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Effects of the Bamboo Communities on Microclimate and Thermal Comfort in Subtropical Climates

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Abstract: Urban greening is the most effective way to regulate the microclimate environment and thermal discomfort. However, despite being an important type of vegetation, relatively few studies have investigated the effect of bamboo on microclimate characteristics and thermal comfort. In this study, the microclimate characteristics and the differences in the thermal comfort provided by common bamboo communities in East China were investigated in summer and winter, and the effects of canopy structure characteristics on microclimate and thermal comfort were analyzed. The results showed that there were significant differences in microclimate between bamboo communities and the control check in summer, but the differences in air temperature in winter were not obvious. In the daytime during summer, the maximum daily average temperature of the bamboo community decreased by 2.6 °C, and the maximum temperature–humidity index (THI) decreased by 1.1 °C. In the daytime during winter, the maximum daily average temperature increased by 0.5 °C and the maximum THI increased by 0.8 °C. Among the different bamboo communities, *Sinobambusa tootsik* var. *laeta* and *Pseudosasa amabilis* had better effects on improving microclimate and thermal comfort, while the effects of *Phyllostachys nigra* and *Phyllostachys heterocycla* 'Pubescens' were relatively small. Aspects of canopy structure, especially leaf area index and canopy coverage, had the greatest influence on the microclimate environment, while air temperature made the greatest contribution to thermal comfort. The goal of our study is to quantify the data to confirm the role of bamboo in improving urban climate problems and human comfort and to further select the appropriate bamboo species for urban green spaces and to utilize the ecological benefits of bamboo to optimize the human living environment.

Keywords: bamboo community; microclimate; canopy structure; temperature–humidity index

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1. Introduction

With continued urbanization, human production and initiated activities have undoubtedly caused global warming, mainly through greenhouse gas emissions [1]. The Intergovernmental Panel on Climate Change stated that in the near future global temperature could rise by 1.5 °C or temporarily break through 1.5 °C [2]. Rising global temperatures bring more environmental problems, such as increased risk of air pollution, and increased energy consumption especially exacerbates the urban heat island effect [3–6]. The great changes in the characteristics of the underlying surface affect the movement and distribution of heat and water vapor in the city, which increases the thermal risk imposed on local areas by high temperatures [7–9]. High-intensity heat stress can seriously affect human thermal comfort; for example, reduced thermal comfort adversely affects work efficiency, causes heat cramps or heat stroke, and, in severe cases, can even lead to death [10–13]. In China, the total mortality rate reached 336,900 (38.4 per day) from 1996 to 2015, and heat-related mortality accounted for 1.5% to 3.0% of the total mortality in the warm season [14]. At the same time, the negative impact of global climate issues included lower temperatures in the cold season in some areas, and the proportion of deaths caused by cold was higher than that caused by heat [15]. In response to the problems caused by global climate change, mitigation and adaptation strategies, such as optimization of urban structure and increased use of reflective roofs and cool pavements, have been extensively explored [16–19]. Among these strategies, green spaces are seen as important resources for regulating the climate and microclimate [20–22]. Therefore, studying the influence of green spaces on the microclimate and finding mitigation strategies to better plan urban climate-oriented green space construction are key issues for sustainable urban development.

As an integral part of green spaces, plants have received extensive attention from researchers. Trees mainly cool the surrounding environment by shading and evapotranspiration, their leaves absorb and reflect most of the sun's radiation, and they use the heat from the air to evaporate water to cool the ambient temperature [23–26]. Through field measurements and software simulations, a large amount of research has been carried out on plants [27–30]. In Putrajaya, by simulating urban environments, Morris et al. discovered the increase in vegetation per square kilometer reduced the average daily temperature by 0.047 °C [31]. In Madison, Wisconsin, sampling was performed using a bicycle-mounted measurement system. Ziter et al. found that vegetation cover can lower average temperatures by more than 1.5 °C within a radius of 60 to 90 m [32]. Some studies have confirmed that in winter, urban vegetation has a heating effect of up to 4 °C at extremely low temperatures (~−30 °C) [33]. At the same time, by regulating air temperature and humidity, vegetation helps improve thermal comfort for the human body [34,35]. Although a large number of scholars have confirmed the effect of vegetation on the improvement of thermal environments, there are often large differences in thermal benefits between different vegetation types. For example, clusters of *Caesalpinia pluviosa* lowered air temperature by 0.9 to 1.3 °C and physiological equivalent temperature (PET) by 12.5 to 14.3 °C, while *Delonix indica* could only reduce air temperature and PET from 0.2 to 0.7 °C and from 0.6 to 2.7 °C, respectively [27]. The difference depends largely on the characteristics of the vegetation, including tree morphology, plant leaf color brightness and canopy properties. Moreover, canopy structural characteristics have a crucial influence on the microclimate [36–39]. Trees with dense canopy were found to have more obvious heat stress reduction ability and lower local temperature. When the canopy coverage exceeds 40%, the cooling range is the largest [32].

However, among the plant physical properties involved in the existing research, leaf area index (LAI) is the most widely studied, and relatively little research has been carried out on other indicators of the plant canopy, such as canopy coverage (CC) and sky view factor (SVF), and their relative contributions to the thermal environment and thermal comfort [26,40,41]. Additionally, most of the related studies have been focused on local common coniferous or broad-leaved woody plants rather than on bamboos. Although they are herbaceous plants taxonomically, bamboos are able to form large canopies during their growth. There are abundant bamboo resources in the world, especially in China and Indonesia [42–44]. Bamboo is widely used in urban green spaces due to its diverse forms, colors and ecological characteristics, such as conserving water, improving soil quality and fixing carbon [45–47]. Furthermore, to the best of our knowledge, to date, only a few studies have investigated the effects of tall plants in winter on outdoor climate and thermal comfort, with most relevant studies focusing on hot summers. Therefore, it is necessary to conduct targeted research on the effects of bamboos on the microclimate environment and human comfort in the summer and winter seasons, respectively, to provide more data support for urban planners and policymakers in landscape planning and urban construction, as well as to bring richer mitigation strategies to the negative impacts caused by global climate change.

