the proposal was revised based on several reviews and deliberations. In addition, the design team developed a long-term plan that focuses on creating the area as a fully pedestrian place. Currently, the city government is considering three development phases. Fig. 2 shows the three-phased plan. The first phase indicated the current conditions based on 12 lanes of vehicular roads on both East and West sides, and an isolated public square in the center. The second phase presents the selected short-term plan with reduced 6 lanes of roads, and renovated square on the West side. A small forest and four-season garden are planned with a randomized, multistory planting scheme. Increased green space are approximately 17,000 sq. m. with 300 trees, 3000 shrubs, and ground cover. Various water spaces, such as water fountain and mirror pond are added, and distributed to the West area. The third phase indicates the long-term plan of a fully pedestrianized environment through vehicular underpass. Symmetrical plantings are added and evenly distributed to the East side. Approximately 45,500 sq. m. of green space with 1000 trees, and 12,000 shrubs is planned (Fig. 2). Table 1 indicates the percentage comparison of building and landscape elements of three phases.

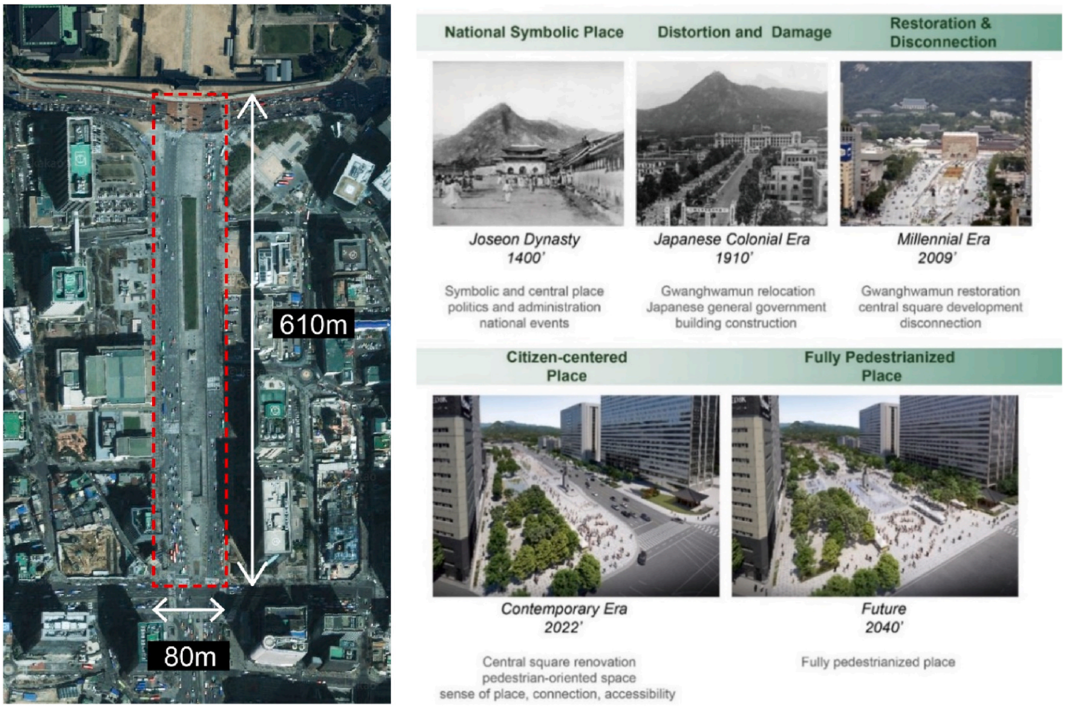


**Fig. 1.** Gwanghwamun square, Seoul, South Korea.

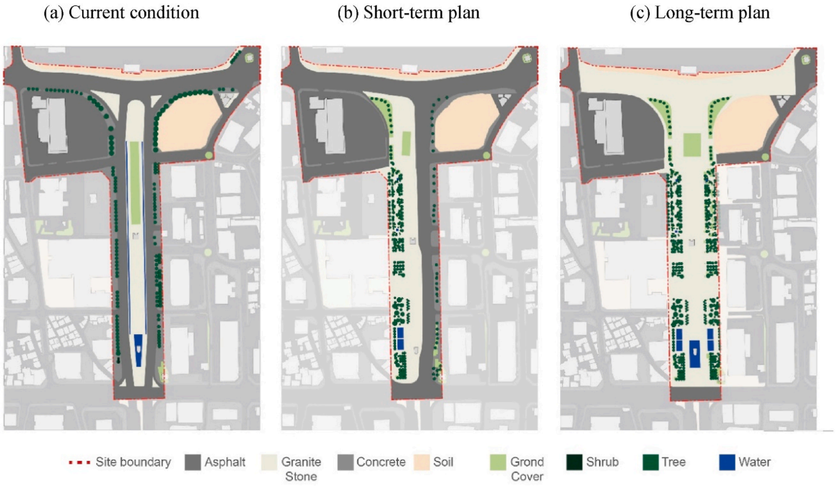

(a) Current condition
(b) Short-term plan
(c) Long-term plan

**Fig. 2.** Masterplan of the three development phases and landscape parameters.

**Table 1**
Landscape elements comparison.

| Parameters | | Current | Short-term | Long-term |
|---|---|---|---|---|
| Buildings | | 4.87 | 4.87 | 4.87 |
| Plantings | Trees (ea.) | 66 | 254 | 503 |
| | Shrubs (ea.) | 47 | 318 | 318 |
| | Ground cover (%) | 2.79 | 3.97 | 6.63 |
| Water space (%) | | 1.75 | 0.40 | 1.61 |
| Paving Materials (%) | Asphalt | 48.80 | 42.70 | 15.80 |
| | Concrete | 13.40 | 9.80 | 1.92 |
| | Granite stone | 17.88 | 27.75 | 58.66 |
| | Soil | 10.51 | 10.51 | 10.51 |
| Total (%) | | 100 | 100 | 100 |

### 2.2. *Modeling and parameters for OTC simulation*

Fig. 3 shows 3-dimensional modeling of the three-phased plan, looking North. (a) The current condition has a central square with traffic lanes on both sides, while (b) the short-term plan has a square with traffic lanes on only one side. (c) Long-term plan has fully pedestrianized space with traffic underpass. Current condition model is composed of 16% tree coverage, 5% green space coverage, and 4% water space coverage. In short-term plan, tree coverage increased to 22% and green and water space coverage either slightly decreased or increased. In long-term plan, tree and green coverage increased up to 38% and 11%, respectively. Same water space to current condition was arranged differently with urban forest in both sides. For all phases, building foot print, height and layout remains same.

For landscape plantings, tree types, layout and area were set based on current, short and long-term planting plan. Tree types are largely divided into evergreen tall tree, deciduous tall tree, evergreen shrub, deciduous shrub, and ground cover. For simulation, based on ENVI-met tree library, evergreen trees were set with conic, medium trunk, sparse leaves, and medium height. And deciduous trees were set with cylindrical, medium trunk, dense leaves, and medium height. Since ENVI-met (4.3.4 version) tree library had single category for shrub(hedge dense, 2 m height) and groundcover(grass dense, 50 cm height).

For thermal comfort simulation, ENVI-met 4.3.4 program was used. ENVI-met is a three-dimensional microclimate CFD-based model that has been widely used for microclimate simulation studies; in particular, more than half of the vegetation thermal effect simulations used ENVI-met[3]. Unlike other models, the strength of ENVI-met is that it can simulate the surface–plant–air interactions. It enables very detailed vegetation representation with high resolution, in which plants can interact with the surroundings by evapotranspiration[3].

The simulation accuracy of ENVI-met has been proved in varying conditions. Although inaccuracy is found in architectural transitional spaces, most research conducted in different urban contexts showed high agreement between the simulation results and field measurements[32,39–45]. For example, the results from simulated vegetation model under varying weather conditions showed high accuracy in terms of both magnitudes and variations[42], and the results from simulation and measurements showed high agreement while studying the effects of trees under both sunny and cloudy conditions [40]. Other results studying plantings with different built densities (i.e., SVF) also showed similarly accurate results[45]. In addition, the measured and simulated results from open and tree-shaded points in the N–S oriented street canyon showed fairly good correlation[32]. These precedents indicate that the

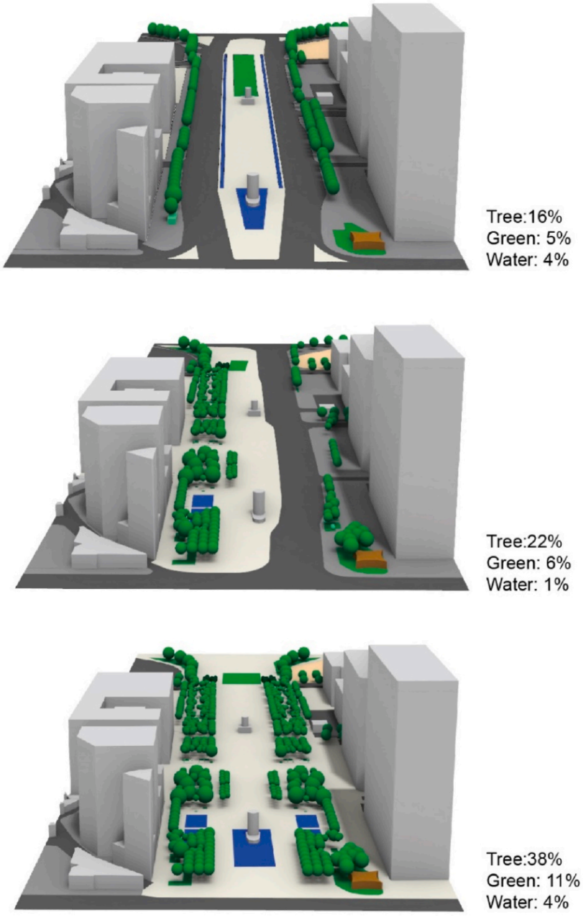


**Fig. 3.** Base modeling of the three development phases, looking North.

ENVI-met is a reliable model for studying the effects of trees in enhancing thermal comfort.

