Effects of urban street trees on human thermal comfort and physiological indices: a case study in Changchun city, China

Zhibin Ren^{1,4} · Hongbo Zhao² · Yao Fu^{1,3} · Lu Xiao^{1,4} · Yulin Dong^{1,4}

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Abstract Planting trees along urban streets is one of the most important strategies to improve the urban thermal environment. However, the net impacts of urban street trees on human thermal comfort and physiological parameters are still less clear. On three similar east–west orientated streets with different degrees of tree cover—low (13%), medium (35%), and high (75%), urban microclimatic parameters and human physiological indices for six male students were simultaneously measured on three cloudless days in summer 2018. The results show that the differences in tree cover

were predominant in influencing urban thermal environment and comfort. The street with the highest tree cover had significantly lower physiological equivalent temperature (*PET*) and more comfortable than the other two streets. The frequency of strong heat stress (*PET* > 35 °C) was 64%, 11%, and 0%, respectively, for streets with low, medium, and high tree cover. For the six male university students, human physiological indices varied greatly across the three streets with different tree cover. Systolic blood pressure, diastolic blood pressure, and pulse rate increased with decreasing tree cover. The results also suggest that urban thermal environment and comfort had considerable impact on human physiological parameters. Our study provides reasons for urban planners to plant trees along streets to improve the thermal environment and promote urban sustainability.

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Corresponding editor: Yu Lei.

✉ Hongbo Zhao
zhaohbhwm@163.com

Yao Fu
fuyao@iga.ac.cn

¹ Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, P. R. China

² Key Research Institute of Yellow River Civilization and Sustainable Development & Collaborative Innovation Center On Yellow River Civilization Jointly Built By Henan Province and Ministry of Education, Henan University, Kaifeng 475001, P. R. China

³ School of Geography and Engineering of Land Resources, Yuxi Normal University, Yuxi 653100, P. R. China

⁴ University of Chinese Academy of Sciences, Beijing 100049, P. R. China

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Introduction

Urban heat islands (UHI) and global warming have presented a combined threat to urban residents' health and well-being (Wu 2014; Kroeger et al. 2018; Li et al. 2018). Intensive heat, especially in summer, can lead to high energy usage for air conditioning (Gago et al. 2013), reduce urban comfort levels (Hwang et al. 2017), negatively impact public health, and even lead to mortality (Hall and Warner 2018; O'Lenick et al. 2019). Therefore, how to improve the urban thermal environment has become a major research focus. Urban greenspace can create cool areas and moderate the UHI effect, depending on the amount and structures of vegetation (Bowler et al. 2010; Roeland et al. 2019; Lo Piccolo

and Landi 2021). Understanding how to design urban greenspace is critical for city planners to improve the urban thermal environment.

Urban streets are the most numerous and visible public space in cities (Astor 2019). In well-developed cities, streets can comprise more than 80% of public spaces (Araldi and Fusco 2019; Astor 2019). Streets are importance places for activities such as walking, sitting, cycling, and doing business for people of all ages (Jin et al. 2019). The urban thermal environment is predominantly related to the properties of streets to provide an engaging environment that assures comfort and enjoyment (Ginner et al. 2015; Lee and Mayer 2018). Street geometry, such as street direction, building height-to-width ratios, sky view factor can essentially shape the urban thermal environment (Chatzidimitriou and Yannis 2017; Sharmin et al. 2017; Qaid et al. 2018). Street trees provide important shading in hot summers, decrease direct sunlight on people and buildings along streets, and reduce energy for cooling (Lee and Mayer 2018; Qaid et al. 2018). Trees along urban streets are important for moderating urban temperatures and improving the urban environment (Wang and Akbari 2016). Therefore, planting trees along streets has been one of the main strategies to enhance the urban thermal environment (Revelli and Porporato 2018; Gebert et al. 2019).