To provide a reference for improving the urban thermal environment by using urban greenery, this study focused on the quantitative relationships between local-scale microclimate factors, plant canopy structure and thermal comfort in summer and winter. Specifically, we investigated, evaluated and analyzed the following: (1) the changes and differences in the microclimate environment in bamboo and nonbamboo communities;

(2) the thermal comfort of the different bamboo and nonbamboo communities; and (3) the relationship between microclimate factors, thermal comfort and canopy structure of the different bamboo communities and the effect of canopy structure on the microclimate environment and the thermal comfort.

2. Methodology

2.1. Study Area and Measurement Sites

Hangzhou (29°11′~30°33′ N, 118°21′~120°30′ E), the capital of Zhejiang Province, is located in southeastern China and has a subtropical monsoon climate. It is hot in summer, cold in winter and humid throughout the year. July and August are the hottest months, with an average temperature of more than 28.4 °C, and December to January are the coldest months, with an average temperature of less than 4.3 °C [48,49]. Daylight hours in summer and winter are 6:15–18:45 and 7:00–17:45, respectively.

This study was carried out in the Bamboo Culture Park in the southwest of Lin 'an District, Hangzhou, covering an area of 70 ha (Figure 1a). It covers a high percentage of greenery, and the main vegetation consists of members of the Bambusoideae, containing 20 genera and 120 species (including varieties) of bamboo; thus, this is an essential site for studying the cultivation and application of bamboo and its ecological benefits [50]. We selected 9 different bamboo communities to carry out the experimental study and numbered them 1–9, and a patch of grass with no shade was chosen as the control check (CK). The detailed characteristics of the vegetation at these sites are shown in Table 1. To avoid the interference from other environmental factors, the measurement sites were selected to have an area of more than 900 m^2, and the ages of the bamboo communities were all similar. The distance between each site edge was more than 15 m, the distance from the road was over 15 m, and there was no water source within 30 m.

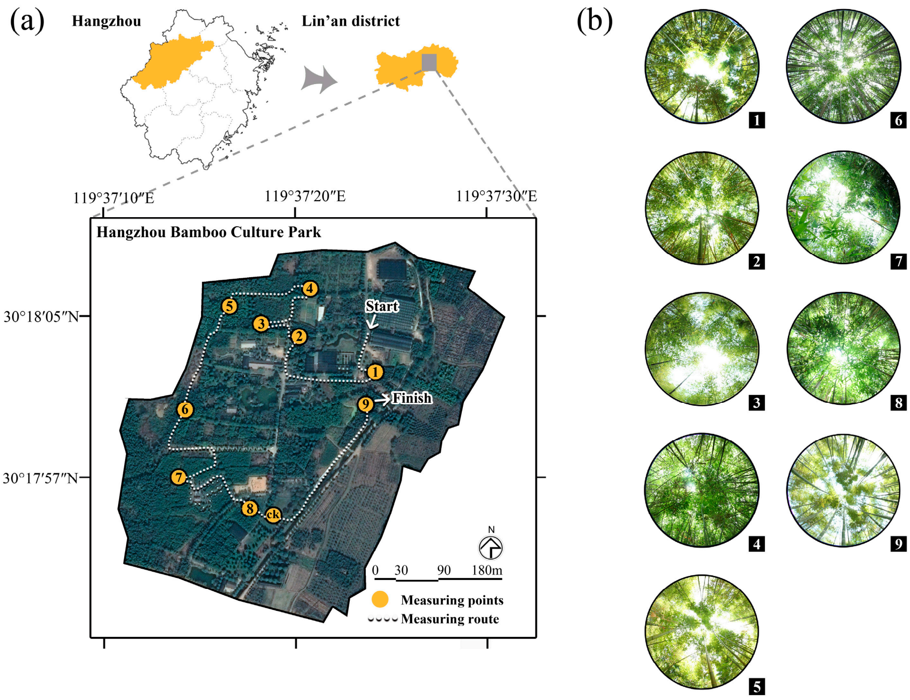

Figure 1. Study site and characteristics of measurement points. (**a**) Location of the site and (**b**) fisheye photos of nine bamboo communities.

Table 1. Structural characteristics of the bamboo communities.

No.	Bamboo Communities	Label	AH/m	DBH/cm	PD/T·m^{-2}	LAI	CC/%	SVF
1	*Phyllostachys praecox* 'Prevernalis'	PP	4.5	4.2	3.50	1.60	74.3	0.178
2	*Phyllostachys aureosulcata* 'Spectabilis'	PAS	5.3	2.0	9.20	1.35	68.2	0.204
3	*Phyllostachys nigra*	PN	4.7	1.1	9.20	1.15	62.0	0.302
4	*Sinobambusa tootsik* var. *laeta*	ST	5.0	1.8	15.80	2.61	85.1	0.145
5	*Indosasa gigantea*	IG	7.4	3.8	6.80	1.67	76.6	0.223
6	*Phyllostachys bambusoides* f. lacrima-deae	PB	7.0	3.0	6.00	1.66	73.5	0.181
7	*Oligostachyum lubricum*	OL	3.7	0.8	15.20	1.47	72.8	0.213
8	*Pseudosasa amabilis*	PA	5.0	1.9	21.00	2.32	86.7	0.145
9	*Phyllostachys heterocycla* 'Pubescens'	PH	8.9	8.3	2.00	1.33	72.3	0.263
10		CK	/	/	/	0.49	91.0	0.960

AH: Average height (m); DBH: Diameter at breast height (cm); PD: Planting density (T·m^{-2}); P: Plant; LAI: Leaf area index; CC: Canopy coverage (%); SVF: Sky view factor.