Table 2 shows the local climate data of Gwanghwamun area found from a meteorological observatory, located at Songwol-dong 1-1, Jongno-gu, Seoul, which is approximately 900 m distant from the study site. Based on the measured local data, during August, the hottest month of the year, the average air temperature in the region ranges (25.9–27.2) °C for the last three years. For the same period, the average relative humidity ranged (69–85) %, and the average air velocity ranged (1.6–2.3) m/s at 10 m above ground. The

**Table 2**
Initial atmospheric input and simulation configuration settings for the simulation.

| | | |
|---|---|---|
| Location and date | Location | Seoul, Republic of Korea (37° N, 126° W) |
| | Simulation Day (DD.MM.YYYY) | 26.08.2020 |
| | Simulation start time (HH:MM:SS) | 6:00:00 |
| Meteorological condition | Wind speed at 10 m above ground (m/s) | 3.4 |
| | Wind direction (°, clockwise from 0°: N) | 67.5 |
| | Roughness length (m) | 0.01 |
| | Atmospheric temperature (°C) | 27.00 (min), 34.40 (max) |
| | Relative humidity (%) | 54 (min), 82 (max) |
| Built forms | Street/road orientation, material | N–S, Asphalt, Granite stone paving |
| | Building height, material | 12–97 m, Concrete (light weight), brick wall, terracotta |
| Landscape elements | Tree type, height, density | Shrub = hedge 2 m, dense<br>Deciduous tree (cylindrical, medium trunk, dense, 15 m height, 9 m crown)<br>Evergreen tree (conic, medium trunk, sparse, 15 m height, 7 m crown) |
| | Green space | Grass 50 cm average, dense |
| Simulation settings | Output interval main files (min) | 60 |
| | Boundary Condition | Simple Forcing |
| | Grid size (m) | 3 × 3 × 5 |

meteorological condition of the hottest day (Aug 26, 2020) was used.

For built forms, building heights range from 12 m to 97 m and most building materials were set as light-weight concrete. For street and road, asphalt and granite stone paving was used. For landscape elements, two types of tree were introduced; one is deciduous tree with cylindrical, medium trunk, dense leaf, 15 m height, and 9 m crown. The other is evergreen tree with conic, medium trunk, sparse, 15 m height, and 7 m crown. Shrub with 2 m hedge and dense leaf, as well as, grass with 50 cm average height and dense leaf were arranged.

### 2.3. Thermal comfort index

Several thermal comfort indices have been developed to accurately calculate and describe thermal stress[46,47]. Initiating from separate indices for cold and hot climate conditions, universal indices have been developed, such as the Standard Effective Temperature (SET), Physiological Equivalent Temperature (PET), and Universal Thermal Climate Index (UTCI)[48]. These indices use two node model and measure the level of relative thermal comfort felt by the human body in a modeled mechanism in a given environment, based on the theories of basic heat-related science and human energy balance. Predicted Mean Vote (PMV) uses a static, one node model based on human body heat balance, and was developed based on thermal sensation votes from more than 1300 human subjects [49]. Unlike other indices, Wet Bulb Globe Temperature (WBGT) is calculated using only environmental variables, and was developed for the U.S. army for training safety purpose in the field[50]. While PMV and SET have a strong basis for the indoor environment, PET has been primarily designed for outdoor use[51]. PET is defined as the air temperature when human energy budget is balanced with the same core and skin temperature, as in the complex outdoor condition for the assumed indoor setting[52,53]. PET enables people to compare and connect their thermal experiences in complex outside environments with those in the standard indoor condition[52–54]. Lastly, UTCI is developed through the collaboration of scientists from different fields based on the latest thermos-physiological models, combining a human temperature control model and a state-of-the-art clothing model[55,56]. For this study, we selected PET for the thermal comfort evaluations of three development phases. This is because it has been used widely in different climatic conditions worldwide, has been assessed as an accurate index, and showed positive results when the outcomes from simulations were compared with field monitoring data, thus increasing reliability [47,48]. PET is also an easily comprehensible index, using Degree Celsius for urban planners and policy makers who may not be familiar with meteorological terms[57].

### 2.4. Field measurements and model validation

For validation, the measured and simulated results were compared to evaluate the accuracy of the ENVI-met model. Field measurements for the current condition were conducted at two selected locations; one in the shade (section 25: two rows of street trees), and the other in open areas (section 17: open square) from 10:00 to 16:00 on Sep 13 and Sep 30, 2019 (Fig. 4). The day was windless and had clear sky. The instruments used in field measurement were two weather stations (Davis Vantage Pro 2 Plus) mounted on tripods. The weather stations collected meteorological data for air temperature (0.3 °C accuracy) and relative humidity (2% accuracy) every 1 min (Table 3).

Fig. 5 shows the correlation and RMSE between the simulated and measured values for air temperature (Ta), relative humidity (RH), and mean radiant temperature (mrt). RMSE is the sum of the degree of systematic error, and is a typical method to show the deviation between the simulated value and measured value to describe the accuracy of the simulation model. A comparison of 104 sets of data between the measured and simulated results showed strong correlation for Ta (0.78) and RH (0.76). In addition, the P values of the two sets of data were less than 0.001 for all three parameters. The RMSE for T and RH were 2.13 °C and 5.09%, respectively. These indicate that the ENVI-met simulation model reflected the actual measurement characteristics. Considering that the accuracy of sensor is 0.3 °C and 2% respectively, the deviation can be regarded as acceptable. Mean radiant temperature (MRT), the most important parameter for thermal comfort, was calculated according to ISO 7726 standards:

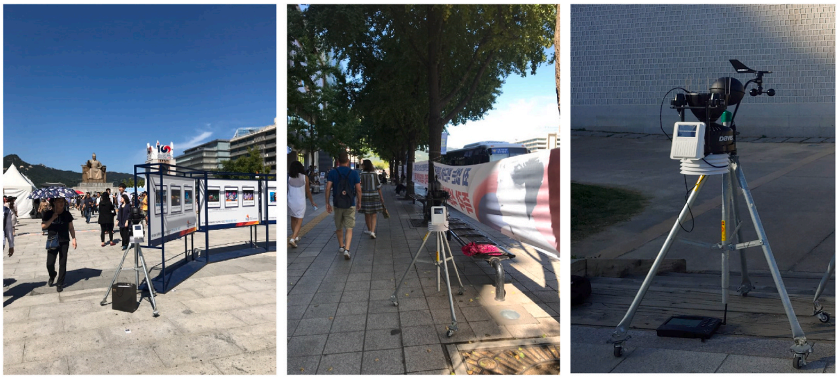
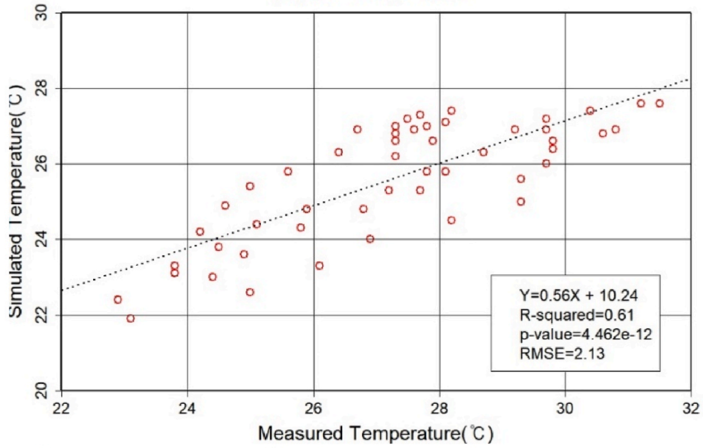