Although the quantitative effects of street trees on the thermal environment is necessary for efficient street design to improve the environment, most studies have focused on the effects of urban street trees on air temperatures (Tsiros 2010; Vailshery et al. 2013; Ginner et al. 2015; Muniz-Gaal et al. 2020). Urban thermal conditions, the complex indicator that involves temperature, wind speed, and solar radiation cannot be solely explained by air temperature (Aljawabra and Nikolopoulou 2018; Cheung and Jim 2018). To humans living under different temperature conditions, their thermal comfort level is dependent on physical and climate factors, and it could be simulated for greater understanding of thermal environments (Aljawabra and Nikolopoulou 2018; Galagoda et al. 2018). Urban thermal comfort represents the integral effects of climate, including air temperature, wind speed, humidity and solar radiation (Salata et al. 2017; Lee and Mayer 2018; Yang et al. 2018). However, the effect of urban street trees on human thermal comfort is not well understood.

Urban street trees can provide opportunities for outdoor physical activities, social contacts, and relaxation (Galenieks 2017). A growing number of studies have shown that urban green spaces can impact human health such as physical activity, over-weight or obesity, and even mental stress (Hordyk et al. 2015; Tilov et al. 2017; Lanki et al. 2017; Dzhambov et al. 2018, 2019; Crouse et al. 2020). Human physiological indices, (such as blood pressure and pulse rate) are important indicators for urban resident health (Duncan

et al. 2014; An et al. 2018). However, the quantitative effects of urban trees on human physiological indices are still unclear. In addition, people are increasingly concerned about urban heat exposure, and how to assess this risk becomes increasingly important (Kuras et al. 2017). The impacts of urban environmental heat on morbidity and mortality are well documented (Hall and Warner 2018). Compared with mortality, human physiological indices should be more sensitive to urban heat expose (Meade et al. 2020; Morris et al. 2020). However, little is known about the effect of the urban thermal environment on human physiological indices by urban streets with different tree cover.

This study investigates the effects of street trees on urban thermal comfort and human physiological indices in a highly urbanized and intensively populated city. Changchun is a city with a temperate climate, rapidly urbanizing and with increasing summer temperatures. With human bio-meteorological measurements on three different streets, the objectives of this research are to: (1) identify the daily differences in urban thermal comfort and human physiological conditions on different streets; and, (2) explore the quantitative relationships between urban thermal comfort and human physiological indices. Our study can provide useful information on the design of urban streets to improve urban thermal environments.

Materials and methods

Study site

This study was carried out in Changchun city (125°09' E–125°48' E, 43°46' N–43°58' N), the capital of Jilin Province in northeastern China. Within downtown Changchun, there is a 285 km² area with 45% vegetation cover, with a population of 4.1 million at the end of 2019. It has temperate climate, with annual precipitation of 567 mm, and average summer temperature 24 °C. The temperatures have increased 1.9 °C over 60 years from 1951 to 2018. The urban thermal environment has deteriorated in recent years (Ren et al. 2018), making Changchun appropriate for this research (Fig. 1).

Three urban streets were selected (Table 1). Tree cover was obtained from Satellite Pour l'Observation de la Terre (SPOT) remote sensing data with high resolution. We interpreted the tree cover with SPOT images which was 13% (low), 35% (medium), and 75% (high) for the three streets (Fig. 1). For minimizing the “non-tree” influence on the microclimate, using indicators for the ratio of building height and street width (H:W), streets were selected with the similar H:W range of 0.20–0.27 with the same orientation (Table 1).

Fig. 1 The study area located within the fourth-loop road in the city of Changchun, P. R. China

Table 1 Urban street characteristics

Street geometry	Urban street a	Urban street b	Urban street c
Building Height (m)	18 m	15 m	15 m
Street width (m)	42 m	36 m	38 m
Building Height/ Street Width	0.43	0.42	0.4
Orientation	East–west	East–west	East–west
Tree cover	3%	35%	75%

Data collection

Urban thermal measurement on pedestrian walkways

Measurements of the urban thermal environment of three streets were taken simultaneously over three days, July 10th, 12th and 15th of 2018. The data were assumed to represent the best synopsis of meteorological conditions in summer for Changchun city for the three urban streets. Three HOBO devices for each street collected thermal data at 1.5 m above the ground, which is most relevant to human perception. In addition, measurements were taken at the center of sidewalks shaded by trees.