2.2. Measurement of Microclimatic Parameters and Canopy Structure Indices

We monitored microclimate factors at 10 measurement sites between 8:00 and 18:00 every two hours from July 25 to 27 and December 8 to 10 in 2017, and three consecutive days of clear and windless (wind speed $\leq$2 m/s) weather were measured in each season. The factors monitored include air temperature (AT), relative humidity (RH) and light intensity (LI). The AT and RH were measured with a temperature and humidity sensor (Tes-1365, Taipei, Taiwan; TA/RA accuracy = $\pm$0.5 °C/$\pm$10%–95%) at a height of 1.5 m above ground level. A digital light meter (Tes-1332A, Taipei, Taiwan) was used for LI measurements. The central position of each community was set as the measurement site, and four readings were collected in the east, south, west and north directions at 5 m from the center.

Furthermore, we measured the canopy structure characteristics, including LAI, CC and SVF, of the bamboo communities and the CK at the same measurement sites (Table 1). Fisheye photos of communities were taken by fisheye lens combined with digital camera (Canon EOS 6D Marked II, Sigma 8 mm Circular Fisheye Lens, Sigma Co., Ltd., Koriyama, Japan), and the results were obtained by taking the photos into HemiView 2.1 SR5 Plot Canopy Analysis System (Delta-T Devices Ltd., Burwell, UK) for calculation (Figure 1b). The above data were obtained by averaging the measured values at each site. Since bamboo is an evergreen plant, the data for summer and winter were the same.

2.3. Thermal Comfort Index

After completing the monitoring of microclimate factors and canopy characteristics of the bamboo communities at the sample sites, we also calculated the human thermal comfort at these sites. Human thermal comfort was defined as "the state of mind that expresses satisfaction with the thermal environment" [51]. It is influenced by environmental factors, such as air temperature, air humidity, wind speed and sun radiation but also by individual factors, such as human clothing and physical characteristics [10,52–54]. There are dozens of indices for evaluating human comfort, and this study used the temperature–humidity index (THI), an index provided by the National Weather Service in 1959, to assess the combined effects of temperature and humidity on heat stress levels. It is still widely used to assess the thermal effects on the surrounding environment [55–57]. According to the index, the degree of heat discomfort is graded into eight levels and the THI can be calculated as follows (Figure 2) [58]:

$$\mathrm{THI}\ (^{\circ}\mathrm{C}) = \mathrm{AT} - (0.55 - 0.0055\mathrm{RH})(\mathrm{AT} - 14.5) \quad (1)$$

where THI is the temperature–humidity index, AT is the air temperature (°C) and RH is the relative humidity (%).

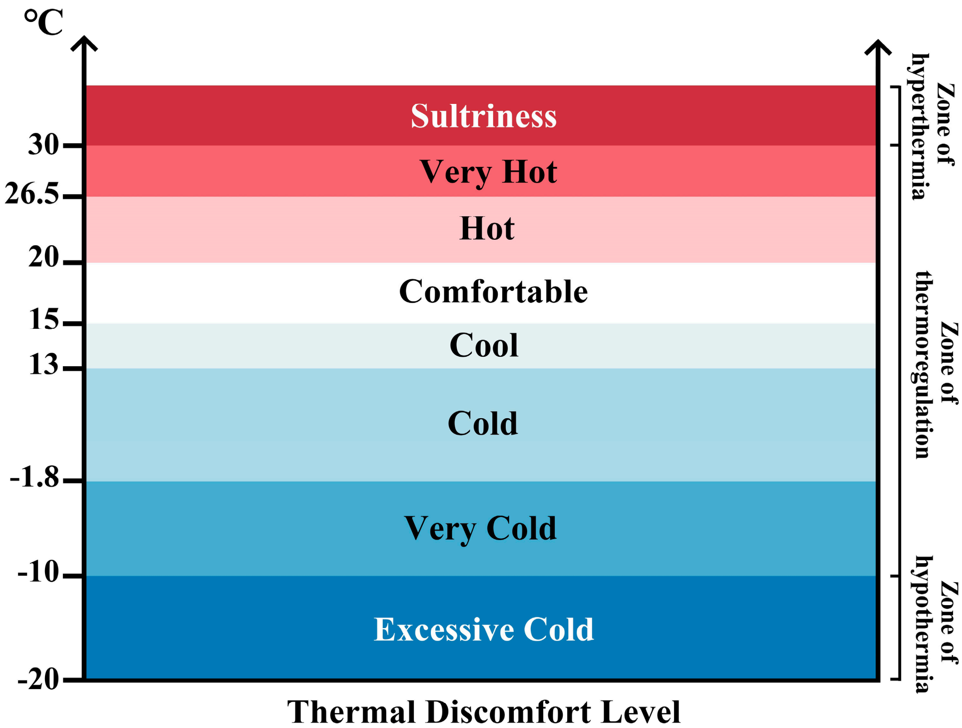

Figure 2. Division of THI and thermal discomfort level.