**Fig. 4.** Field measurements setting in open and shaded sections.

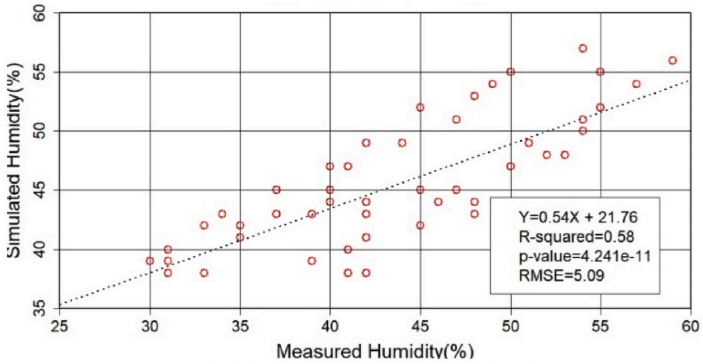
**Table 3**
Equipment, sensors, parameters, accuracy and response time.

| Equipment | Sensor | Parameter measured | Accuracy | Response time |
|---|---|---|---|---|
| Davis Vantage Pro 2 Plus | PN junction silicon diode | Air temperature | +-0.3 °C | 10 s |
| | Film capacitor element | Relative humidity | +-2% | 50 s |
| | Solid state magnetic sensor | Wind velocity | +-5% of full scale | 2.5 s |
| | Standard radiation shield | Solar Radiation | +-5% of full scale | 50 s |
| Testo 440 | TE type K (D = 150 mm) | Globe temperature | Class 1(K-type) | 60 s |

(a) Air Temperature



(b) Relative Humidity



(c) Mean RadiantTemperature

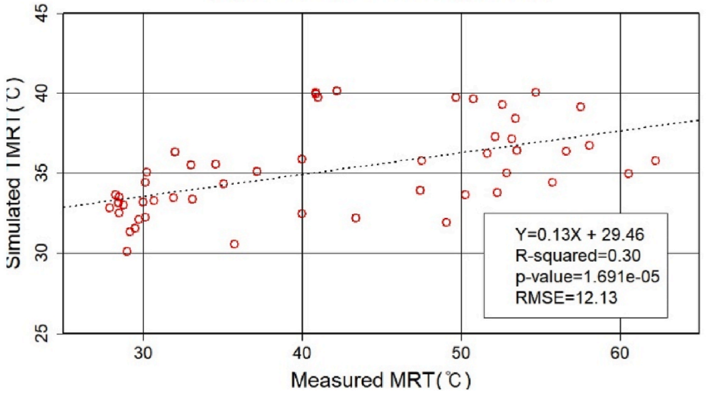


**Fig. 5.** Model validation for air temperature, relative humidity, and mean radiant temperature.

$$\text{MRT(mean radiant tmeperature)} = \left[(\text{GT} + 273.15)^4 + 2.5 \bullet 10^8 \bullet {v_a}^{0.6}\ (GT - T_a)\right]^{\frac{1}{4}} - 273.15$$

where GT is globe temperature (globe diameter and emissivity set to 0.05 m and 0.95 for a black globe), Ta is air temperature, and $v_a$ is wind velocity. The correlation and RMSE of measured and simulated MRT were 0.56 and 12.13, respectively.

### *2.5. Spatial and temporal OTC comparison of three practical design interventions*

In order to effectively compare and evaluate OTC of three design interventions, this study tested different ways to calculate the averaged thermal comfort values of each alternative with temporal and spatial scales. For overall comparison, comfort and discomfort cell percentage for selected times was calculated and compared. In addition, to investigate the hybrid, complicated real-world conditions of the three practical plans as they are, we conducted bottom-up comparison analysis based on the equally subdivided thirty sections (Fig. 6). The size of each section was 30 m × 60 m. This dimension is effectively divide whole area, compatible to landscape spatial data, and helpful to examine spatial composition. We extracted the PET values at 2 p.m. when there is the least influence of building shadow cast, as well as, 10am and 5pm when there are the greatest changes in extracted values. The PETs of all cells were compared within single phase, as well as, between phases.

### *2.6. The influence of TCR, WCR, GCR on thermal comfort level*

The relationship between landscape parameters and outdoor thermal comfort was statistically analyzed. Tree shade cools air temperature by blocking solar radiation and subsequently lowers surface temperature, thus affecting thermal comfort. Tree canopy coverage ratio can be representative variable indicating major landscape interventions[58]. For landscape parameters, tree coverage ratio (TCR) was calculated for each cell using vegetation LAD (Leaf Area Density) function in ENVI-met, which determines the cell percentage with tree leaf density at 12.5 m. Green coverage ratio (GCR) and water coverage ratio (WCR) were calculated using Auto CAD program. For OTC, PET values for each cell were extracted using ENVI-met simulation result. Table 4 shows three landscape parameters in each cell for three phases. Subsequently, statistical analysis of correlation and multiple regression was conducted using R studio 4.2.0. Table 5 shows independent and dependent variables used for analysis.

Statistical analysis was conducted in two phases. While the variable values in all the cells of three phases were included for the first phase, for the second phase, the variable value changes in identical cell location between different phases were used for the analysis. Differences in PET(ΔPET) between phases with different greening coverages were defined as follows.

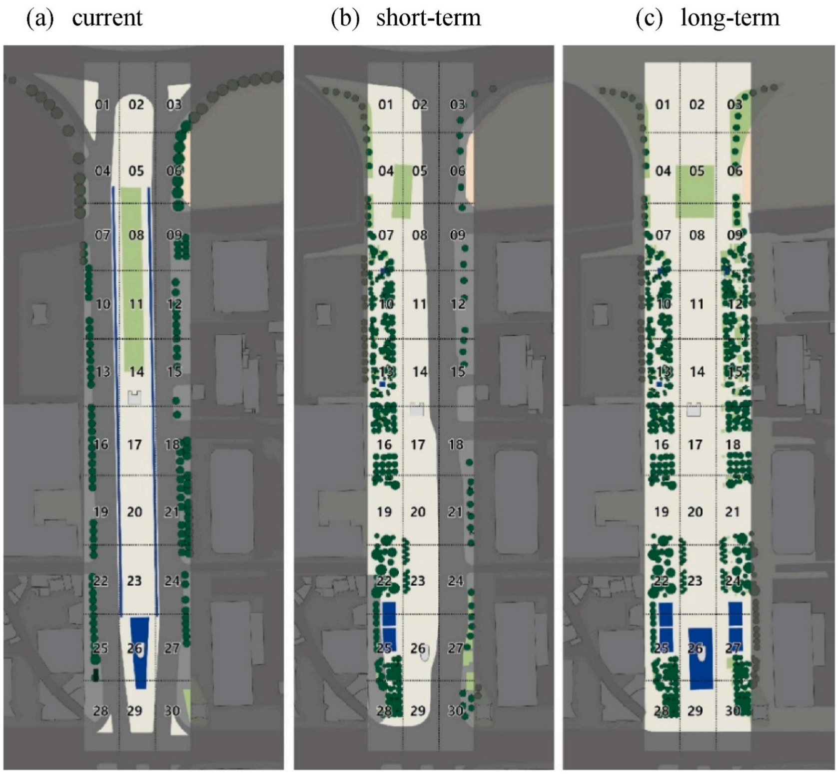


**Fig. 6.** Evenly divided thirty sections of each design intervention.

**Table 4**
TCR, GCR, WCR in thirty sections for three interventions.

| Phases | Landscape parameter | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | … |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Current | TCR (%) | 0.00 | 0.00 | 11.26 | 5.63 | 0.00 | 50.65 | 9.09 | 0.00 | 37.66 | 23.38 | 0.00 | … |
| | GCR (%) | 0.00 | 0.00 | 0.00 | 0.00 | 11.81 | 0.00 | 0.00 | 54.89 | 0.00 | 0.00 | 54.83 | … |
| | WCR (%) | 0.00 | 0.00 | 0.00 | 1.46 | 1.36 | 0.00 | 6.26 | 6.26 | 0.00 | 6.26 | 6.26 | … |
| Short-term | TCR (%) | 0.00 | 0.00 | 11.26 | 8.66 | 0.00 | 24.24 | 38.53 | 0.00 | 28.14 | 71.43 | 0.00 | … |
| | GCR (%) | 4.82 | 0.00 | 0.00 | 26.32 | 12.01 | 0.00 | 23.87 | 4.24 | 0.00 | 22.55 | 0.00 | … |
| | WCR (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.62 | 0.00 | 0.00 | 0.71 | 0.00 | … |
| Long-term | TCR (%) | 0.00 | 0.00 | 8.66 | 8.66 | 0.00 | 34.20 | 39.39 | 5.19 | 67.10 | 70.56 | 13.85 | … |
| | GCR (%) | 4.82 | 0.00 | 35.91 | 18.03 | 49.62 | 19.23 | 19.68 | 19.51 | 19.56 | 22.55 | 0.00 | … |
| | WCR (%) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.62 | 0.00 | 0.62 | 0.71 | 0.00 | … |