Air temperature (T_a), relative humidity (RH), wind speed (W_s) and solar radiation (SR) were measured based on stationary surveys at the street level. The urban microclimatic measurement logger was from HOBO (Inc., Lakeville, MN, USA) which measures temperatures from $-20\text{ }^{\circ}\text{C}$ to $70\text{ }^{\circ}\text{C}$ with an accuracy of $\pm 0.5\text{ }^{\circ}\text{C}$ and a resolution of $0.1\text{ }^{\circ}\text{C}$. The loggers were set to record data from 9:00 to 19:00 every 15 min interval. There were 40 urban microclimatic data for each day. The HOBO loggers were located at a tree-shaded sites for 10 h. The means of urban microclimate data on three summer days for each street were used for comparative purposes.

The physiological equivalent temperature (*PET*) is a popular and useful bioclimatic indicator widely used to represent urban human thermal perception (Ketterer and Matzarakis 2016; Jung and Yoon 2018). *PET*, a concept born of the human energy balance, can be computed by the Munich Energy Balance Model for individuals that simulates, through overall physiological indicators, the thermal conditions of the human body (Matzarakis et al. 2013).

RayMan software evaluated the mean radiant temperature (T_{mrt}) and *PET*, with the thermo-physiology of the human body (sex, height, activity, clothing resistance for heat transfer, shortwave albedo, and long wave emissivity of the surface) and the integral effect of the meteorological parameters. The microclimate parameters T_a , *RH*, *SR* and *Ws* were used in the human thermal comfort estimation of *PET*. The configuration of the representative personal data, clothing, and activity level in RayMan software is as follows: 1.75 m (height), 76 kg (weight), 22 years (age), male (gender), 0.9 (clothing index) and 80 W (activity). The assessment scale used in this study to classify cold stress ($PET < 13\text{ }^{\circ}\text{C}$), thermal comfort ($13\text{ }^{\circ}\text{C} \leq PET \leq 29\text{ }^{\circ}\text{C}$) and heat stress ($PET > 35\text{ }^{\circ}\text{C}$) is described by Matzarakis et al. (1999, 2013).

Human physiological measurement for pedestrians

Six male university students (aged 22 ± 1 year; Table 2) participated in this study to detect the effects of urban street trees on human physiology. There was an attempt to minimize differences of physiology, and the participants were healthy with similar body weights and heights. It was assumed that participants with similar physiological conditions would have similar thermal perceptions. The subjects were informed about the procedures involved before the experiment. No statistically significant differences were found in the psychological response of the six participants before the experiment. This study was performed under the regulations of the Ethics Committee of the Center for Environment, Health, and Field Sciences, China. Field measurements of human physiological indices were taken simultaneously for three streets on three summer days: July 10th, 12th, and 15th of 2018. The six participants were randomly assigned to three groups, two per group for repeat observations, and each group participated in the experiment for one day. Physiological indices were measured every 15 min from 9:00 to 19:00, which is consistent with urban microclimatic

measurements. Three physiological parameters including systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse rate (PR) were measured by an oscillometric digital blood pressure monitor (HEM1010; Omron, Japan). For each street, the mean SBP, DBP, and PR of the three groups on the three different days were used for comparative purposes.

Data analysis

Four microclimatic and physiological indices for the six participants on three measured days for each urban street were averaged from 9:00 to 19:00 and used as representative values for the next analysis ($N = 120$). Urban microclimatic and physiological indices followed a normal distribution. An analysis of variance (ANOVA) was used to compare *PET*, SBP, DBP, and PR among the three urban streets at the level of $\alpha = 0.05$ ($p < 0.05$).