2.4. Data Processing and Analysis

To analyze and compare the changes in microclimate factors and THI at different times in different communities, the data were calculated as follows:

$$
\begin{gathered}
\text{Air temperature difference } (^\circ\text{C}): \text{ deltaAT} = \text{ATck} - \text{ATbc} \\
\text{Air temperature change rate } (\%): \text{ deltaAT\%} = (\text{ATck} - \text{ATbc})/\text{ATck} \times 100\% \\
\text{Relative humidity difference } (\%): \text{ deltaRH} = \text{RHck} - \text{RHbc} \\
\text{Relative humidity change rate } (\%): \text{ deltaRH\%} = (\text{RHck} - \text{RHbc})/\text{RHck} \times 100\% \\
\text{Light intensity difference } (10^4): \text{ deltaLI} = \text{LIck} - \text{LIbc} \\
\text{Light intensity change rate } (\%): \text{ deltaLI\%} = (\text{LIck} - \text{LIbc})/\text{LIck} \times 100\% \\
\text{THI difference } (^\circ\text{C}): \text{ deltaTHI} = \text{THIck} - \text{THIbc} \\
\text{THI change rate } (\%): \text{ deltaTHI\%} = (\text{THIck} - \text{THIbc})/\text{THIck} \times 100\%
\end{gathered}
$$

where ck and bc represent the control site in the unshaded open space and the sample site in the bamboo community, respectively.

The coefficient of variation and daily mean of canopy structure characteristics (LAI, CC and SVF), microclimate factors (AT, RH and LI) and THI were analyzed by one-way analysis of variance (ANOVA), and a multiple comparison was conducted using Duncan's method ($p < 0.05$). Pearson correlation analysis ($p < 0.05$) was used to examine the relationships and trends between canopy structural characteristics (LAI, CC and SVF), microclimate factors (AT, RH and LI) and THI. Using simple linear regression methods, the relative contribution of different canopy structural characteristics to microclimate factors and their contribution to THI was further quantified. Analysis of variance and correlation was performed using SPSS software (IBM SPSS Statistics 24.0, Armonk, NY, USA). Normality test and homogeneity of variance test were carried out in statistical analysis in this study.

3. Results and Analysis

3.1. Quantitative Analysis of Microclimatic Characteristics

3.1.1. Air Temperature

According to Figure 3a,b, the daily mean AT of the nine bamboo communities and the CK showed a single peak trend during the daytime, with an ascending and then descending trend. During the daytime in summer (Figure 3a), the highest AT of the day occurred between 12:00 and 14:00, and the AT in the bamboo communities was generally lower than that in the CK. Among the nine bamboo communities, the minimum average AT and the maximum deltaAT were found in the PA community, while the maximum average AT and minimum deltaAT were found in the PN community (Table 2).

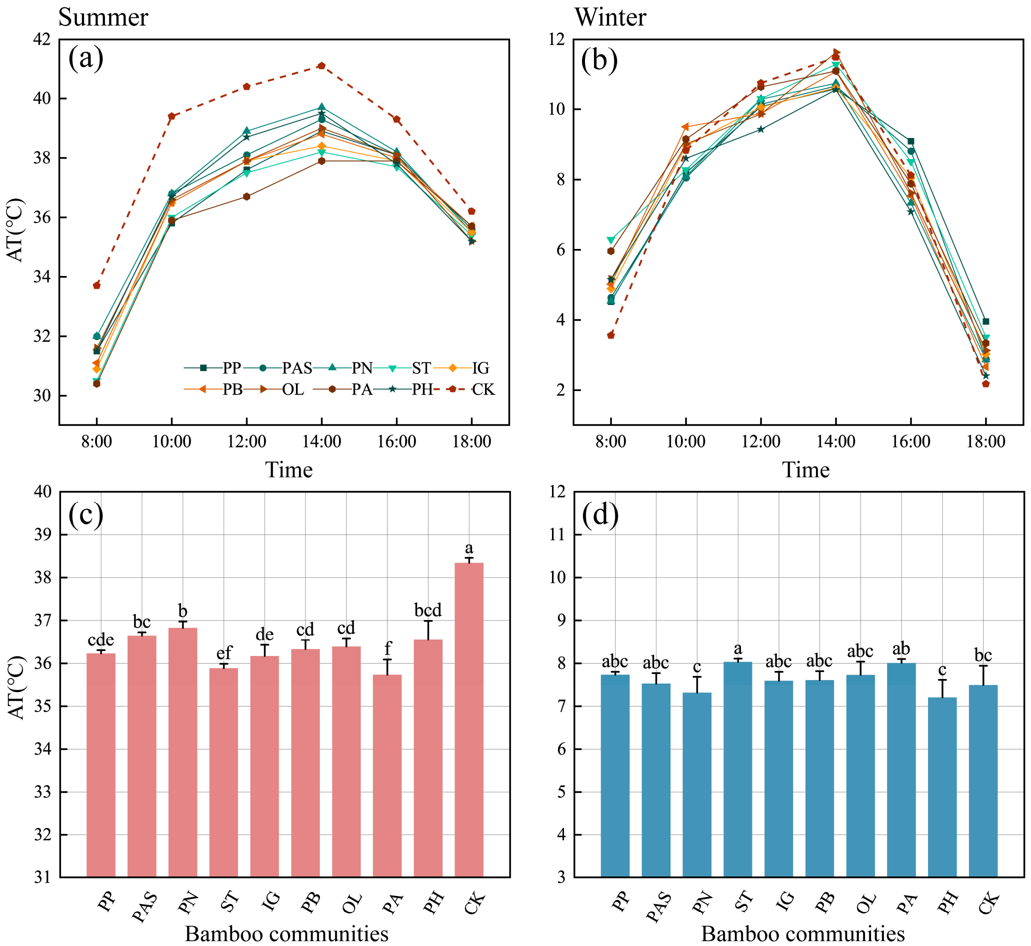

Figure 3. Diurnal changes in AT of the different bamboo communities and the CK in summer (**a**) and winter (**b**) and comparison of daily mean AT in summer (**c**) and winter (**d**). The lowercase letter above the daily mean AT represents multiple comparisons of the different communities (Duncan's method, $p < 0.05$).