**Table 5**
Variable types and parameters for correlation and regression analysis.

| Variables types | 1st parameters (all phases) | 2nd parameters (between phases) |
|---|---|---|
| Dependent variable | Thermal Comfort Index, PET (°C) | ΔPET (+-, °C) |
| Independent variable | Tree Coverage Ratio (%) | ΔTCR (+-, %) |
| | Water Coverage Ratio (%) | ΔWCR (+-, %) |
| | Green Coverage Ratio (%) | ΔGCR (+-, %) |
| Controlled variables | Surrounding building foot print, height, material | |

$$\Delta \mathrm{PET} = PET_{phase,i} - PET_{phase,j}$$

where i, j = 1,2,3, referring to current, short-term, and long-term; $PET_{phase,i\ or\ j}$ reflects PET values derived from each phase when $i \neq j$. Same calculations were applied to TCR, WCR, and GCR.

$$\Delta \mathrm{TCR} = TCR_{phase,i} - TCR_{phase,j}$$

$$\Delta \mathrm{WCR} = WCR_{phase,i} - WCR_{phase,j}$$

$$\Delta \mathrm{GCR} = GCR_{phase,i} - GCR_{phase,j}$$

The degree of influence of landscape interventions for N–S urban canyon can be different depending on contextual factor such as building density (i.e. high or low SVF), and building shadow cast (i.e. no shade or shade times), side location (East or West). In order to examine the difference of tree's influence under different conditions, the thirty sections and the measured data are re-categorized based on sky view factor, shaded and unshaded times, and side location. Table 6 shows the specific standard in order to divide groups based on contextual factors. The group differences were examined for the influence of tree coverage ratio on thermal comfort under different building contexts.

## 3. Results and discussion

### 3.1. Spatial and temporal OTC comparison of three landscape design interventions

The first part of the analysis compares the overall simulation results of the three development phases. Fig. 7–8 present the thermal conditions including air temperature and PET of the three phases at 1.5 m height on Aug 26, 2020, the hottest day recorded in 2019. The results of 10 a.m., 2 p.m., and 5 p.m. were selected when there are the greatest changes in sun directions, and building shadow condition and heavy pedestrian traffic are expected. The maps indicate that air temperature in the short- and long-term plans tends to decrease, compared to the current plan (Fig. 7). In particular, lower temperatures were found, in particular, in the areas where landscape elements, such as small forest, street trees, and garden, are actively introduced; for example, the West area (10, 13, 16, 22, 25, & 28 in Fig. 6) in the short-term plan, and the East area (12, 15, 18, 24, 30 in Fig. 6) in the long-term plan. Similar trends were more clearly shown in Fig. 8, in that lower PET values were measured around the planting area of the short- and long-term plans. In

**Table 6**
Different groups considering contextual factor.

| | | | |
|---|---|---|---|
| Contextual Factor Groups | SVF, | high | Section 1~15 |
| | | low | Section 16~30 |
| | Building shadow cast, | unshaded time | 2pm |
| | | shaded time | 10am & 5pm |
| | Building location, | East | Section 3,6,9,12,15,18,21,24,27,30 |
| | | West | Section 1,4,7,10,13,16,19,22,25,28 |

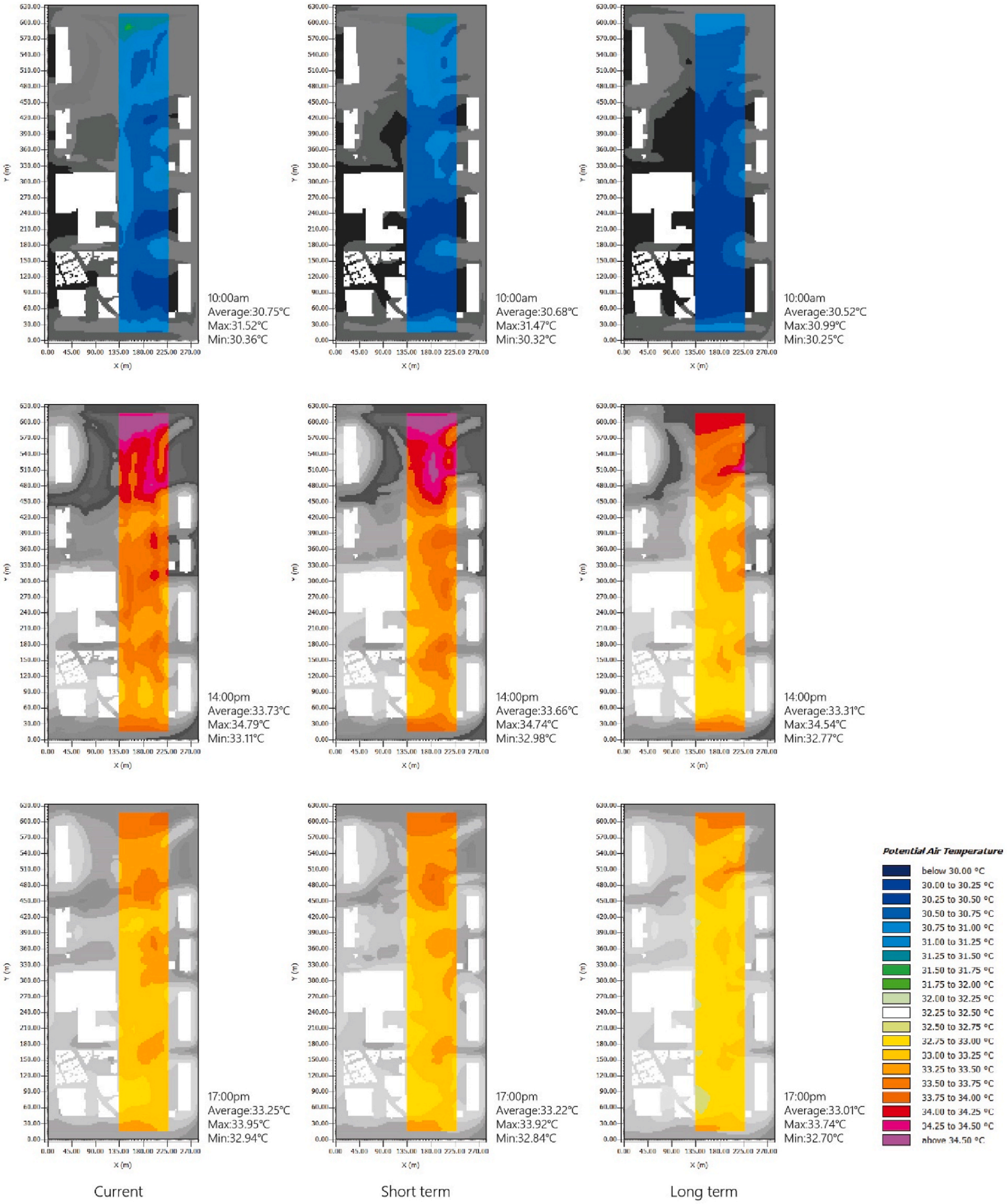


**Fig. 7.** Air temperature comparison of the three intervention phases.

particular, the single cooling effect of street trees and small forest are clearly shown at 2 p.m., the hottest time of the day, when there is little shadow cast from buildings. However, the air velocity map shows a slight decrease in the short- and long-term plans, suggesting that the ventilation or air flows can be disturbed by newly added trees and shrubs (Appendix).

Considering both temporal and spatial scales, the averaged thermal comfort values of each alternative were calculated and compared. Table 7 shows the cell percentages of PET levels of <35 °C and >41 °C at 10 a.m., 2 p.m., and 5 p.m. in the three phases. The

