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Effects of the tree distribution and species on outdoor environment conditions in a hot summer and cold winter zone: A case study in Wuhan residential quarters

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ABSTRACT

Residential district is the important space for people living and outdoor activities. Vegetation is proved to be effectively regulate microclimate. Living in Wuhan, residents have to suffer heat stress in summer and strong cold wind in winter simultaneously. It is necessary to dictate vegetation types and layout in residential area to get comfortable environment both in hot summer and cold winter. This study examined the vegetation influences of residential wind environment in hot and cold seasons by using the ENVI-met model V4. Field measurement validated the performance of ENVI-met model. The simulation was based on multi-story buildings representing the current primary form of residential area in Wuhan. 3 scenarios with three tree arrangements and 8 vegetation species were simulated. Height-to-distance ratio of trees (as “Aspect ratio of trees”, ART) was used to describe the tree distribution. Results showed that the impact of vegetation on both heat environment and ventilation depended on tree arrangement, LAI, crown width and tree height. The comparison of 3 tree distributions revealed that trees with an ART < 2 should be a priority to mitigate hot environments due to the large effects on PET reduction in summer. Evergreen species with an ART < 2 also effectively decreased wind speed in winter as well as blocked direct sunlight, resulting in negative effects on PET. Tall trees with a large LAI and canopy diameter should be a priority to improve the comfort of outdoor environments.

1. Introduction

1.1. Background of study

An increasing number of people reside in cities due to rapid urbanization. Residential areas are the primary outdoor spaces for recreational activities. Comfortable outdoor residential environments encourage people to leave their homes and develop social activities. Many cities in China, such as Wuhan, Nanjing and Changsha, are located in hot summer and cold winter zones based on the Building Thermal Design Code of China (GB50176-93) [6]. Residents in this climate zone face high temperatures in summer and strong winds in winter [16]. This type of climate is not conducive to outdoor activities.

1.2. The cooling and ventilation effects of vegetation

Many researchers suggest some effective ways to mitigate high temperatures based on building layouts, building materials, pavements, roofs and landscape environments [2,4,17,24,29,32,35,36,41,48]. Vegetation is an effective method to cool hot temperatures in summer [5,8,46]. The cooling effects of trees are much more obvious than those of grass [23,37] because trees provide more shade, which effectively reduces radiant temperature [31,44]. Various building environments and increased vegetation clearly decrease heat stress [28,33], Ng [50] performed a parametric study in the high-density city Hong Kong and suggested that tree coverage should be approximately 30% of the urban area. This amount of tree planting was feasible and effectively mitigated heat from the environment. Different tree species exert various impacts on cooling because of their different transpiration rates, leaf area indexes, and crown diameters [3,11,40]. Planting patterns and trees layout also influence the decline in hot temperature [10,30]. Vegetation apparently decreases wind velocity due to the drag force of plants' canopies [43]. Plants exert positive effects on strong winds in winter [12,15] and establish a comfortable wind environment. Most

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previous researchers have investigated the physical characteristics of plants or the relationship of plants and buildings.

Vegetation in China is generally used to create spaces for outdoor activities in residential quarters. Studies on the cooling and ventilation effects of residential vegetation from a spatial view are necessary and interesting. Few studies have simultaneously focused on the cooling and ventilation effects of plants in various spatial compositions. Vegetation in a hot summer and cold winter zone should play a regulatory function to mitigate heat stress and the effects of strong cold winds.

1.3. This research

This research determined the vegetation types and layout from a spatial perspective in a residential area needed to achieve a comfortable environment in a hot and cold environment. This research 1) analyzed the effect of various vegetation distributions and species on summer and winter environments, 2) identified the optimal vegetation distribution to achieve better environments in hot and cold seasons, and 3) determined the most appropriate vegetation species to establish a comfortable environment in Wuhan residential districts.

2. Climate and sites

Wuhan is located in central China (30°35′N, 114°17′ E, altitude 23 m). It includes 8 million urban dwellers, which makes it the 5th largest city in China. Wuhan exhibits a typical tropical monsoon climate with abundant solar radiation, hot summers and cold winters. The summer season occurs from June to September, and the hottest days are concentrated in July and August. The average temperature in July and August is 29.8 °C (Fig. 1), and the extreme maximum temperature reaches 39.4 °C. Wind velocity in the summer is low, with a mean speed of 1 m/s from the southwest. The cold season occurs from December to February. The average temperature in winter is 3 °C. The average wind gust in winter is 4–5 m/s from the north. Average relatively humidity is about 73–77% all year around.

A residential district with multistory buildings was chosen for this study because it was currently the primary form of residential areas. The general land development intensity was extracted from a building survey and land use map of Wuhan in 2013. A general residential block was constructed on a 200 × 200 m area for simulation (Fig. 2). Six-story buildings (12 × 50 m) occupied 31.5% of the total area in this general residential block.

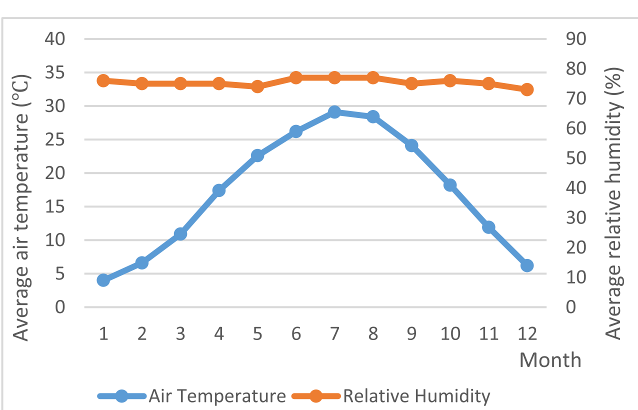

Fig. 1. Monthly temperature and humidity in Wuhan. Data source: China Meteorological Administration, climate data in Wuhan (1980–2010).

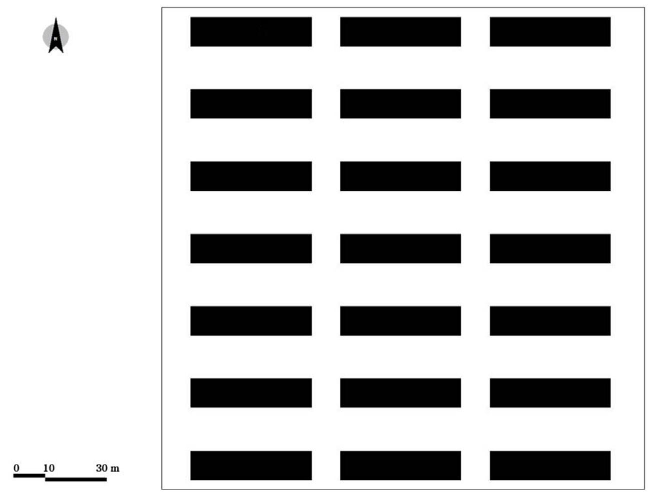

Fig. 2. The general residential block for simulation.

3. Methodology

3.1. ENVI-met model description

ENVI-met is a three-dimensional microclimate model that simulates outdoor environments. It can simulate surface-plant-air interactions of urban environments with a spatial resolution of 0.5–10 m and time resolution of 10 s [28]. ENVI-met is a computational dynamics model that is used to simulate aerodynamics, thermodynamics and radiation balance. The ENVI-met model is widely used to simulate the wind flow, pollutant dispersion, radiation fluxes and soil temperature [30]. Plants in the ENVI-met model are described as a porous media that interacts with surroundings via transpiration, evapotranspiration and photosynthesis. Leaf area density (LAD) is an important parameter that is used to model the turbulence and heat exchange between vegetation and surroundings. LAD may be obtained from the leaf area index (LAI) [11,22,30]. There are also some limitations in the ENVI-met model. Diurnal variations of the air temperature and relative humidity at the boundary conditions of the model area are improved in ENVI-met 4.0, but the wind conditions and cloudiness are not changed. The model cannot calculate the influence of anthropogenic heating, and the radiative fluxes are not calculated as accurately as reality. ENVI-met overestimates turbulent productionκin areas with acceleration or deceleration in the standard κ-εclosure, e.g., the flow around a building, which causes inaccuracies in wind speed [1,19,21].