To understand the relevance of human physiology and the urban thermal environment in a statistically robust manner, correlation and modeling analyzes were applied with the thermal indices (T_a , *RH*, *WS*, and T_{mrt}) as independent variables and the human physiological indices (SBP, DBP, and PR) as dependent variables. Correlation value was first conducted between the thermal indices and *PET* with the human physiological indices. Modeling of ordinary least squares regression was established to quantify the relationship between indices. The determination coefficients (R^2) from regression modeling were used to represent the degree of thermal indicators to human physiological indices. All statistical analyses were performed using SPSS, version 20.0 (IBM Corp., Armonk, NY, USA).

Results

Effects of urban street tree on human thermal comfort

The results show that all urban microclimatic indices (T_a , R_H , W_s , and T_{mrt}) varied considerably from 9:00 to 19:00 among the three streets with different tree cover (Figs. 2, 3 and Table 3). Daytime variations in urban microclimates were similar among the three streets, reaching a peak from 13:00 to 15:00. The T_a and T_{mrt} of the street with low tree cover surged and departed from *RH* and *Ws* from 13:00 to 15:00, which suggests that urban street trees had a stronger

Table 2 Participant demographics

Parameters	Total sample number	Sex	Age (years)	Height (cm)	Weight (kg)	SBP (mmHg)	DBP (mmHg)	Heart rate
Value (Mean + Standard deviation)	6	Male	22 ± 1	174.5 ± 1.5	76.2 ± 2.3	123.4 ± 6.6	83 ± 5	75.6 ± 6.2

Fig. 2 Dynamic changes of the urban thermal environment and comfort on three different streets

cooling effect during 13:00–15:00 (Fig. 2 I, IV). The maximum T_a and T_{mrt} (29.6 $^{\circ}\text{C}$ and 48.6 $^{\circ}\text{C}$) were observed on the street with low tree cover, while low T_a and T_{mrt} was observed on streets with high tree cover (Figs. 2, 3). The urban street with a high tree cover had significantly lower T_a and T_{mrt} (Fig. 3 I, IV). RH also increased with the increase of tree cover with mean values of 35.8%, 36.5%, and 37.1%.

Urban thermal comfort also varied among the three streets (Figs. 2, 3). The PET of the streets with high and medium tree cover were lower than those with low tree cover during the day from 9:00 to 19:00. Urban street trees could reduce PET more during 13:00–15:00 than at any other time of day (Fig. 2 V). The PET of the urban streets with high and medium tree cover was distinctly lower than the street with low tree cover (Fig. 3 V). Compared to the street with low tree cover, the mean daytime cooling in PET was about 5.1 $^{\circ}\text{C}$ and 13.7 $^{\circ}\text{C}$ for the streets with medium and high tree cover, respectively. The lower PET values under tree canopies indicated lower level of thermal stress compared to an urban site without trees. Figure 6 i illustrates the frequency of PET for the three different streets with the distribution right-skewed toward high values. Our results show that the frequency for $PET > 35$ (Strong Heat Stress)

was 64%, 11%, and 0%, respectively, for streets with low, medium, and high tree cover. The street with sparse tree cover had no PET from 18 $^{\circ}\text{C}$ to 23 $^{\circ}\text{C}$ (No Heat Stress), which indicated a more stressful thermal environment. However, the frequency for PET from 18 $^{\circ}\text{C}$ to 23 $^{\circ}\text{C}$ increased to 10% and 28%, respectively for streets with medium and high tree cover.

Effects of urban street tree on human physiological indices

The values of SBP, DBP, and PR (9:00–19:00) in the three streets with different tree cover are shown in Figs. 4, 5 and in Table 3. All the human physiological indices (systolic blood pressure SBP, diastolic blood pressure DBP, and pulse rates PR) varied greatly among the three different streets. The SBP in the street with high tree cover was distinctly lower for most of the day than the street with low tree cover (Fig. 4 I), with mean values of 111.7 mmHg, significantly lower than that in the streets with low and medium tree cover with mean values of 130.1 mmHg and 129.5 mmHg (Fig. 5 I). DBP also varied greatly among the three streets with a mean value of 92.5 mmHg, 86.6 mmHg, and 63 mmHg, respectively, for the

Fig. 3 Urban thermal environment and comfort among different streets; letters indicate significant difference between any couple of the three comparisons; bars above columns indicate standard errors.