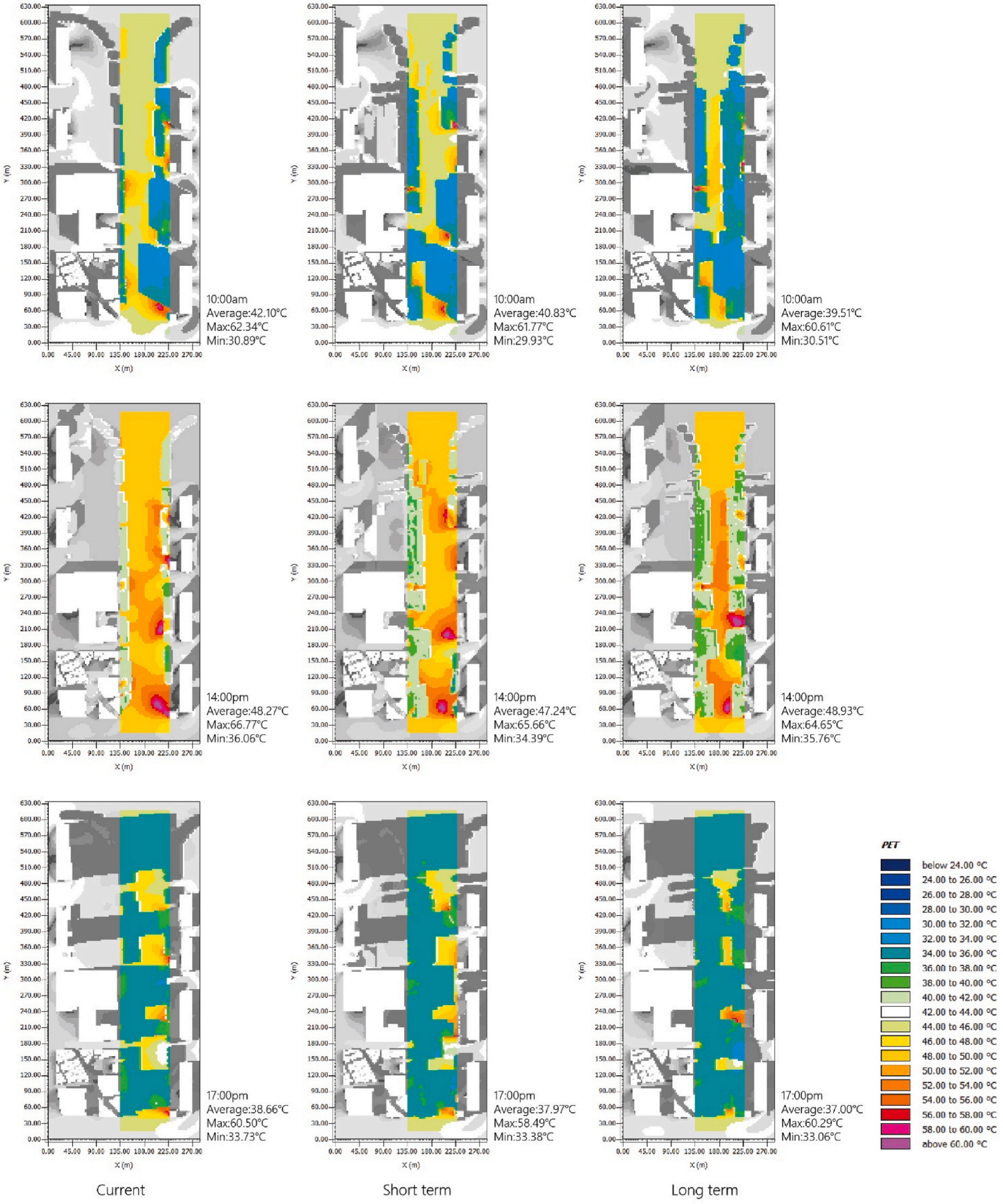


**Fig. 8.** PET comparison of the three intervention phases.

**Table 7**
Cell percentages of the thermal comfort level at < 35 °C and >41 °C at selected times for the three development phases.

| | <35 °C | | | >41 °C | | |
|---|---|---|---|---|---|---|
| | 10:00 | 14:00 | 17:00 | 10:00 | 14:00 | 17:00 |
| Current | 24.97 | 0.00 | 20.62 | 66.04 | 90.77 | 29.98 |
| Short-term | 36.05 | 0.10 | 25.66 | 56.70 | 78.30 | 24.25 |
| Long-term | 42.90 | 0.00 | 44.63 | 45.08 | 65.41 | 16.50 |

results show that the cell percentages <35 °C significantly increased in the short- and long-term plan sequentially, compared to the current plan, at all the times except 2 p.m., when these is almost no cell of <35 °C, suggesting the cooling effect of the increased landscape elements. In the same vein, the cell percentages of >41 °C are significantly decreased in the short- and long-term plans at all three times. At 2 p.m., although the cell percentage of <35 °C was nearly zero for all three phase plans, the cell percentages of >41 °C clearly decreased in the short- and long-term plans.

Fig. 9 shows the temporal variations of the thermal comfort range share of the three development plans. The results indicate that the discomfort zone of >41 °C decreases in the short- and long-term plans for most times. In addition, the lightest grey zone, which is < 35 °C, shows slight increases in the short- and long-term plans during morning and late afternoon.

### 3.2. Relationship between landscape elements and thermal comfort

#### 3.2.1. Averaged TCR, WCR, GCR and PET of all sections

The averaged results show that PET tend to decrease as landscape element ratios increase for all measured times of 10am, 2pm and 5pm (Fig. 10). Compare to current condition, PET decreases up to 2.6 °C as TCR increases 22% in long-term phase, which proves overall cooling effect of landscape interventions for new Gwanghwamun square.

#### 3.2.2. Correlation between TCR, WCR, GCR and thermal comfort

Fig. 11 presents the PET valuesat 2 p.m. (lines) and TCR, WCR, GCR percentages (columns) for all thirty sections. The different colors of dotted lines indicate three phase interventions and different colors of vertical bars present three different landscape parameters. When comparing three phases, long-term PETs (red line) created several clearly lowest points and larger variations between the sections. While within long-term phase, the PET spatial difference was up to 11.4 °C, in current condition, the maximum difference was 7.9 °C. The result suggest that add to averaged thermal comfort, spatial distribution of thermal comfort becomes quite different based on spatial characteristics.

For the relationship between thermal comfort and landscape element, the result shows the tendency of the lower PETs in higher TCR sections when comparing three lines(PET variations) with dark green columns (TCR variations). In specifics, the lowest and highest PETs for long-term phase (dotted red line) were found in section 24 (TCR 74.46%, East multi-layer forest as indicated in Fig.s. 6) and 14 (TCR 7.79%, central open square as indicated in Fig. 6), respectively.

In the same vein, the scatter plot results of the correlation analysis between PET and three landscape parameters were shown in Fig. 12. Based on statistical analysis of ninety data sets of all the cells from three interventions at no building shade time, the results present strong negative correlation between TCR and PET (−0.85), however, there was no strong correlation between thermal comfort and either WCR (0.07) or GCR (−0.20) (Fig. 12). In addition, same analysis for building shaded time was conducted for comparison. The results also present strong correlation between TCR and PET (−0.61), however, the degree of correlation became smaller. Both WCR (−0.13) and GCR (0.07) did not show strong correlation.

Within single phase, the interpretation of correlation results analysis is complicated because the surrounding built forms and conditions are all different in thirty sections. Therefore, for the second phase correlation and regression analysis, in order to control building factors, the TCR, WCR, GCR and PET value changes in identical cell location between different phases were used. The results show a stronger correlation between TCR and PET when controlling building factors; no building shade condition (−0.89) and building shade condition (−0.77) (Fig. 13). Correlation magnitude was slightly higher for no building shade condition. Similar to the first analysis, no strong correlations for WCR (−0.02, 0.03) and GCR (−0.38, −0.23) were found for both shade conditions.

Overall multiple regression result under controlled building factors provides evidence about the significant influence of trees on outdoor thermal comfort level in study site (Table 8). The coefficient of determination (R-square) represents the proportion of the change in outdoor thermal comfort (PET), which a provided regression model can explain. In addition, the standardized coefficients of the predictive model represent the relative contribution of landscape design variables to the difference in outdoor thermal comfort levels. In this model, WCR and GCR variables did not show statistically significant values, however, tree coverage ratio ($P < < 2e\text{-}16$ ***) showed significant importance among the landscape (Table 8). These results can be predicted because tree coverage affects the inflow of the solar radiation which directly affects thermal comfort in a street canyon and is also helpful to enhance thermal comfort due to evapotranspiration and long-wave radiant heat absorption[36,58].

### 3.3. The influence of trees on thermal comfort under different contextual factor

Another focus of this study is to investigate the different influence magnitude of trees under different contextual factor including building shadow cast, building density and location. In order to compare different groups and conditions, three types of regression