However, ENVI-met is one of the most widely used models in studies of the impact of vegetation on thermal environments, and it is an effective simulation model [27,39]. Field measurement is commonly used to verify ENVI-met. Many initials settings for simulation including model configuration and boundary conditions are presented in Table 1. The coefficient of determination (R^2), the Root Mean Square Error (RMSE) and the Willmott's index of agreement (d) are widely used to validate simulation results and measurement data.

3.2. Field measurements and ENVI-met calibration

The field experiment was performed in the residential area of Xiyuan, which is located on the west side of Huazhong Agricultural University (Fig. 3) in Wuhan. The site consisted of 6- and 11-story buildings in rows. There were approximately 30 types of plants in the Xiyuan residential block. Trees were divided into 8 categories according to height, crown diameter and ecological habits. Table 2 lists detailed data of 8 typical trees. A meteorological station (no. 1053) was located 1.8 km to the east, at Huazhong Agricultural University. This station provided the meteorological data for the simulation on the

Table 1
Parameters of ENVI-met model involved in studies.

Study	Model		Domain		Boundary condition settings							
	Size of gird cells (Δx, Δy, Δz) (m)	Number of gird cells (Δx, Δy, Δz)	Nesting grids	Model rotation out of girds	Air temperature (°C)	Relative humidity (%)	Wind speed at 10 m (M/S)	Wind direction (°N)	Roughness length at reference (m)	Cloudy cover (octans)	Specific humidity in 2500m (g/kg)	Solar adjust factor
[49]	√	√	√	√	√	√	√	√	√	√	√	√
[42]	√	√	√	√	√	√	√	√	√	√	√	√
[20]	√	√	-	√	√	√	√	√	√	-	√	-
[18]	√	√	√	√	√	√	√	√	√	-	√	√
[7]	√	√	-	-	√	√	√	√	-	-	√	-
[48]	√	√	-	-	√	√	√	√	-	-	√	-
[36]	√	√	√	-	√	√	√	√	√	√	√	-
[25]	√	√	-	-	√	√	√	√	√	-	√	-
[45]	√	√	√	-	√	√	√	√	-	-	-	-
[47]	-	-	-	-	√	√	√	√	-	-	√	-
[38]	√	√	√	√	√	√	√	√	√	√	√	√

Study	Soil data			Building					Plants	LBC type	Parameters used to evaluate models performance
	Initial temperature and relative humidity of soil upper layer (k, %)	Initial temperature and relative humidity of soil middle layer (k, %)	Initial temperature and relative humidity of soil deep layer (k, %)	Inside temperature (K)	Heat transmission walls (W m^{-2} $K^{-1)}$	Heat transmission roofs(W m^{-2} $K^{-1)}$	Albedo walls	Albedo roofs			
[49]	√	√	√	-	-	-	√	√	√	-	R^2, RMSE,
[42]	√	√	√	-	-	-	√	√	-	-	RMSE,
[20]	-	-	-	√	√	√	√	√	√	-	RMSD
[18]	√	√	√	√	√	√	√	√	√	-	RMSE
[7]	-	-	-	-	-	-	-	√	√	-	Data
[48]	-	-	-	√	√	√	√	√	-	-	Data
[36]	√	√	√	√	√	√	√	√	√	-	R^2, RMSE, d
[25]	√	√	√	√	√	√	√	√	√	-	RMSE, d
[45]	-	-	-	√	√	√	√	√	√	-	RMSE, d
[47]	√	√	√	√	√	√	√	√	-	-	Correlation
[38]	√	√	√	√	√	√	√	√	√	-	R^2, RMSE

Note: R^2 is the coefficient of determination; RMAE is the root mean square error; d is the Willmott's index of agreement.

Fig. 3. Location and surrounding of study area. (1) Field measurement domain (yellow outline); (2) The map showing the location of field study. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

measurement day (Fig. 4). Field measurements were performed from 9 a.m. to 6 p.m. on August 16, 2016, in summer and January 14, 2017, in winter. Various locations of 5 mobile meteorological stations were fixed in summer and winter to identify the influence of trees on high temperature in summer and strong winds in winter. Locations 1 and 3 were located under trees, locations 2 and 4 were fixed near green land with trees and grass, and location 5 was located near trees in summer (Fig. 5). Locations 1 and 5 were fixed under or near trees in an east-west orientation space and locations 2, 3 and 4 were located in a north-south orientation space from upwind to leeward, respectively, in winter. Locations 2 and 3 were fixed under trees, and location 4 was set in an intersection without trees nearby. Climate data such as air temperature (Ta), global temperature (Tg), wind speed (V) and relatively humidity at 1.5 m high were recorded in every minute. Mean radiation temperature (Tmrt) was defined by the data Ta, Tg and v based on Eq. (1):

$$\text{Tmrt} = \left[(\text{Tg} + 273.15)4 + \frac{1.1 \times 10^{8} v^{0.6}}{\varepsilon D^{0.4}} \times (\text{Tg} - \text{Ta})\right]0.25 - 273.15 \tag{1}$$

Where D is global diameter, ε is global emissivity.

The ENVI-met model was based on the actual configuration of the site, which contains 18 m and 33 m tall buildings. Table 3 lists the simulation settings used. The model was simulated for 48 h starting at 6 a.m. The first 24 h were used for the full simulation, and data from the last 24 h were used for analysis.

The air temperature and wind speed at 1.5 m were examined from 9 a.m. to 18 p.m. Data from each of monitor locations were extracted from the simulation results. Fig. 6 shows the observed and simulated results of Ta, V and Tmrt in a summer and winter day. The simulation of Ta and Tmrt were closely similar to field data. While field data of V showed more variable than simulated results for more complex wind environment in reality. Calibration of each variable from two days was based on the 50 pairs of simulation results and measurement data collected at the five measurement sites. The relationship of the results of each variable was linearly correlated. The R-squared value indicated a strong correlation between the simulation and experiments of Ta and Tmrt (Fig. 7). The correlation was slightly lower for V and Ta on a cold day. The R-squared value of V was a little lower for summer and winter days compared with Ta. The primary reason for this difference was the more complex air flow in reality than the simulation. RMSE, mean absolute error (MAE) and d were calculated to assess the differences between simulated and measured data [10]. The results revealed that the RMSE of the variables was close to 0 and d was close to 1, which indicated that the simulation using ENVI-met reasonably approximated actual measurements (Table 4). The ENVI-met model capably simulated the microclimate in a residential green area in hot and cold seasons.

3.3. *Trees species and arrangement*

There were more than 50 species of plants in the Wuhan residential districts. Trees over 2 m tall were primarily analyzed for their effects on pedestrians. The 8 most commonly used trees based on plant height, ecological habits, and morphology were chosen for simulation. Table 2 lists the height, crown diameter and LAI of each species.

The tree coverage in the 3 planting patterns was the same as 25% of the residential block area to allow the study to focus on the planting patterns and species based comparison. Three planting patterns were constructed according to the height-to-distance ratio between trees (as the "Aspect ratio of trees", ART). Sparse woods or open space was created when the ART was < 1 to allow many residents to gather. This tree arrangement was defined as the "sparse" case. The ART of "sparse" cases was 2/3 or 4/5 in terms of 25% tree coverage because of the various tree heights. The "covering" case was a semi-enclosed space with an ART of 1, which provided more shaded activity spaces. The "density" case was dense woods with overlapping crowns and an ART of 2. Every selected tree was evenly planted with a different ART. The "sparse" case could not be built with species of CD, MG, ED and MD because of the various tree heights in a limited space. For example, there should be 7 m between every CD tree in the sparse case; however, a tree coverage of 25% renders it was impossible to plant CD trees with

Table 2
Vegetation classification.

Vegetation Classification	Vegetation	Code	Height (m)	Crown Diameter(m)	Leaf Area Index
NET	Cedrus deodara	CD	12	7	2.32 (S) 2.32 (W)
NDT	Metasequoia glyptostroboides	MG	12	5	2.45 (S) 0.18 (W)
BET	Cinnamomum camphora (L.) Presl.	CC	8	7	3.80 (S) 3.80 (W)
BDT	Koelreuteria paniculata	KP	8	7	2.68 (S) 0.20 (W)
BET	Elaeocarpus decipiens Hemsl.	ED	8	5	1.84 (S) 1.84 (W)
BDT	Magnolia denudata	MD	8	5	2.80 (S) 0.13 (W)
BET	Osmanthus fragrans (Thunb.) Lour.	OF	4	5	3.45 (S) 3.45 (W)
BDT	Prunus x yedoensis	PY	4	5	1.08 (S) 0.27 (W)

Note: NDT, needle-leaf deciduous tree; BDT, broadleaf deciduous trees; NET, needle-leaf evergreen trees; BET, broadleaf evergreen trees; S and W represent summer and winter, respectively.