Similar to daytime in summer, during the daytime in winter (Figure 3b), the daily average AT still tended to decrease after rising, and the highest AT of the day also occurred between 12:00 and 14:00. Before sunrise, the daily mean AT of the CK was low, and increased gradually after sunrise, from 12:00–16:00, to be slightly higher than that of the bamboo communities, but after sunset, the CK's AT gradually decreased to its lowest value. Among the nine bamboo communities, the daily mean AT was higher than that of the CK except for in the PN and PH communities (average low 0.2 and 0.3 °C, respectively), and the maximum difference in deltaAT was 0.5 °C in the ST and PA communities (Table 2). The standard errors of AT of different bamboo communities at different time points in data analysis are shown in Appendix A (Table A1).

The one-way ANOVAs performed on the daily mean AT of the different bamboo communities and the CK showed that differences were significant in summer (with a mean deltaAT of 2.0 °C) but not significant in winter (with a mean deltaAT of 0.2 °C) (Duncan's multiple comparisons, $p < 0.05$) (Figure 3c,d). The results indicated that bamboo has a remarkable cooling effect during the daytime in summer, but only ST has strong warming effects in winter. Generally, the influence of bamboos on AT in summer was significantly greater than that in winter, and the variability among the nine bamboo communities was not significant except for ST and PA in summer (Figure 3c,d, Table 2).

Table 2. Air temperature, relative humidity and light intensity in different communities.

Season	Community	AT/°C				RH/%				LI/lx			
		X	α	β	γ	X	α	β	γ	X	α	β	γ
Summer	PP	36.2	38.9	7.4	5.5	54.8	73.9	30.1	7.6	969	1468	1032	98.3
	PAS	36.6	39.3	7.3	4.4	54.0	72.0	28.4	6.0	1277	2457	1893	97.7
	PN	36.8	39.7	7.8	4.0	54.8	72.6	28.8	7.5	2519	4013	3134	95.5
	ST	35.9	38.2	7.8	6.4	58.9	77.3	29.4	15.5	75	224	203	99.9
	IG	36.2	38.4	7.6	5.7	55.9	75.1	29.3	9.7	909	1637	1453	98.4
	PB	36.3	38.8	7.7	5.2	56.9	76.1	29.8	11.7	584	979	795	99.0
	OL	36.4	39.0	7.4	5.1	54.5	72.2	28.1	6.9	2012	3715	3232	96.4
	PA	35.7	37.9	7.5	6.8	58.6	77.5	30.9	15.0	229	378	340	99.6
	PH	36.6	39.5	8.0	4.7	55.9	74.5	30.7	9.6	1238	1777	1481	97.8
	CK	38.3	41.1	7.5	/	50.9	64.0	22.6	/	55,880	92,104	81,784	/
Winter	PP	7.7	10.6	7.0	3.3	51.7	77.8	49.0	11.5	437	1061	1061	98.3
	PAS	7.5	10.7	8.1	0.6	54.4	79.0	50.8	6.9	1126	2734	2734	95.5
	PN	7.3	10.7	7.9	−2.4	56.2	80.3	46.5	3.7	1171	2884	2884	95.3
	ST	8.0	11.3	7.8	7.2	49.6	80.5	58.3	15.0	160	368	368	99.4
	IG	7.6	10.6	7.6	1.5	51.2	79.8	51.1	12.3	355	865	865	98.6
	PB	7.6	11.1	8.4	1.7	51.6	82.1	55.2	11.7	486	1495	1495	98.1
	OL	7.7	11.6	8.5	3.3	53.4	78.6	50.4	8.6	462	1249	1249	98.2
	PA	8.0	11.1	7.7	7.0	48.4	75.6	50.5	17.2	162	381	381	99.4
	PH	7.2	10.6	8.1	−3.8	52.4	79.2	52.5	10.2	537	1424	1424	97.9
	CK	7.5	11.5	9.6	/	58.4	83.7	47.8	/	25,155	37,290	37,290	/

AT: Air temperature; RH: Relative humidity; LI: Light intensity; X: Diurnal mean value; α: Maximum value; β: Difference value; γ: Effect value (deltaAT%; deltaRH%; deltaLI%).

3.1.2. Relative Humidity

The variation trend in the daily mean RH of the different bamboo communities and the CK was opposite that of AT in summer and winter (Figure 4a–d). During summer days, the daily mean RH was highest at approximately 8:00, lowest from 14:00–16:00, and slowly rose from 16:00–18:00. Compared to the RH of the bamboo communities, the average daily RH of the CK was significantly lower from 8:00–16:00 but increased rapidly at 18:00, approaching the RH of the bamboo communities (Figure 4a). During the experiment, the maximum of the average daily RHs and deltaRHs were found in the ST community, while the minimum of the average daily RHs and deltaRHs were found in the PAS community (Table 2).

During the daytime in winter, the highest daily mean RH value was found at approximately 8:00 (Figure 4d). In general, the trend of daily mean RH was consistent with that of summer, and the CK's average daily RH was consistently slightly higher than that of the bamboo communities. During the experiment, the minimum average daily RH and the maximum deltaRT were in the PA community, and the maximum average daily RH and the minimum deltaRH were in the PN community (Table 2). The standard errors of RH of different bamboo communities at different time points in data analysis are shown in Appendix A (Table A1).

One-way ANOVAs of the daily mean RH of the nine bamboo communities and the CK showed significant differences between them in summer and winter (Figure 4c,d). This indicates that bamboo has a significant effect on atmospheric humidity during these two seasons. Moreover, differences among the different bamboo communities were more significant in summer than in winter (Figure 4 and Table 2).