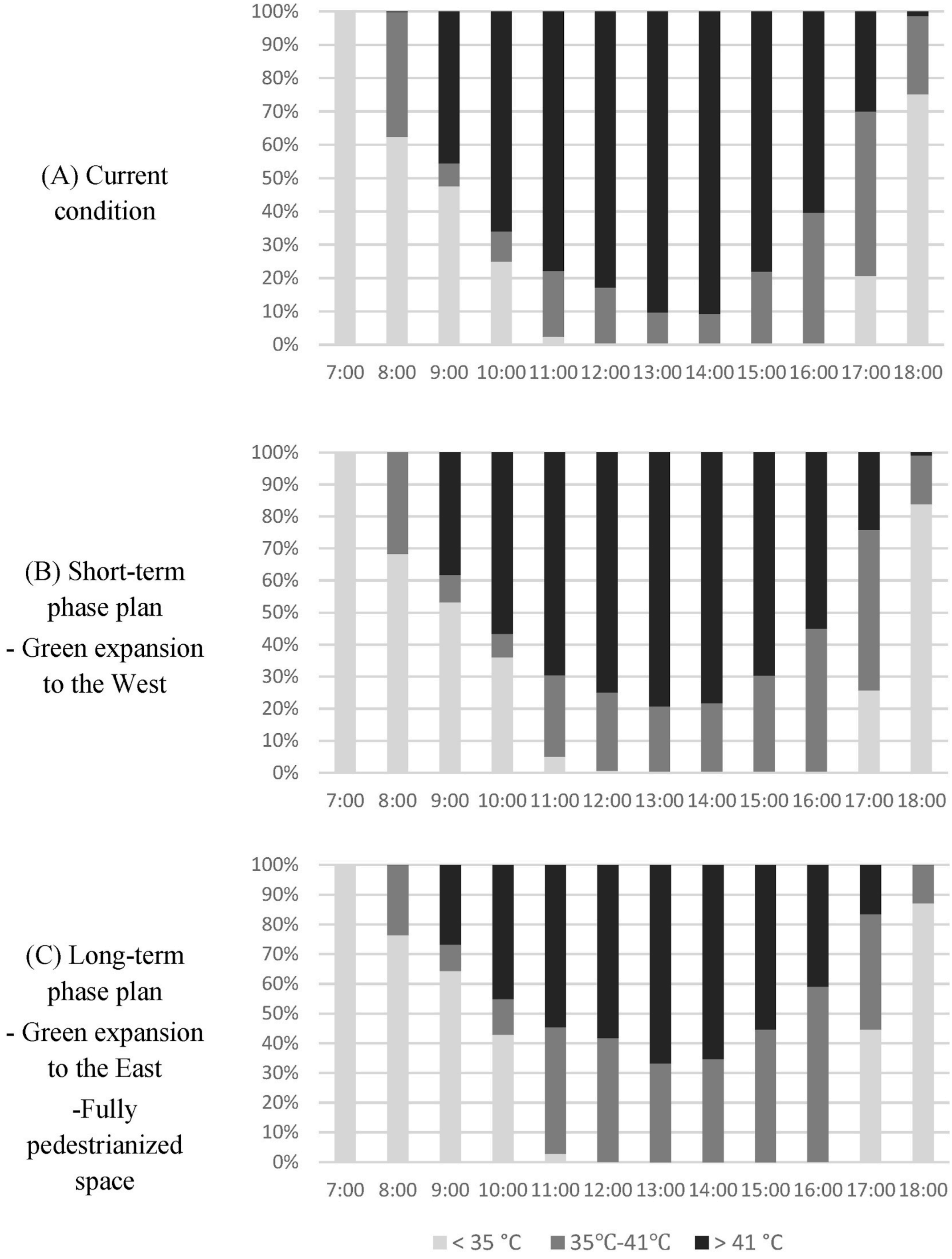


**Fig. 9.** Temporal variations of the thermal comfort range share of the three interventions.

analysis are conducted and compared. For all the conditions and groups, the relationship between PET and TCR was significant. The results show that the maximum difference in the magnitude of correlation and regression line slopes were found for different building shadow cast groups (Fig. 14). When there is no building shade, the standardized coefficient was −0.096, which indicate 0.096 °C decrease in the case of 1% increase of TCR. When there is building shade, the standardized coefficient was −0.062, which indicate 0.062 °C decrease in the case of 1% increase of TCR.

The result sugesst that in no buildng shade condition, the influence of trees was slightly larger compared to the bulidng shade condition. In the same vein, for low building density (high SVF) group, the influence of trees was slightly larger compared to low SVF

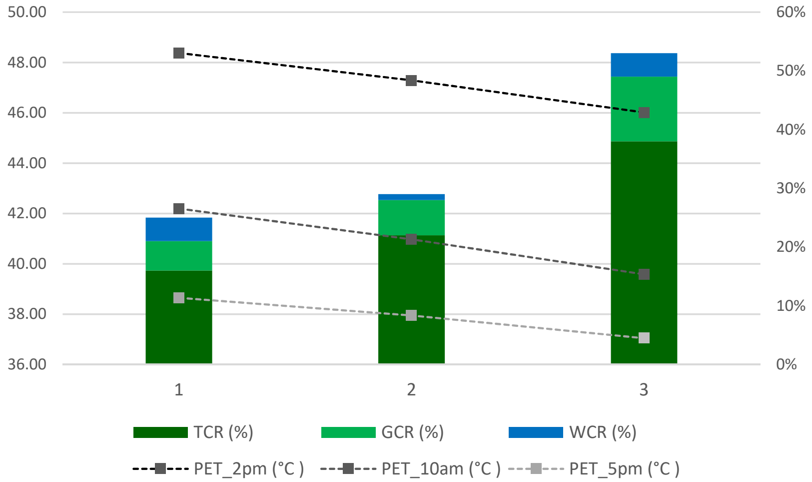


**Fig. 10.** Averaged PET and landscape parameters comparison of three interventions (1: current, 2: short-term, 3: long-term).

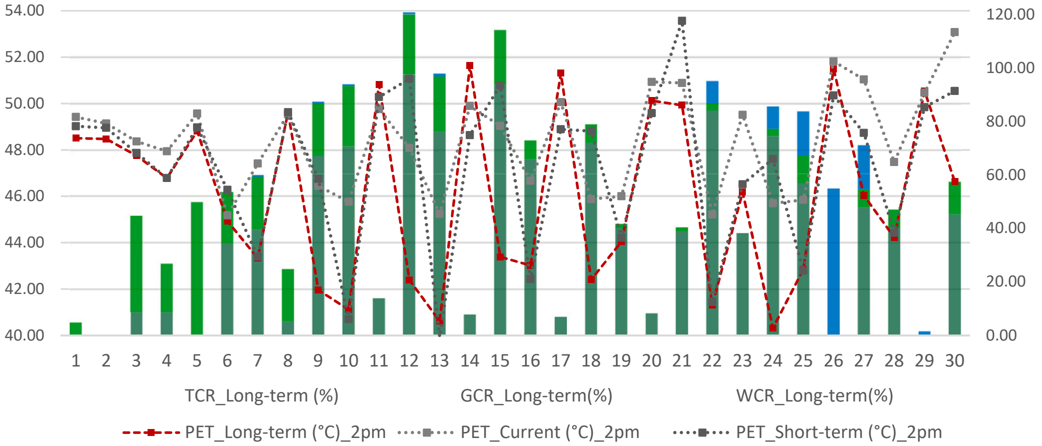


**Fig. 11.** Landscape parameters and PET of three alternative plans at 2pm.

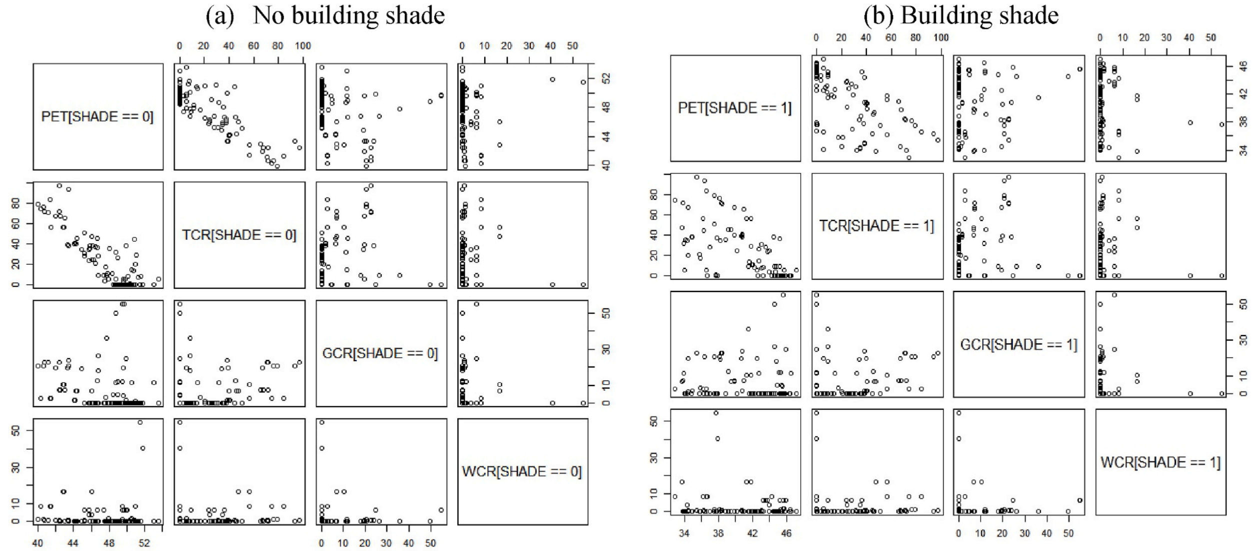
group. For building location, the difference was nigligible. In sum, planted trees had significant influenc on thermal comfort level under different contexts. While there was slight difference in the magnitude of tree influence, the difference was not large. This suggest that planting trees can also be effective enough in enhancing thermal comfort when building shadow cast exist and where building density is high.