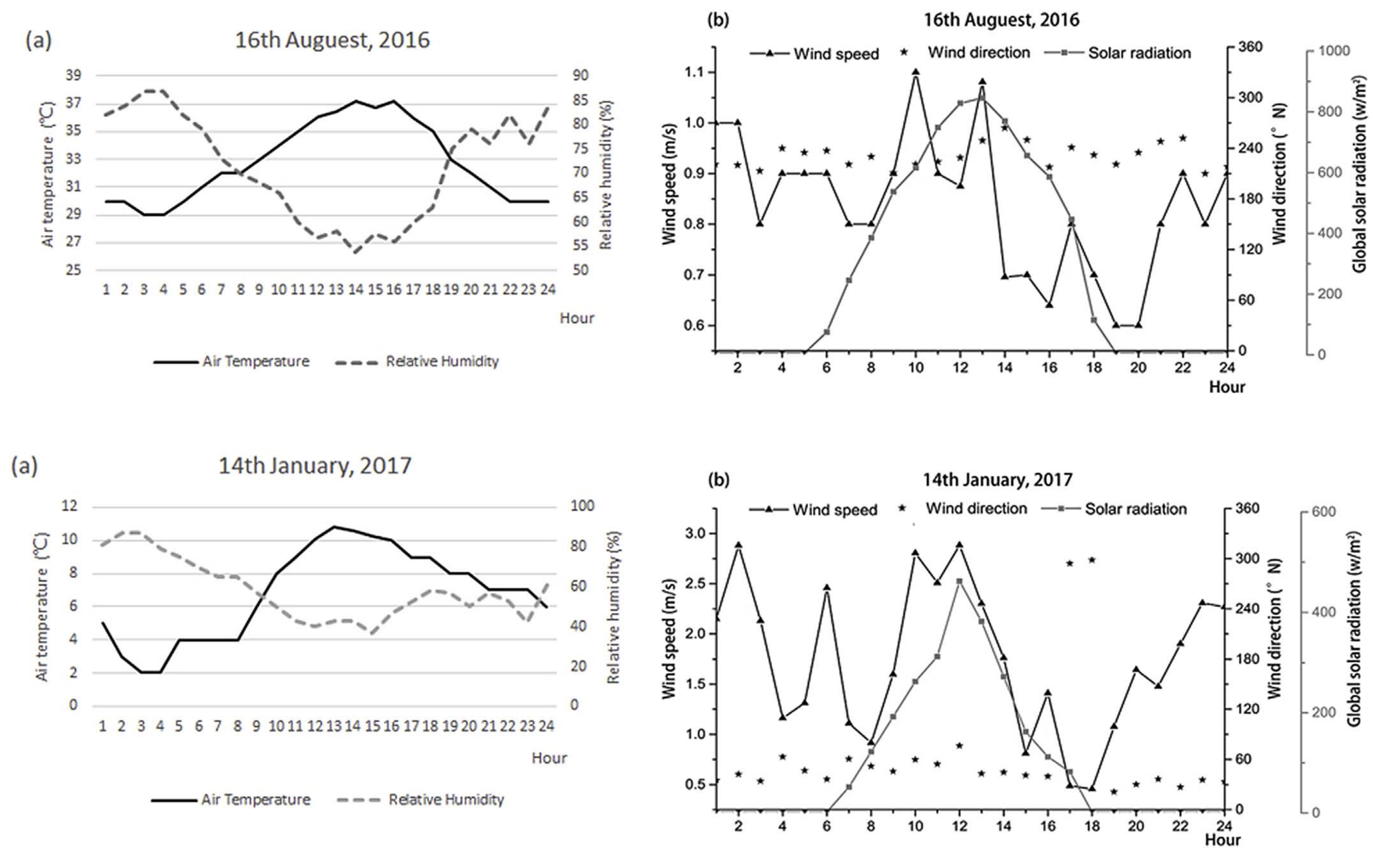

Fig. 4. (a) Hourly air temperature and relative humidity on 16th August 2016 and 14th January 2017. (b) Hourly global solar radiation, wind speed and direction on 16th August 2016 and 14th January 2017.

a distance of 7 m in a residential block of 200 × 200 m. The same situation occurred for coverage using MG. Nineteen vegetation cases were ultimately established.

3.4. Model initialization

August 22, 2015, and December 11, 2015, were simulated to represent a typical hot summer and cold winter day, respectively. The atmospheric data for these 2 days were obtained from the Wuhan Meteorological Station. The mesh of a 100 × 100 grid was arranged on the entire model area (200 × 200 m), with a horizontal resolution of 2 m. Vertical grids started with telescoping grid heights of 0.9 m and increased by factors of 20%. Table 5 lists the simulation parameters used. The model was simulated for 48 h starting at 6 a.m. Data from the models were saved every hour, and data from the last 24 h were used for analysis.

Note: the parameters with * sign are sourced from the default values of ENVI-met; S and W represent summer and winter, respectively.

A general residential block without vegetation was simulated to analyze the effects of vegetation on the environment in a hot summer and cold winter.

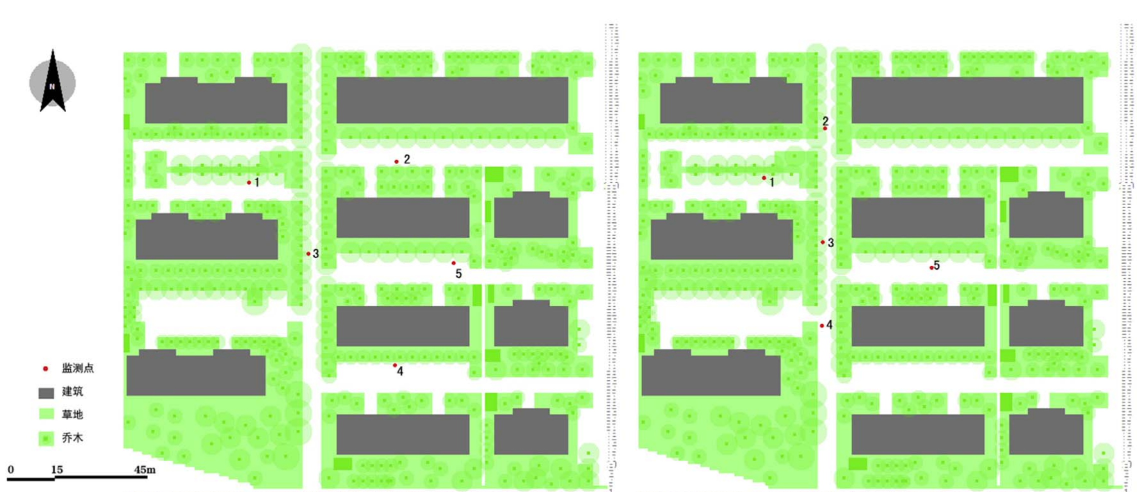

Fig. 5. Field measurement points set on 16th August 2016 (left) and 14th January 2017 (right).

Table 3
Verified ENVI-met simulation settings.

Model domain	Size of grid cells (Δx, Δy, Δz)	2, 2, 0.9 (vertical grid with a telescoping factor of 20%)
	Number of grid cells (Δx, Δy, Δz)	80, 78, 18
	Nesting grids	5
	Soil profiles in nesting grids	Default
Meteorology inputs	Air temperature	Hourly data from weather station No. 1053
	Relative humidity	Ditto
	Wind speed	1 m/s (S) 2.3 m/s (W)
	Wind direction (°)	225 (S) 30 (W)
	Specific humidity in 2500 m	7 g/kg*
	Roughness length at reference	0.01*
Plants	3D tree	Table 2
	1D grass	Grass 50 cm aver. dense
Building	Albedo of roofs	0.3
	Albedo of walls	0.2

Note: the parameters with * sign are sourced from the default values of ENVI-met; S and W represent summer and winter, respectively.