Air temperature **I**, Relative humidity **II**, Wind speed **III**, Radiation temperature **IV** and Physiological Equivalent Temperature **V**

Table 3 Descriptive statistics of urban microclimatic indices on three urban streets

Microclimatic indices		Low	Media	High
T_a	Max	32.5	29.8	25.8
	Min	24.4	23.0	19.3
	Mean	29.6	27.2	24.1
	SD	1.7	1.3	1.5
RH	Max	60.5	55.6	57.1
	Min	31.2	31.7	31.8
	Mean	35.8	36.5	37.1
	SD	7.1	5.7	5.7
W_s	Max	3.8	5.6	2.8
	Min	0.8	0.9	1.0
	Mean	1.5	2.4	0.7
	SD	0.6	1.2	0.7
T_{mrt}	Max	58.9	56.0	54.5
	Min	19.9	17.5	14.3
	Mean	48.6	45.7	44.98
	SD	9.7	9.1	10.3

Air temperature (T_a), Relatively humidity (RH), wind speed (W_s) and solar radiation (SR), mean radiant temperature (T_{mrt})

low, medium and high tree cover (Fig. 4 II, 5 II). We also found that the PR of the streets with high and medium tree cover were lower than those with low tree cover during the day from 9:00 to 19:00. The PR of the streets with high and medium tree cover were distinctly lower than the street with low tree cover (Fig. 5 III). Figure 6 II shows the frequency of SBP for the three streets. On the street with high tree cover, the frequency for SBP (< 120 mmHg) was typically high (91%), while the frequency for streets with low and median tree cover were generally 22% and 18%, respectively. The results show that the frequency for DBP above 90 mmHg was 60%, 40%, and 10%, respectively, for streets with low, medium, and high tree cover (Fig. 6 III). Pulse rates (PR) also varied among the three streets with means of 94, 81, and 67, respectively, for low, medium, and high tree cover. On the streets with medium and high tree cover, the PR (< 80 beats min^{-1}) had the highest frequency (50% and 90%). The frequency for PR (> 90 beats min^{-1}) was high in the street with low tree cover (Fig. 6 IV). The comparison of SBP, DBP and PR provides more information about the variation of the effect of street trees on human physiology.

Fig. 4 Dynamics of human physiological parameters on three streets

Fig. 5 Human physiological parameters on different streets; letters indicate significant differences between any couple of the three comparisons; bars above columns indicate standard errors. Systolic blood pressure **I**, diastolic blood pressure **II** and pulse rate **III**

Effects of urban microclimate on human physiological indices

Table 4 lists the Pearson's correlation coefficients between the urban thermal environment and human physiological parameters. The results show that most of the human physiological parameters (i.e., SBP, DBP, and PR) were strongly affected by air temperature (T_a) and the physiological equivalent temperature (PET). The mean radiant temperature (T_{mrt}) had relatively strong correlations with pulse rates (PR). In addition, the correlation varied among the human physiological parameters. T_a , T_{mrt} and PET had the largest correlation with PR, followed by SBP and DBP, which suggests that the urban thermal environment affects PR more than it affects SBP and DBP. The correlation coefficients between PET and human physiological parameters were higher than other thermal indices. In general, the results in Table 4 demonstrate that PET could play a more important role in impacting SBP, DBP and PR and thus the physiological equivalent temperature should not be ignored when exploring relationships between urban thermal environment and human physiological parameters.