Based on regression results, in order to further investigate trees' influence under different building shadow casts (i.e. measured time), three One-way ANOVA analysis was conducted (Fig. 15). According to the box plots of PET values by measurement times, unshaded time (2pm) indicate that the distribution of PET values is more concentrated and separate rather than varied and overlapped, compared to shaded times (10am and 5pm). The reason was that the influences of building shadows were not significant in this time, so relatively similar PET values were calculated for different sections. In sum, these results show that measurement times (i.e. building shadow cast) are significant factor for outdoor thermal comfort level in N–S urban canyon.

In other hand, this pattern continues for different TCR density groups. However, when comparing tree density groups, PET differences by measured times greatly reduced in high TCR group compared to low TCR group. This results suggest that trees can play a role in mitigating thermal comfort gap depending on shaded times, relaxing the extreme condition,.

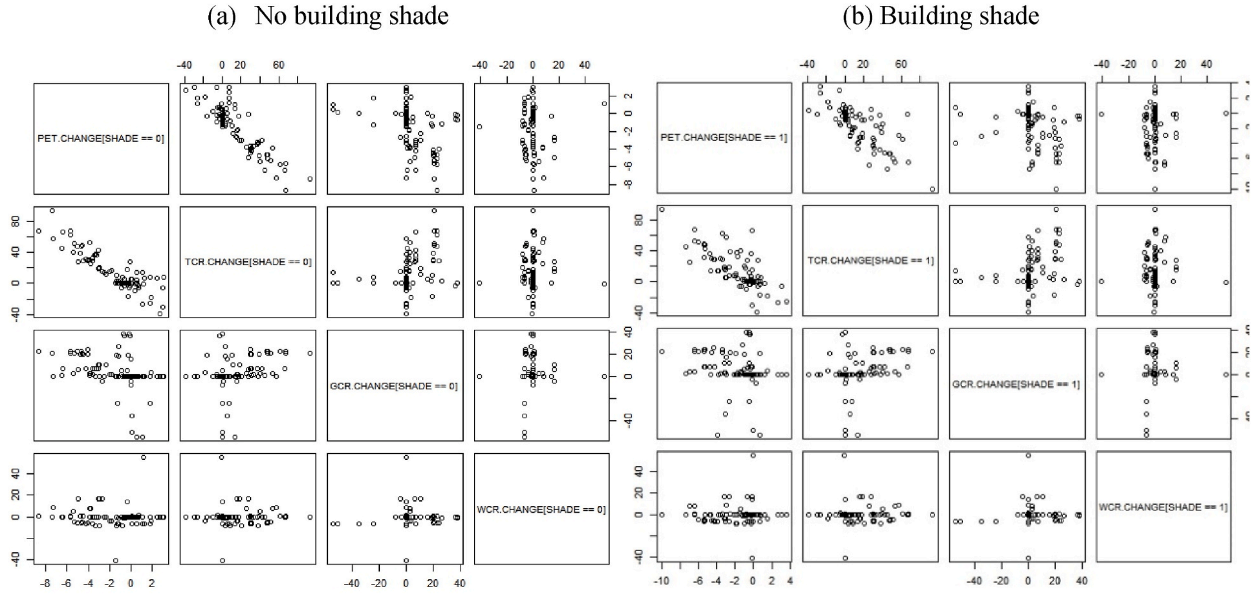
## 4. Conclusion

While landscape design elements have been proved to provide heat mitigation effect and enhance outdoor thermal comfort in much


(a) No building shade

(b) Building shade

**Fig. 12.** Correlation between PET and TCR, GCR, WCR


(a) No building shade

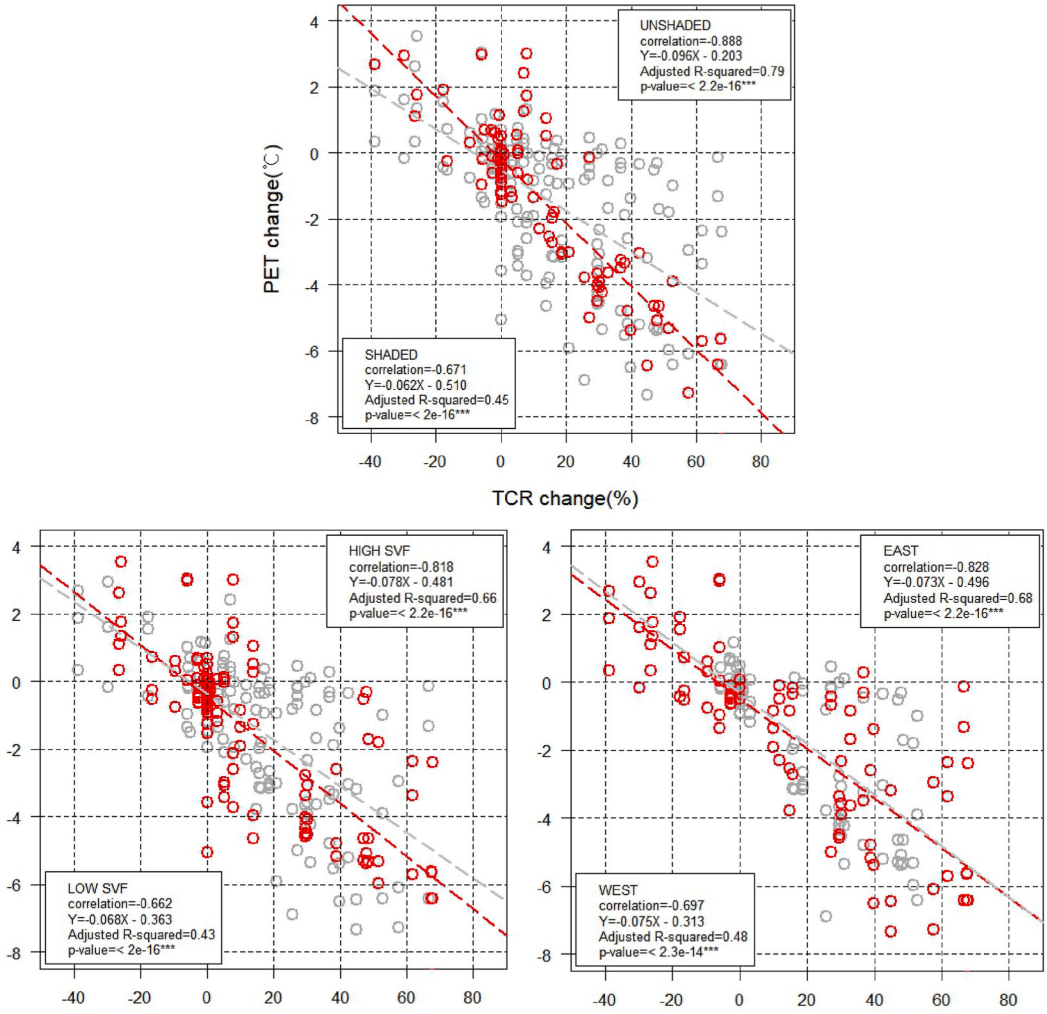
(b) Building shade

**Fig. 13.** Correlation analysis between PET change and TCR, GCR, WCR change.

**Table 8**
Multiple regression analysis between the PET changes and TCR, GCR, WCR changes.

| Variables | Coefficient<br>Estimate | Std. error | t ratio | Pr(>\|t\|) |
|---|---|---|---|---|
| TCR change (%) | −0.0734873 | 0.0041430 | −17.738 | <2e-16 *** |
| GCR change (%) | −0.0009131 | 0.0061454 | −0.149 | 0.881994 |
| WCR change (%) | 0.0120336 | 0.0107594 | 1.118 | 0.264396 |
| R-squared | 0.5629 | | | |
| Adjusted R-squared | 0.558 | | | |

(a) Building shadow cast



(b) Building density (SVF) (c) Building location (E-W)

**Fig. 14.** Regression results between PET change and TCR change under different contextual factors.

research, there is a lack of understanding on the relative magnitude of their influence under different built contexts. This study investigated the cooling effect of landscape elements (i.e., trees, water) in N–S oriented urban canyon where building shadow cast changes. This study focused on real-world hybrid conditions with practical design alternatives, rather than experimental scenarios. In particular, the study investigated how cooling effect of trees became different under different contextual factors including building shadow cast change. The major conclusions are summarized as follows.