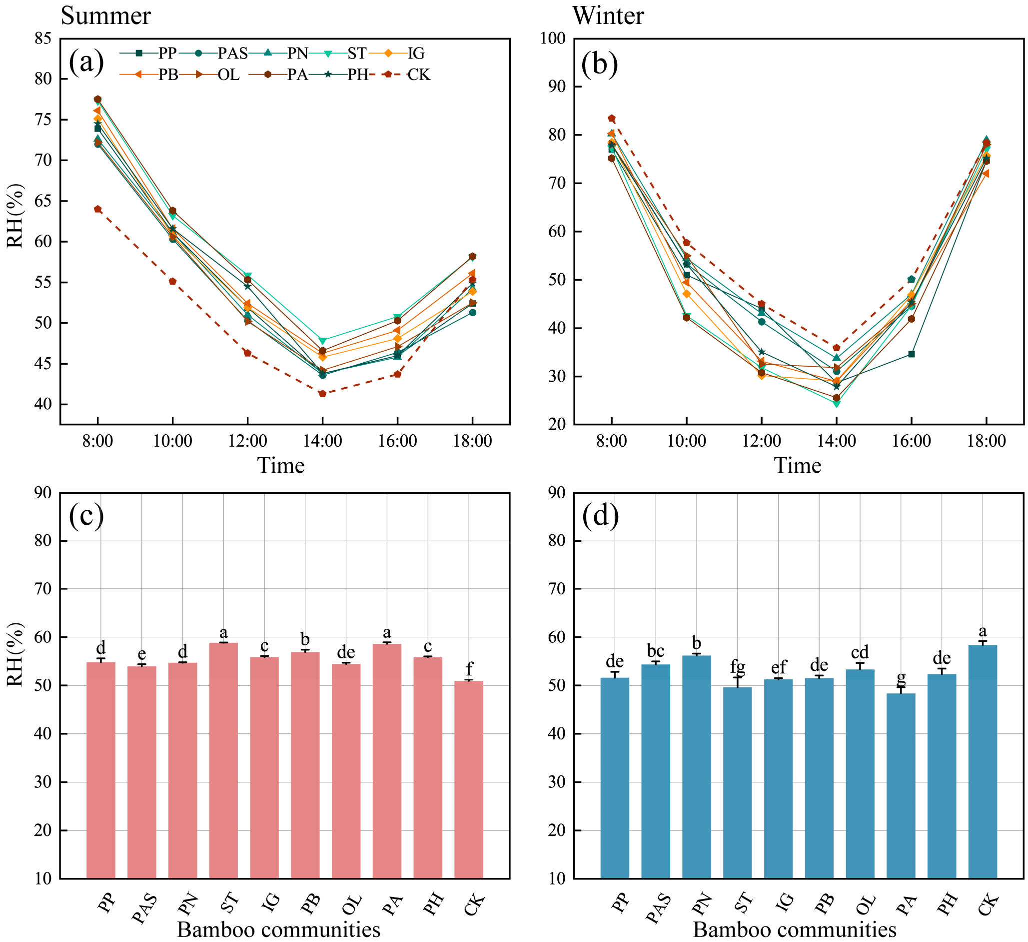

Figure 4. Diurnal changes in RH of the different bamboo communities and the CK in summer (**a**) and winter (**b**) and comparison of daily mean RH in summer (**c**) and winter (**d**). The lowercase letter above the daily mean RH represents multiple comparisons of the different communities (Duncan's method, $p < 0.05$).

3.1.3. Light Intensity

Figure 5a,b show that the diurnal mean LI variation in the bamboo communities and the CK was unimodal during summer and winter, with the peak usually occurring at approximately 12:00. During the daytime in summer, the LI of the CK was apparently higher than that of the bamboo communities; it increased rapidly after 8:00 and decreased at a greater rate after 12:00 (Figure 5a). In comparison with the CK, the deltaLI of the bamboo communities ranged from 53,361 to 55,805 lx, and the deltaLI% ranged from 95.4% to 99.9%, with a mean of 98.0%. In the nine bamboo communities, the maximum deltaLI was in the ST community, and the minimum value was in the PN community (Figure 5 and Table 2).

The trend of the average daily LI on winter days was basically the same as that in summer. The LI of the CK dropped slowly from 12:00–14:00, after which it dropped dramatically, and the LIs of all the bamboo communities and the CK dropped to zero at 18:00 (Figure 5b). The deltaLI of the bamboo communities ranged from 23,983 to 24,995 lx, and the deltaLI% ranged from 95.3% to 99.4%, with a mean of 97.8%. In the nine bamboo communities, the maximum deltaLI was in the ST community, and the minimum value was in the PN community (Figure 5 and Table 2). The standard errors of LI of different bamboo communities at different time points in data analysis are shown in Appendix A (Table A1).