3.5. Thermal comfort in hot summer

Physiological equivalent temperature (PET) was used to assess outdoor thermal comfort. PET is a thermal index derived from the Munich Energy Model [34] and is defined as the air temperature at which, in a standard indoor setting, the human energy budget (80 W activity, thermal resistance of clothing of 0.9 clo) is maintained by the skin and core temperature under the outdoor conditions to be accessed [9,13,26]. PET is suitable for evaluations of outdoor thermal comfort because of the combination of the influence of long- and short-wave radiation fluxes with the body heat balance in reality [34]. Micro-climate data, such as air temperature, relative humidity, wind speed and mean radiation temperature, obtained from the simulation were entered into the RayMan model for PET [30]. The measurements of an average person (male, 1.75 m tall, 35 years old, 75 kg weight, 80 W activity, and resistance of clothing of 0.9 clo for summer and 1.0 clo for winter) were used for the PET calculations. The impact of trees on thermal comfort was calculated as:

$$\Delta PET = PET_{veg} - PET_{res} \tag{2}$$

Where

ΔPET was the influence of trees on the average PET in the residential block at the pedestrian level at 3 p.m.

PET_{veg} was the average PET in the residential block with trees at the pedestrian level at 3 p.m.

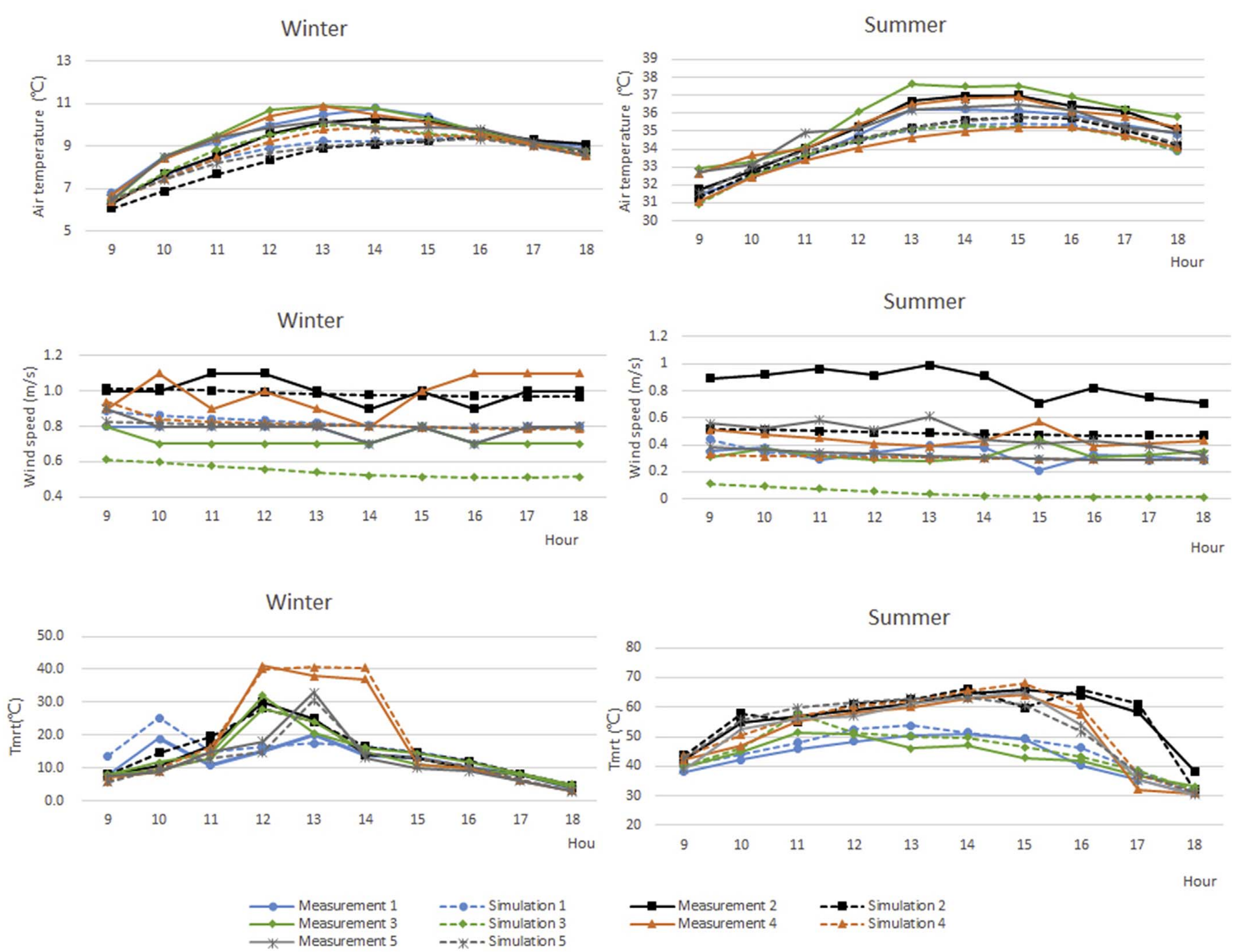

Fig. 6. Comparison of measured and simulated data for air temperature, wind speed and Tmrt.

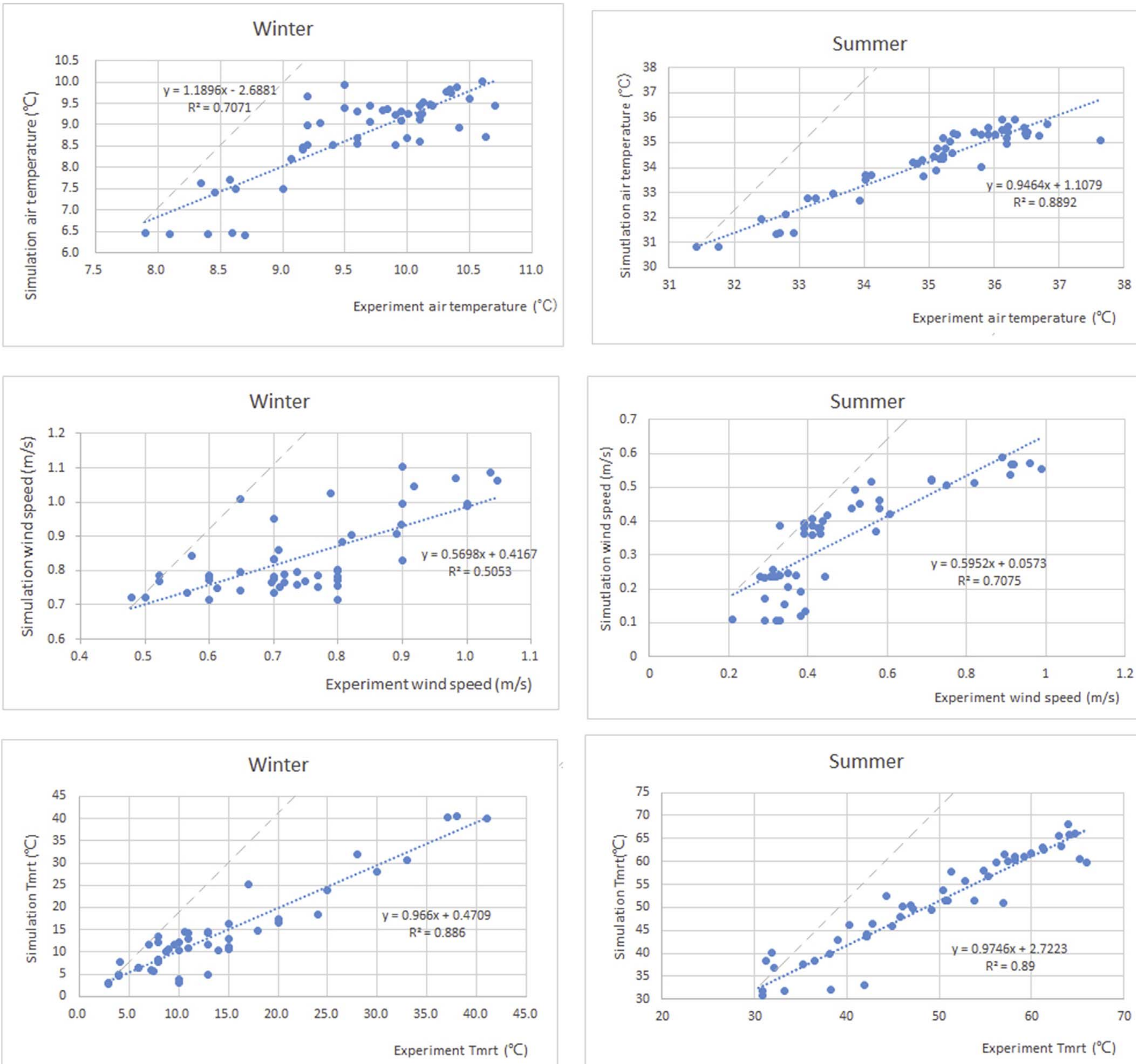

Fig. 7. Comparison between simulated and measured results of air temperature, wind speed and Tmrt both on August 16, 2016 and January 14, 2017, respectively.