1) Overall, compared to the current condition, in the short- and long-term plans, the comfort zone increased almost two times, and the discomfort zone decreased to approx. 70%. As TCR increases 22%, PET decreases up to 2.6 °C in average. In sum, the cooling effect of newly added trees was clearly shown at noon, when there was rare building shadow cast. In the same vein, the cooling effect of trees in the West was greatest in the morning, while those of the East were greatest in the late afternoon. Therefore, for the N–S oriented street canyon, trees can be effective at reducing heat during the most active time, as well as complementing the absence of building shadow effect.
2) While trees had a significant influence on outdoor thermal comfort under diverse built form contexts, flat water and green space did not show significant influence statistically. Trees' influence was slightly larger for no building shadow cast; however, the influence is still effective under building shadow cast. Moreover, for high tree density area (TCR>50%), temporal gap of thermal comfort between measured time that mainly caused by building shadow change was greatly reduced compared to low tree density area (TCR<5%). This emphasizes the role of tree in providing consistent thermal comfort.

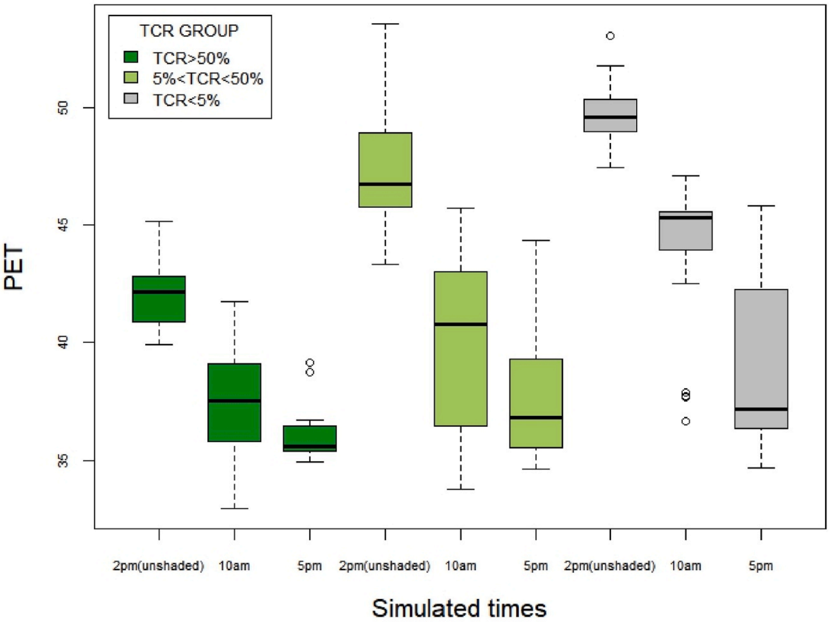


**Fig. 15.** One-way ANOVA tests of PET by measurement times for different TCR group.

3) The influence of trees was slightly different for different contexts; however, the difference was not noticeable. Slightly larger cooling effect was found in the low-SVF area where there may be better air ventilation. Since average wind velocity input for this study site was very small (3.4 m/s), the difference can be underestimated. As proved in precedent studies, plantings in the low building density condition can produce the best outcome in thermal comfort enhancement, however, planting trees in high density also provides similar thermal benefit as proved in this study.

This study provides scientific evidence for trees' cooling effect and its relative magnitude under diverse built contexts of N–S oriented urban canyon. The results clearly reveal that trees enhance thermal comfort under both building shaded and unshaded conditions. However, further investigation regarding the methodology to measure the influence of other landscape elements should continue to ensure comprehensive understanding and provide meaningful landscape design guideline. One challenge for this study is to process thermal comfort data being comparable to spatial landscape element data. Simulated PET data is based on fixed cell dimension (3 m × 3 m). While ENVI-met provides density estimation function for trees of each cell, it doesn't provide similar data for other landscape elements (i.e. water and open green). Instead, we used auto CAD area function and need to utilize larger grid dimension for efficiency. Therefore, there is a need of study for more convenient way to process thermal data adapt to spatial scale to examine.

This study contributes to developing an inclusive thermal evaluation for the effective comparison of real-world design alternatives. However, further investigation to develop a specific method or methodological consensus for an inclusive thermal comfort evaluation index for design alternatives is necessary. Temporally, the comfort level can possibly be evaluated for each spatial cell based on the percentage of comfort time among whole year data predicted, and additional weight may be given to active day time. Spatially, each cell's evaluation based on a temporal scale can be examined again for a specific spatial boundary considering occupancy and etc.

For further investigation, the integration of field measurements, simulation and artificial neural network techniques (Yi and Malkawi, 2011), as well as, the investigation of thermal comfort performance determination based on annual basis climate diversity (i.e. weather types) [59] would be an option for increasing reliability of data, enhancing temporal and spatial variability, providing annual basis thermal information, and comprehensive evaluation.

The study enlightened further study area; for shaded and unshaded conditions, the different degrees of errors between measured and simulated data (i.e. mrt, PET) need to be studied further for more accurate data interpretation. In addition, the same site needs to be studied with higher wind velocity input to examine the influence of trees on air ventilation. Also, the influence of multi-layered plantings with small trees and shrubs needs to be further investigate for thermal friendly planting strategy.

## Author contribution statement

Yuha Han: Conceived and designed the experiments; Performed the experiments.
Yongjun Jo: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.
Eujin Julia Kim: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

## Data availability statement

Data included in article/supplementary material/referenced in article.

## Declaration of competing interest

The authors report no declarations of interest.

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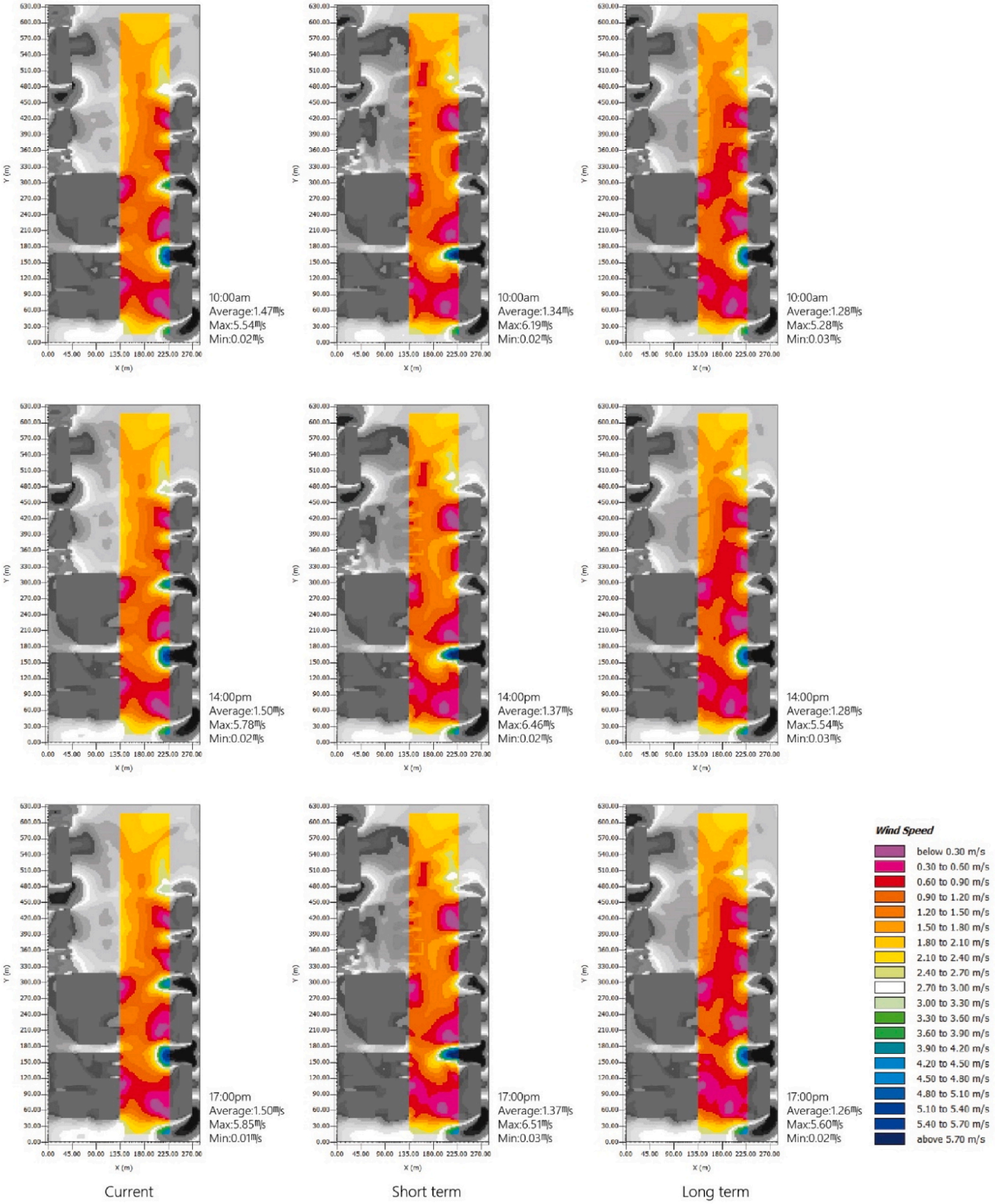
## Appendix



Air velocity comparison of the three development phases at three selected times.

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