To quantify relationships between urban thermal environment and human physiological parameters, regression models were developed (Fig. 7). The results demonstrated that T_a , T_{mrt} and PET had a positive relationship with SBP, DBP, and PR, indicating that they increased with an increase in urban thermal stress. However, the regression models were different for different physiological indices. SBP, DBP, and PR increased by 28 mmHg, 22 mmHg, and 31 beats min⁻¹, respectively, with the increase in air temperature by 10 °C (Fig. 7 I, II, and III). With a 10 °C increase of PET , in comparison, SBP, DBP, and PR increased by 9.4 mmHg, 7.5 mmHg and 13.5 beats min⁻¹, respectively (Fig. 7 V, VI, and VII). Besides the differences in the regression functions,

Fig. 6 Frequency of *PET* I, SBD II, DBP III, and PR IV on three streets with different tree cover

Table 4 Pearson's correlation coefficients between urban microclimate and human health

Health parameters	T_a	RH	W_s	T_{mrt}	PET
SBP(mmHg)	0.521**	-0.228	0.058	0.046	0.618**
DBP(mmHg)	0.479**	-0.169	0.034	0.029	0.55**
HR(n min ⁻¹)	0.645**	-0.028	0.085	0.263*	0.724**

*Correlation is significant at $\alpha=0.05$ level (two-tailed)

**Correlation is significant at $\alpha=0.01$ level (two-tailed)

PET explained more human physiological conditions than T_a . The linear models show that T_a could only explain the variance of 38%, 30% and 42% in SBP, DBP, and PR, respectively, whereas *PET* could explain 40%, 33% and 52%, respectively.

Discussion

For the cooling functions of urban greenspaces, many researchers often pay more attention to urban parks with large areas of many trees (Bowler et al. 2010; Ren et al. 2013). The ecological functions of urban street trees have been relatively neglected by researchers and urban planners (Barton et al. 2009; Galenicks 2017; Araldi and Fusco 2019). Our results demonstrated that T_a , T_{mrt} , and *PET* can be significantly affected by tree cover on urban streets. Streets with high and medium tree cover were approximately 5.4 °C and 2.3 °C cooler for T_a and 3.6 °C and 2.9 °C cooler for T_{mrt} ,

respectively, than the street with low tree cover and confirms that vegetated areas are cooler than areas without tree cover (Chang et al. 2007; Yang et al. 2017). Tree shade is one of the most important opportunities to cooling temperatures. In tropical and subtropical climates, studies have shown that about 80% of the cooling effect of trees is provided by shade (Shashua-Bar et al. 2010). Our findings showed that shade provided by trees is also an important way to cool summer temperatures in temperate cities. Besides tree shade, evapotranspiration also plays an important role for improving the urban thermal environment. Results showed that when relative humidity by transpiration increases, *PET* decreases. Changchun city has a temperate climate with humidity relatively lower than in tropical climates. The evapotranspiration of urban street trees in the city increases the relative humidity and contributes indirectly to the reduction of temperatures and consequently, to the decrease of *PET*. Our results also indicate that urban *PET* differed considerably among the three urban streets as determined by the varied tree cover. In addition, we also found that T_a and *PET* on urban streets with medium and high tree cover were much lower during 13:00–15:00 than at other times of the day, echoing previous findings that the cooling effect of urban trees increase with the higher background temperature (Shashua-Bar and Hoffman 2002; Lin and Lin 2010; Oliveira et al. 2011). The improvement of the urban thermal environment through the establishment of lines of trees along streets will enhance human thermal comfort. Results from this research expand our scientific understanding of the effects of street trees on the urban thermal environment, and provide insights for

Fig. 7 Scatter plots of the urban microclimate on human physiological indices ($n=360$)

urban planners to improve urban thermal comfort by greening streets.