PET_{res} was the average PET in the residential block without trees at the pedestrian level at 3 p.m.

4. Results

The average values for the air temperature, wind speed, relative humidity and mean radiant temperature were calculated using the Leonardo tool. Leonardo is part of the ENVI-met that is used for visualizing and analyzing the simulation results. The extracted average data of climatic variables at 3 p.m. at the pedestrian level were analyzed for activity at 3 p.m. for a hot summer and cold winter.

4.1. Air temperature in hot summer

The average temperatures of vegetation cases were compared to a no vegetation case to analyze the cooling effects of trees in different planting patterns. Fig. 8 presents the results. An increase in the ART from < 1 to 2 decreased the temperature reduction irrespective of the species. Trees in the "sparse" case exhibited better cooling effects than trees in the "covering" case. The temperature reduction in the "density" case was the lowest of the three planting patterns. The main reason for this result was that the distribution of trees in three planting patterns was obviously different (Fig. 9) for various ARTs. For example, trees in

Table 4
Quantitative measures of simulation with observed data.

Variable	RMSE	MAE	d
Air temperature in summer (°C)	1.46	0.77	0.91
Wind speed in summer (m/s)	0.19	0.14	0.77
Tmrt in summer (°C)	5.21	4.82	0.78
Air temperature in winter (°C)	0.97	0.9	0.72
Wind speed in winter (m/s)	0.14	0.1	0.81
Tmrt in winter (°C)	5.03	4.71	0.76

Table 5
ENVI-met simulation settings.

Model domain	Size of grid cells (Δx, Δy, Δz)	2, 2, 0.9 (vertical grid with a telescoping factor of 20%)
	Number of grid cells (Δx, Δy, Δz)	100, 100, 15
	Nesting grids	5
	Soil profiles in nesting grids	Default
Meteorology inputs	Air temperature (°C)	32 (S) 9 (W)
	Relative humidity (%)	72 (S) 78 (W)
	Wind speed at 10 m	1 m/s (S) 4.5 m/s(W)
	Wind direction (°)	230 (S) 30 (W)
	Specific humidity in 2500 m	7 g/kg*
	Roughness length at reference	0.01*
Plants	3D tree	Table 2
	1D grass	Grass 50 cm aver. dense
Building	Albedo of roofs	0.3
	Albedo of walls	0.2

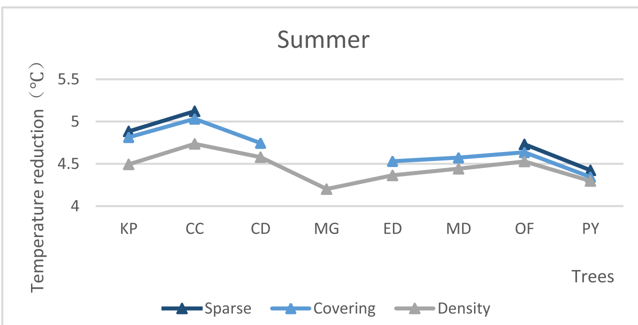

Fig. 8. Temperature reduction due to vegetation in summer.

the “sparse” case of CC were placed evenly throughout the entire empty space, and trees were concentrated in the space between buildings in the “density” case. The tree coverage in the “density” case was 25%, which was the same as in the “sparse” case, but the actual tree coverage was lower than 25% because of the extensive overlapping crowns. This overlap caused more exposed surfaces in the “density” case and resulted in a higher temperature. A comparison of the “sparse” case with the “covering” case revealed that the best cooling effects occurred in the “sparse” case despite identical actual tree coverage in both cases. The main reason for this result was that trees in the “sparse” case and buildings created more shade than trees in the “covering” cases (Fig. 10), which effectively mitigated the hot environment. Therefore, the average air temperature reduction in the “sparse” case was greater than the other two cases.

Different species showed unequal cooling effects, even in the same planting pattern (Fig. 8). Trees with wider crowns exhibited a greater ability to mitigate hot stress than smaller crown trees by creating more shadow. For example, the temperature reduction of wider crown trees, such as CC, KP and CD, were greater than that of other species in the “covering” case. Comparing KP with CC, the temperature reduction of CC was more obvious than that of KP despite the presence of identical heights and crown widths. The main reason for this result was that the larger LAI of CC increased solar attenuation [14]. The faster transpiration rates of CC also reduced the heat load more effectively [3]. Similar patterns were found between ED and MD, OF and PY. Notably, CC, which has a wider crown and larger LAI, had more apparent cooling effects on the heat environment compared to MG. However, OF exhibited similar cooling effects as MD in the “covering” case despite the taller of MD. This result indicated that trees with larger LAI had more impacts on cooling effects.

The cooling effects of trees depend on the LAI, crown width, transpiration rate and green distribution. The tree distribution with an ART < 1 is an optimum choice to mitigate the hot temperature. Tree species with large crowns, fast transpiration rates and large LAIs should be a priority because of their obvious cooling effects on thermal environments.

4.2. Wind speed in hot summer

Vegetation cases were compared with a no tree case to determine the ventilation effects of trees in hot summer. Fig. 11 shows the ventilation reduction due to various tree species and distributions: the wind speed reduction in the “sparse”, “covering” and “density” cases ranged from 0.1 to 0.2, 0.07 to 0.18 and 0.04–0.12 m/s, respectively. The vegetation influence on wind proofing increased as the ART decreased, regardless of species. Scattered trees (“sparse” case) had a clear impact on ventilation and led to a greater wind speed reduction than the concentrated distribution (“density” case). This result occurred because the resistance formed by scattered trees reduced the wind velocity (Fig. 9). More empty space around buildings due to the concentrated distribution in the “density” case was conducive to smooth wind circulation.

Comparisons of CC with KP, ED with MD, and OF with PY revealed that trees with larger LAIs but the same height and crown width more effectively decreased wind velocity regardless of various planting patterns. However, MG in the “density” case more strongly reduced wind speed compared to other species. The reason for this result was that more MG trees were planted based on the same tree coverage (Fig. 12) but with a smaller crown diameter. The width between MG based on an

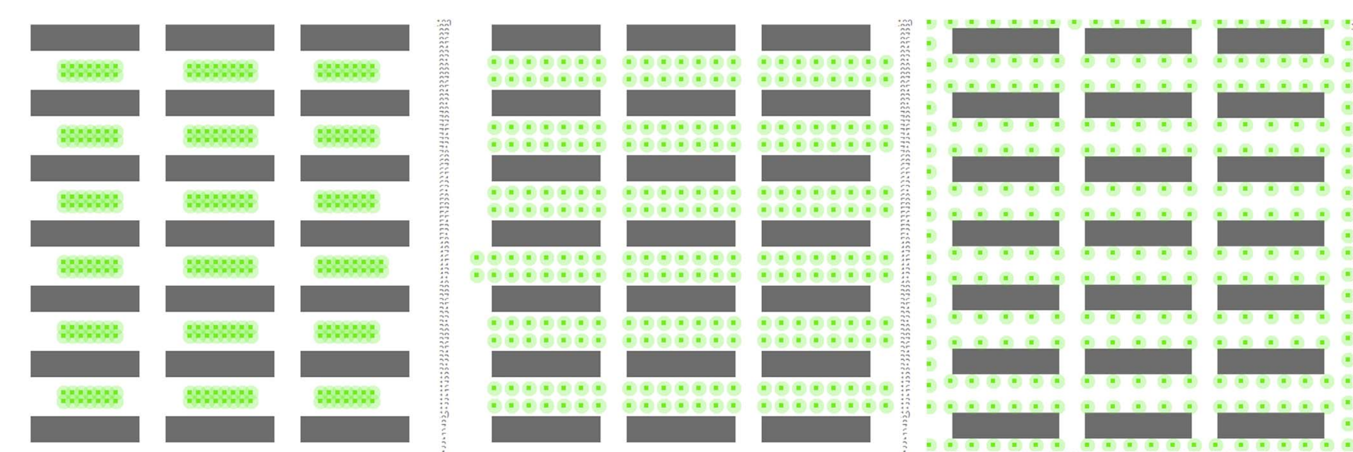

Fig. 9. Tree distribution of CC: left is “density” case, right is “sparse” case, middle is “covering” case.