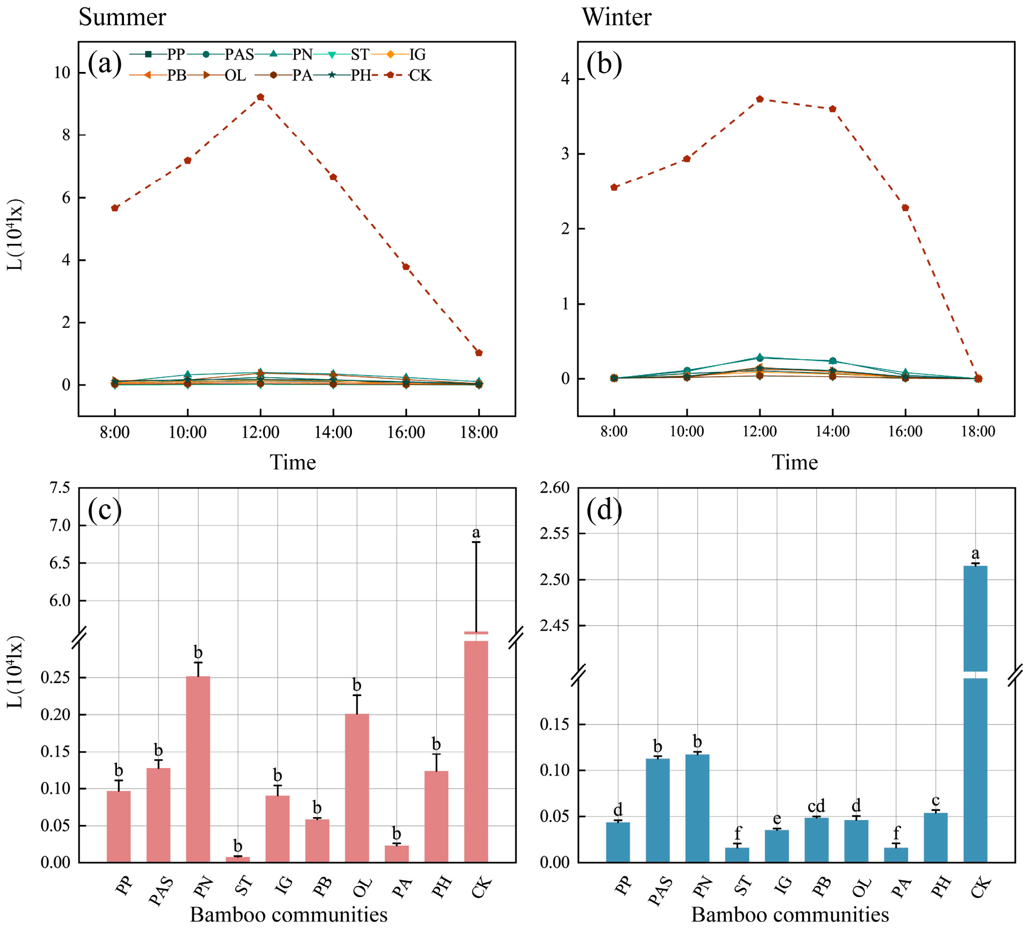

Figure 5. Diurnal changes in LI of the different bamboo communities and the CK in summer (**a**) and winter (**b**) and comparison of daily mean LI in summer (**c**) and winter (**d**). The lowercase letter above the daily mean L represents multiple comparisons of the different communities (Duncan's method, $p < 0.05$).

The results of one-way ANOVAs showed that the daily mean LIs of the bamboo communities were significantly different from those of the CK (Figure 5c,d). This indicated that bamboo significantly reduced the LI of the bamboo community. In addition, the differences among the nine bamboo communities were more significant in winter than in summer (Figure 5 and Table 2).

3.2. THI in Different Bamboo Communities and CK

The comfort levels in the bamboo communities and the CK at different time periods were calculated according to the THI formula (Table 3). During the daytime in summer, the daily average THI of bamboo communities were lower than that of CK, with a 0.7 to 1.1 °C decrease and an average decrease of 0.9 °C. In terms of discomfort ratings, the average daily THI of the bamboo communities was still in the "extremely hot" class during the daytime in summer but was closer to the "very hot" grade than the CK was. Specifically, the THIs of all the bamboo communities and the CK were below 30.0 °C only at 8:00, while only at 18:00 were the PAS, OL and PH values below 30.0 °C, which translates to people feeling "very hot" only at these times; at other times, people in these settings feel "extremely hot". During the experiment, the minimum average daily THI and deltaTHI were found in the PP community, while the maximum average daily THI and deltaTHI were found in the PN and PH communities (Table 3 and Figure 6).

Table 3. THI of different time points in different communities.

Season	Community	8:00	10:00	12:00	14:00	16:00	18:00	Average
Summer	PP	29.0	31.2	31.4	31.3	31.1	30.1	30.7 c
	PAS	29.3	31.9	31.7	31.6	31.1	30.0	30.9 bc
	PN	29.3	32.0	32.3	31.9	31.1	30.2	31.1 b
	ST	28.5	31.7	31.9	31.4	31.4	30.6	30.9 bc
	IG	28.6	31.7	31.7	31.3	31.2	30.2	30.8 bc
	PB	28.9	31.8	31.8	31.6	31.4	30.6	31.0 bc
	OL	29.0	31.8	31.5	31.5	31.2	29.8	30.8 bc
	PA	28.4	31.6	31.2	31.0	31.5	30.8	30.8 c
	PH	29.1	32.0	32.7	31.7	30.9	30.1	31.1 bc
	CK	29.9	33.3	32.7	32.5	31.6	30.9	31.8 a
Winter	PP	5.8	9.9	11.4	12.1	11.0	5.4	9.3 abc
	PAS	5.8	9.7	11.6	12.1	10.5	4.3	9.0 cdef
	PN	5.6	9.7	11.6	12.1	9.4	4.2	8.8 ef
	ST	7.3	10.2	11.9	12.6	10.3	4.9	9.5 ab
	IG	6.0	10.6	11.8	12.1	9.9	4.6	9.2 cde
	PB	6.0	10.9	11.6	12.4	9.6	4.5	9.2 cde
	OL	6.3	10.4	11.6	12.7	9.7	4.5	9.2 bcd
	PA	7.1	10.8	12.1	12.5	10.0	4.9	9.6 a
	PH	6.3	10.1	11.2	12.1	9.3	4.1	8.9 def
	CK	4.5	10.2	11.9	12.5	9.9	3.6	8.8 f

The lowercase letter behind the average value represents multiple comparisons of the different communities (Duncan's method, $p < 0.05$).