In recent years, the effects of the built environment (such as building density, pollution exposure and traffic density) on human health have been studied, including their direct physical and indirect effects on social safety and physical activity (Barton et al. 2009; Ding and Gebel 2012). Some studies also showed that natural environments such as parks and green spaces can have a significant positive effect on human health by relaxing mental stress and anxiety, improving mood and self-esteem (Bird et al. 2018; Tsao et al. 2018). Urban parks are widely recognized for providing

important public benefits to improve individual and community health (Kardan et al. 2015; Fleming et al. 2018; Silva et al. 2018). Urban streets with tree cover can also provide public space for physical activity and fresh air (Barton et al. 2009; Ginner et al. 2015; Chatzidimitriou and Yannas 2017). Few studies have been conducted about the physiological effects of urban street trees and whether they affect human well-being (Salmond et al. 2016; Lai and Kontokosta 2019). Our study showed that urban street trees have the potential to affect human physiological health indices such as blood pressure and pulse rate. Such observations strongly evidence the psycho-evolutionary theory which concluded that natural

environments or components of them can mitigate mental stress and improve human emotions (Nadkarni et al. 2017). For example, people in contact with the natural environment often rid themselves of pessimistic thoughts, with a shift from a bad mood to a better one, thereby mitigating mental stress (Hartig et al. 1996; Hordyk et al. 2015). Moreover, spending time in green spaces could improve student academics (Nadkarni et al. 2017), and even a window view of the natural world could improve student well-being (Felsten 2009; Matsuoka 2010). Therefore, studies have shown that human health can be affected by viewing and being exposed to natural environments. In addition, our study provides quantified effects of the urban thermal environment on human health, however, the relative contribution of urban environmental factors to human health is still not well understood. Urban street trees have numerous ecological functions and impact human health by improving the urban thermal environment. Research has shown that high temperatures and heatwaves are considerable threat to human health in the twenty-first century (Bai et al. 2014; Hajat et al. 2014; Gasparri et al. 2017). The relationship between many physiological indices and the urban thermal environment has not been well documented (Gasparri et al. 2015). In our study, we quantified the impact of the urban thermal environment on human physiological indices. Our study shows that urban thermal environmental factors such as air temperature, mean radiant temperature, and physiological equivalent temperature, affect human physiological indices such as blood pressure and pulse rates.

It should be noted that there are several limitations in the current study. Firstly, field measurements of the urban microclimate on three urban streets were taken only for three days in summer. Long and continuous monitoring should be conducted in future to further identify the effects of street trees on the urban thermal environment and human physiological indices. In addition, our study only examined the thermal environment while other factors such as air pollution and noise may also affect human physiology (Mihankhah et al. 2020). Secondly, we only investigated the relationship between human physiological indices and the urban thermal environment of six young men (22-year-olds) which is a very limited sample, and the results cannot be extrapolated to populations of females or people of different ages. Further studies should consider larger and more diverse groups, crossing age and gender to provide more useful information. Thirdly, the experiment was conducted in summer and thermal comfort votes and thermal sensation votes were not collected. This study focused on physiological equivalent temperatures (*PET*) which we think can represent urban thermal comfort to some extent and the effect of street trees on *PET* values, so the grades of thermal comfort perceptions were adapted from references (Matzarakis et al. 1999). Lastly, other health indicators besides systolic and diastolic

blood pressure and pulse rates could also be examined to provide a more comprehensive understanding of the effects of street trees on health.

Conclusions

With measurements of urban thermal parameters and human physiological conditions on three urban streets with different tree cover in Changchun city, this study quantified the effect of urban street trees on human thermal comfort levels and physiological indices and their relationships. Several meaningful conclusions have been found. The street with the highest tree cover provided a more comfort thermal environment with lower air and mean radiant temperatures, and higher relative humidity and lower physiological equivalent temperatures. Street trees reduced heat stress more during 13:00–15:00 than any other time of the day, and heat stress was lower for streets with higher tree cover. In addition, for the six male Chinese university students, we found that blood pressure and pulse rates increased with the increase of urban thermal stress associated with the decrease in street tree cover. Our study highlights the importance of urban street trees for improving urban thermal comfort and residents' health, which provides justification for urban planners to plant trees along urban streets to promote urban sustainability and improve urban resilience to global warming.

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