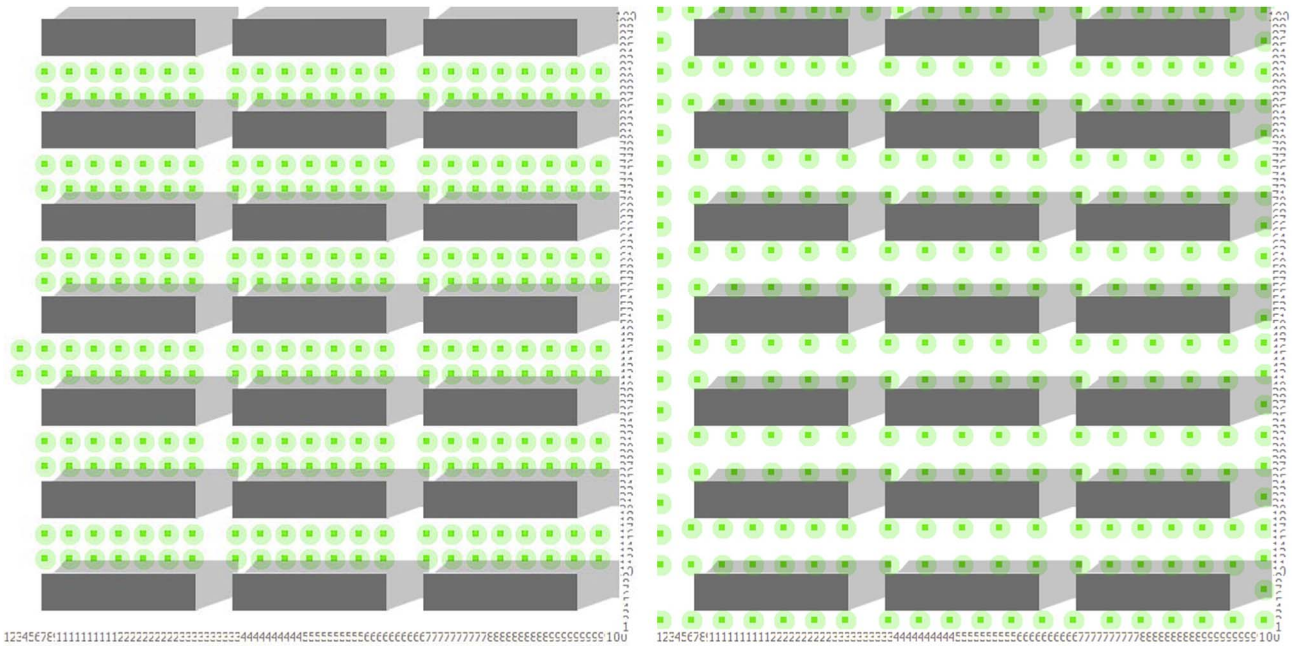

Fig. 10. The building shadow and trees distribution of "covering" (left) and "sparse" (right) scenarios.

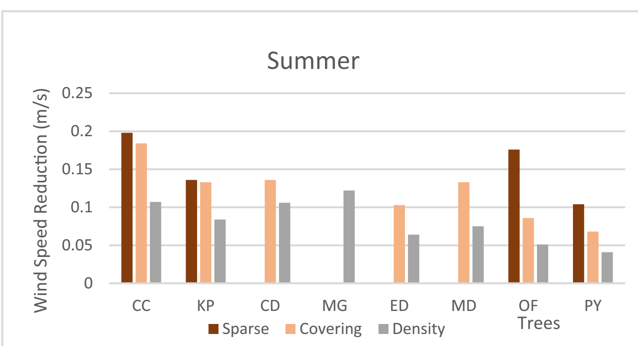

Fig. 11. Wind speed reduction due to vegetation in summer.

ART of 2 was much wider than that of other species because of the 12 m height. These differences created more effective windproof areas in the MG "density" case. The ratio of tree height to crown diameter had an impact on shaping the space. Tall trees with small canopies created a completely different space than expected based on the same ART. These differences influenced ventilation.

The LAI, crown diameter and planting patterns generally influenced the effects of trees on ventilation. The decreasing order for wind velocity for planting patterns in hot summer was "density", "covering" and "sparse". The tree coverage and planting patterns identified that the ratio of tree height to crown diameter remained an important factor for ventilation.

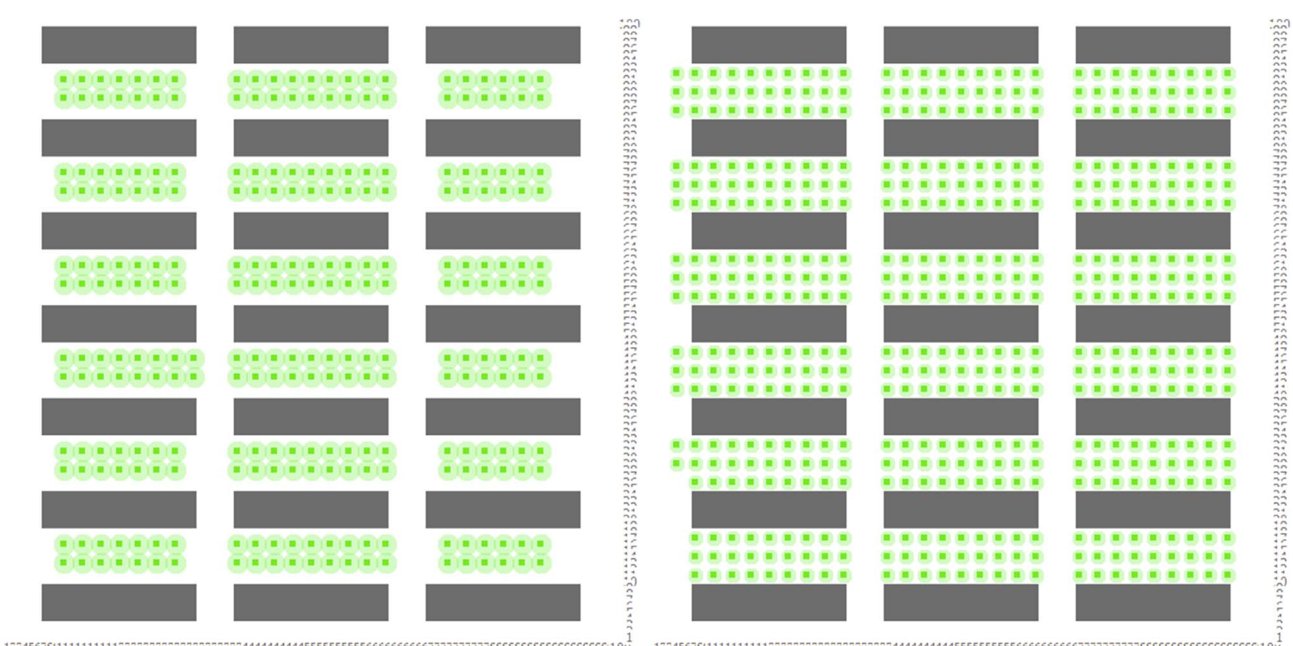

Fig. 12. Tree distribution in "density" case: left is CD; right is MG.

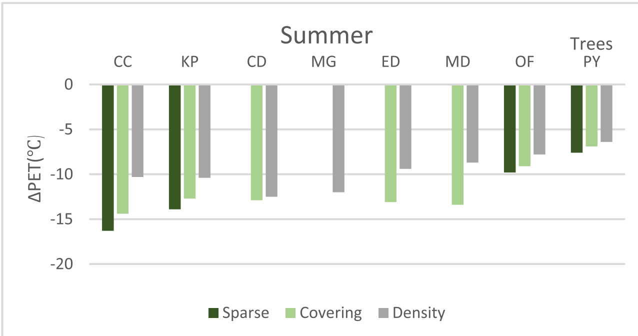

Fig. 13. ΔPET due to vegetation in summer.

Table 6
Effects of 3 tree distributions on temperature, ventilation and PET.

	Sparse	Covering	Density
Temperature reduction(°C)	4.79	4.66	4.45
Wind speed reduction(m/s)	0.15	0.12	0.08
PET reduction(°C)	11.91	10.83	9.78

4.3. Thermal comfort in hot summer

A positive effect ofΔPET was observed for all of the vegetation cases analyzed (Fig. 13). The influence of vegetation in the "sparse" case produced a greater ΔPET regardless of the tree species, and in the "density" case was the lowest. Trees in the "sparse", "covering" and "density" cases had completely opposite effects on air temperature and ventilation. However, the changes in ΔPET were similar to the changes in air temperature. The main reason for this result was that PET was significantly governed by the mean radiation temperature and air temperature in calm hot summer daytime. The shading and sunlight areas influenced the mean radiation temperature. Ignoring the influence of tree species revealed that the tree distribution exerted a greater improving effect on PET (Table 6). The greatest difference in ΔPET of the 3 tree distributions was approximately 2.13 °C, which was more obvious than the temperature and wind speed reductions. "Sparse" and "covering" space (ART < 2) were the optimum planting choices to mitigate hot temperatures on a hot summer day.

Fig. 13 shows that tall trees with a large LAI and wider canopy noticeably improved PET. The ΔPET values of CC, KP and CD in the "covering" case were higher than those other species because of the wider crowns, which created more shadow and intercepted more solar radiation. Trees with the same height and crown width, for example, CC and KP, OF and PY, but a larger LAI, led to a largerΔPET. Species with a larger LAI and wider crowns should be a priority to provide better outdoor thermal comfort.

4.4. Wind speed in cold winter

Data for the simulations with and without trees were compared to analyze the wind environment at the pedestrian level at 3 p.m. The impact of the planting patterns on air flow revealed similar rules for hot summer and cold winter (Fig. 14). Scattered trees in the "sparse" case with an ART below 1 had the most effective wind proofing effect regardless of species. The decreasing order based on wind blockade in winter was the same as in summer: "sparse", "covering" and "density". The wind speed reduction for deciduous trees, such as KP, MG, MD and PY, with smaller LAIs in winter, was less than 0.2 m/s, regardless of the planting patterns. This result occurred because the lower resistance of these trees exerted little effect on airflow. The reduction in wind velocity (above 0.4 m/s) for evergreen trees in the "covering" case was higher compared with deciduous trees. The simulation output also

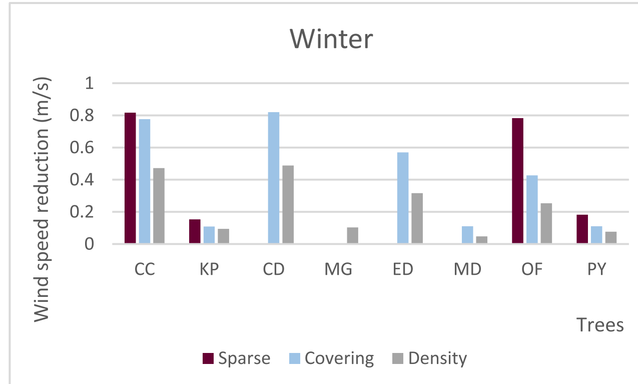

Fig. 14. Wind speed reduction due to vegetation in winter.

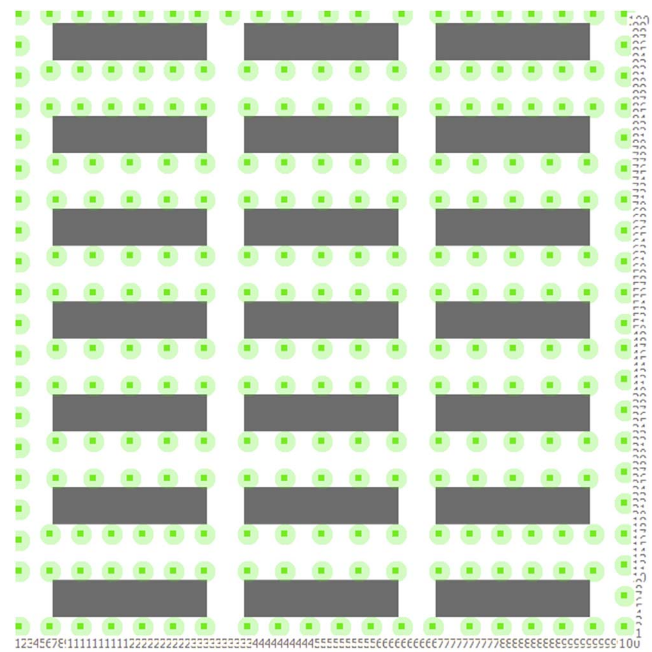

Fig. 15. Trees distribution in "covering" case of CD.

demonstrated that evergreen trees had larger effects on wind proofing than deciduous trees in winter. The wind speed reduction of CC was much greater than CD in the "covering" case, despite the same crown width and ART. This result occurred was because CC has a larger LAI and broad leafs, which caused more resistance than the small LAI and needle-leafs of CD. The distance between shorter tree canopies (CC) was smaller based on the same ART and crown diameter, which created more resistance (Figs. 9 and 15).

However, different results were observed in the "covering" cases of ED and OF. The wind speed reduction of ED was higher than that of based on the same ART, but ED was taller and had a smaller LAI. The reason for this result was that trees of different heights and canopy diameters were planted in various distributions with the same ART, which exhibited a diverse influence on ventilation. A similar distribution was found between ED and CD. The distances between OF and buildings were apparently wider than those of CD (Figs. 15 and 16). More flat space at the site boundary in the OF "covering" case induced a smoother airflow, and the average wind velocity was higher.

4.5. Air temperature in cold winter

Air temperature and solar radiation are important for people who spend time outdoors in winter. Residents prefer spaces with more direct

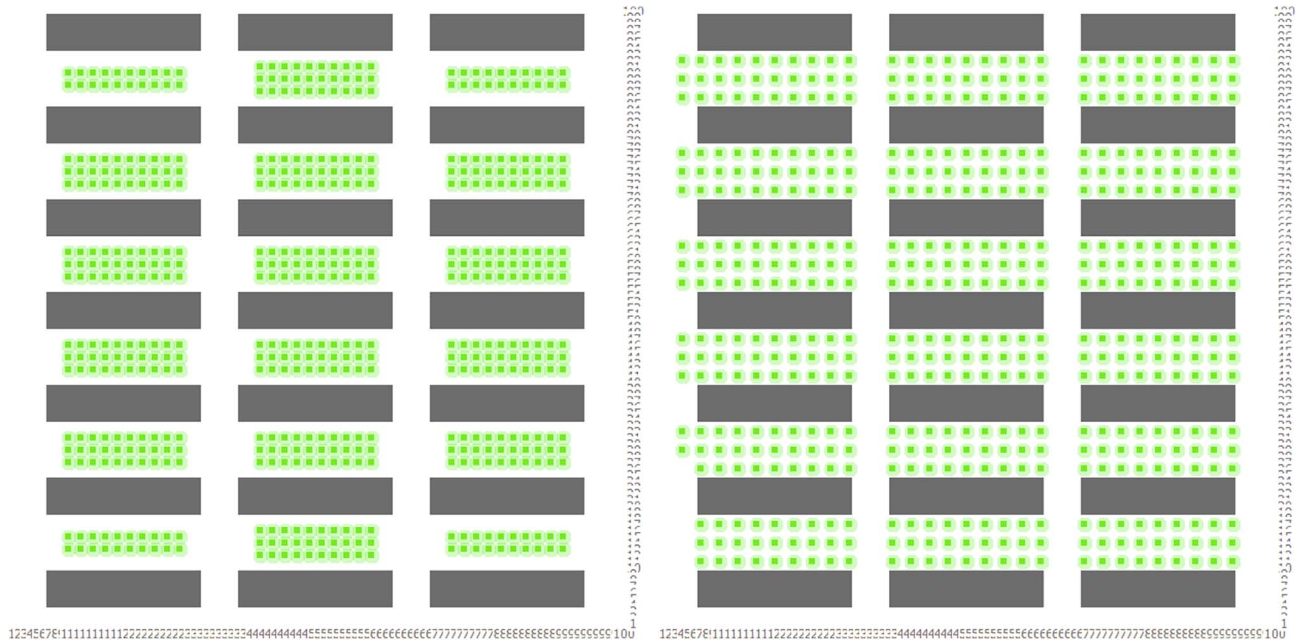

Fig. 16. Trees distribution in “covering” case: left is OF; right is ED.

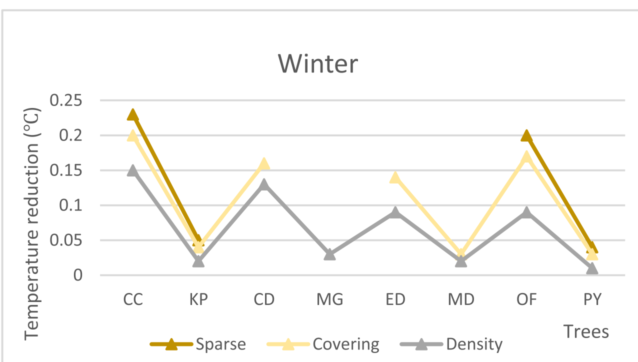

Fig. 17. Temperature reduction due to vegetation in winter.

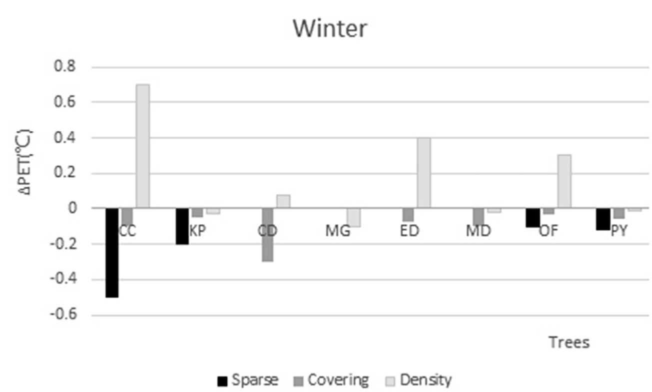

Fig. 18. ΔPET due to vegetation in winter.

sunlight in winter. The influence of various trees in different layouts on temperature was analyzed (Fig. 17). Data from the simulations with and without trees were compared. Deciduous species, such as KP, MG, MD and PY, had little effect on temperature compared with evergreen species. Evergreen trees exerted a slight cooling effect on temperature for shading and solar attenuation. The temperature reduction declined for spaces with more direct sunlight with an increasing ART between evergreen trees. The temperature reduction for deciduous species exhibited little difference as the ART increased. Tall evergreen species with wider canopies and large LAIs, such as CD and CC, also reduced temperatures more than other species in winter. However, the temperature reduction was not good for outdoor activities in winter.

4.6. Thermal comfort in cold winter

Various effects onΔPET were observed for all of the vegetation cases analyzed (Fig. 18). ΔPET increased as the ART increased regardless of species. The PET effects of evergreen species went from negative to positive when ART increased. Deciduous species exhibited a slightly negative influence on PET compared with evergreen trees. The main reason for this result was that deciduous trees without leaves exerted little influence on ventilation reduction and a slight cooling effects on temperature, which caused a slight negative influence on PET. By contrast, evergreen species with different ARTs had clear various effects on the microclimate. Evergreen species, such as CC and CD, in the sparse and covering cases greatly influenced wind speed reduction. These trees blocked direct sunlight and had negative effects on PET. Due to much more direct sunlight and a larger ventilation reduction, evergreen species had a positive influence on PET with trees in the density case (ART ≥ 2). Clustered evergreen trees in the density case reduced ventilation and direct sunlight, which improved outdoor thermal comfort in winter. Tall trees with larger crowns and LAI in the density case exhibited an obvious effect compared to the other species. One exception was that CD exerted a lower improving effect on PET than ED and OF in the density case. The main reason for this result was that the distance between CD was much larger than of, which reduced direct sunlight space and resulted in little improvement in PET.

5. Discussions

5.1. Optimizing tree distribution and species in hot summer and cold winter zones

Residents in a hot summer and cold winter zone face high temperatures and strong cold winds. Residential vegetation should greatly reduce PET during the hot season and improve PET in the cold season to create a comfortable outdoor environment. Our results demonstrated that trees in the sparse, covering and density cases exerted an obvious positive effect on PET in summer. The comparison of 3 tree distributions revealed that, based on the same amount of trees, trees with an ART < 2 should be a priority to mitigate hot environments due to the large effects on PET reduction in summer. Trees with an ART ≥2 weakened the cooling effects on PET because the overlapping crowns caused the less tree coverage than expected. Evergreen species with an ART < 2 also effectively decreased wind speed in winter as well as blocked direct sunlight, resulting in negative effects on PET. Evergreen species with an ART ≥2 should be a priority for improving outdoor PET in winter.

LAI, height and crown width were the main factors that affect vegetation cooling and ventilation. Tall trees with a large LAI and canopy diameter should be a priority to improve the comfort of outdoor environments. However, the tree layout influenced the effects of the same species on the microclimate. The ratio of tree height to crown diameter was another important factor that clearly affected the microclimate.

5.2. Residential vegetation planning strategies from a microclimate perspective

Residential vegetation can shape various outdoor spaces and regulate the microclimate. Conventional residential vegetation is generally planned from an activity space and landscape perspective. The greening rate is the defined code for residential vegetation planning. The outcomes of the present study suggest that trees effectively influence the residential microclimate. It is necessary to pay more attention to tree planning to create better microclimate environments.

Residential vegetation in a hot summer and cold winter zone should be planned from space construction and microclimate regulation to ameliorate heat stress in summer and strong winds in winter. Trees with different ARTs exert different effects on the microclimate in summer and winter, and the choice of the tree distribution and species to better regulate the microclimate should be based on various local residential outdoor spaces. For example, the residential center square is an important outdoor space for activities. It is better for people to have shade in summer and sunlight in winter. A covering space can be created around the central square to mitigate the high temperature and shape the shade space. Tall evergreen trees and deciduous trees with large LAIs and canopy diameters should be planted upwind and leeward, respectively, for winter regulation. Upwind evergreen trees effectively block strong winds, and more sunlight is available in winter leeward because of the presences of deciduous trees. Sparse space may be shaped around buildings to provide the best cooling effects, which reduces indoor temperatures. Evergreen trees may be concentrated windward in winter, with trees perpendicular to the wind direction to windproof against strong wind. Upwind short trees with small LAIs and crowns planted parallel to the wind direction provide better airflow in summer.

Reality presents a more complex environment, and it is difficult to provide complete and perfect guidelines for residential vegetation planning. Many factors, such as nearby lakes or rivers and buildings, affect the local urban climate, especially the wind direction. The different climate situations in summer and winter complicate the creation of environments that are comfortable all year long using only vegetation. Other cooling and ventilation strategies, such as changes in the surface material of buildings and cooling or wind-blocking devices should be considered.

5.3. Further study

The cooling and ventilation effects of residential vegetation may vary in different building layouts at 3 p.m. due to shade and wind proofing by tall buildings. Similar studies should be performed using various building layouts. Many species of trees with different ARTs are naturally planted in real residential blocks. The cooling and ventilation effects of mixed tree distributions and various species should also be investigated. The buildings in this study were perpendicular to wind direction in winter, which blocked the strong north wind. The average wind speed in the residential block likely could not indicate the impact of vegetation on the ventilation environment. The influence of vegetation on ventilation under various wind directions should be examined in subsequent research.

6. Conclusions

Trees in residential districts exert significant effects on outdoor heat environments in summer and effectively impact the ventilation environment in cold winters. Three planting patterns and 8 tree species were simulated to investigate their impact on the outdoor environment at the pedestrian level in summer and winter. The results demonstrated that the tree distribution, crown width and LAI obviously influenced heat stress and ventilation. This study significantly improved our understanding of the effects of residential vegetation on outdoor summer and winter environments. The results helped to determine appropriate vegetation species and layout strategies for residential green planning to create comfortable outdoor environments in a hot summer and cold winter zone.

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