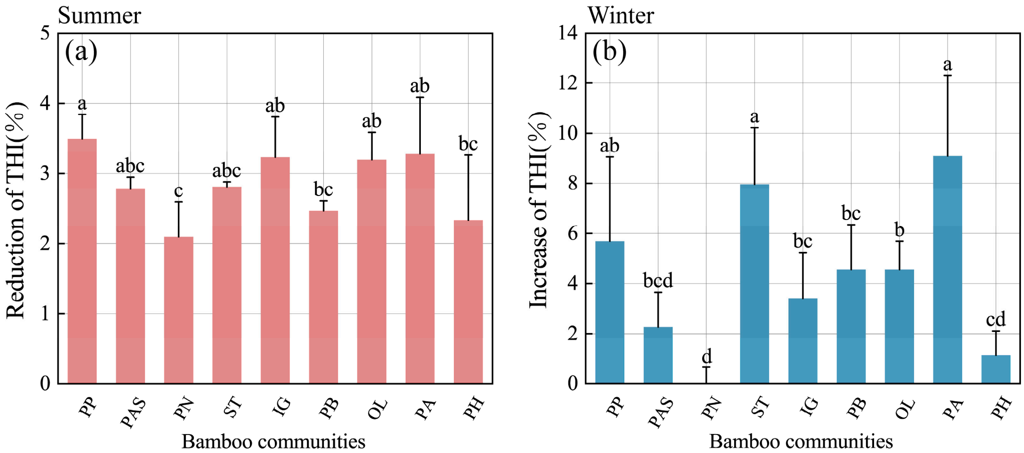

Figure 6. Comparison of deltaTHI% in the bamboo communities in summer (**a**) and winter (**b**). The lowercase letter above the change value of THI represents multiple comparisons of the different communities (Duncan's method, $p < 0.05$).

As illustrated in Table 3 and Figure 6, during the daytime in winter, the THI of the bamboo communities was slightly higher than that of the CK, and the average daily THI increased from 0.1 to 0.8 °C, with an average increase of 0.4 °C. Specifically, the average daily THI in the bamboo communities was still less than 13 °C, which was within the "cold" grade, but was more numerically close to "cool". However, it is noteworthy that during the daytime in winter, the THI of some bamboo communities was lower than that of the CK from 10:00–16:00. During the experiment, the maximum THI was in the PA community, and the minimum value was in the PN community.

The results of the one-way ANOVAs for the average daily THI of the bamboo communities and the CK showed that there were statistically significant differences between them in summer, but the differences in winter were smaller (Table 3). In general, the bamboos were effective in improving thermal comfort in summer, and in winter, most of the bamboo communities had remarkable effects. In addition, the differences in the ability to regulate

THI between bamboo communities were imperceptible in summer but more significant in winter (Figure 6).

3.3. Relationships between Microclimate Factors, THI and Canopy Structural Indices

The results of the correlation analysis of AT, RH and LI are shown in Figure 7. During the summer and during the daytime in winter, the average daily AT and RH were significantly negatively correlated. The average daily LI in summer was significantly positively and negatively correlated with AT and RH, respectively, while the reverse was observed in winter.

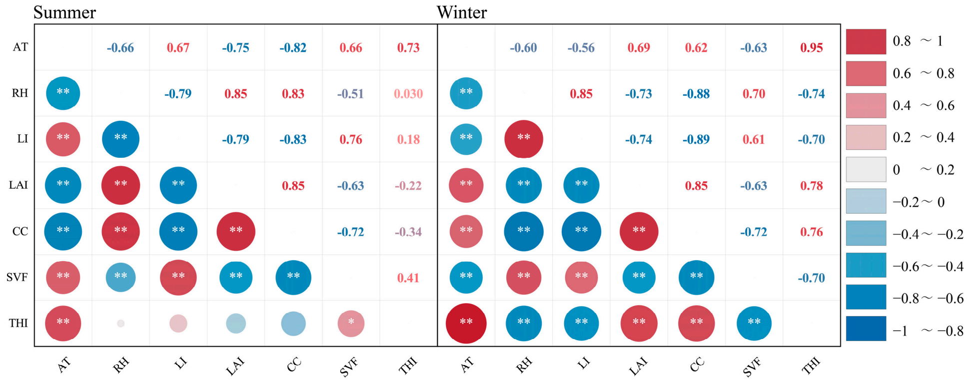

Figure 7. Correlation coefficients between microclimate factors, THI and canopy structure indices in summer and winter. * Significant at the 0.05 level; ** Significant at the 0.01 level.

During the daytime in summer, the average daily AT showed a highly significant negative correlation with LAI and CC and a highly significant positive correlation with SVF; the average daily RH displayed strong positive relationships with LAI and CC and strong negative relationships with SVF (Figures 7 and 8). In contrast to summer, in winter the average daily AT showed a highly significant positive correlation with LAI and CC but decreased with increasing SVF; the average daily RH displayed highly significant negative correlations with LAI and CC and a highly significant positive correlation with SVF in the daytime in winter (Figures 7 and 9). Furthermore, the average daily LI in the bamboo communities showed highly significant negative correlations with the LAI and CC and a highly significant positive correlation with the SVF in both seasons (Figures 7–9).

The local thermal environment is affected by many factors. In this experiment, THI was correlated with both microclimate factors and canopy structural indices (Figures 7–9). The average daily AT had a strong positive correlation with THI in both seasons and the highest correlation among all the influencing factors. During the daytime in summer, there were no significant relationships between the THI and RH, LI, LAI and CC, but THI was significantly related to the SVF. Different from the THI in summer, the THI in winter showed strong negative relationships with RH, LI and SVF and strong positive relationships with LAI and CC, of which LAI presented the highest correlation coefficient among the three indices of canopy structure.

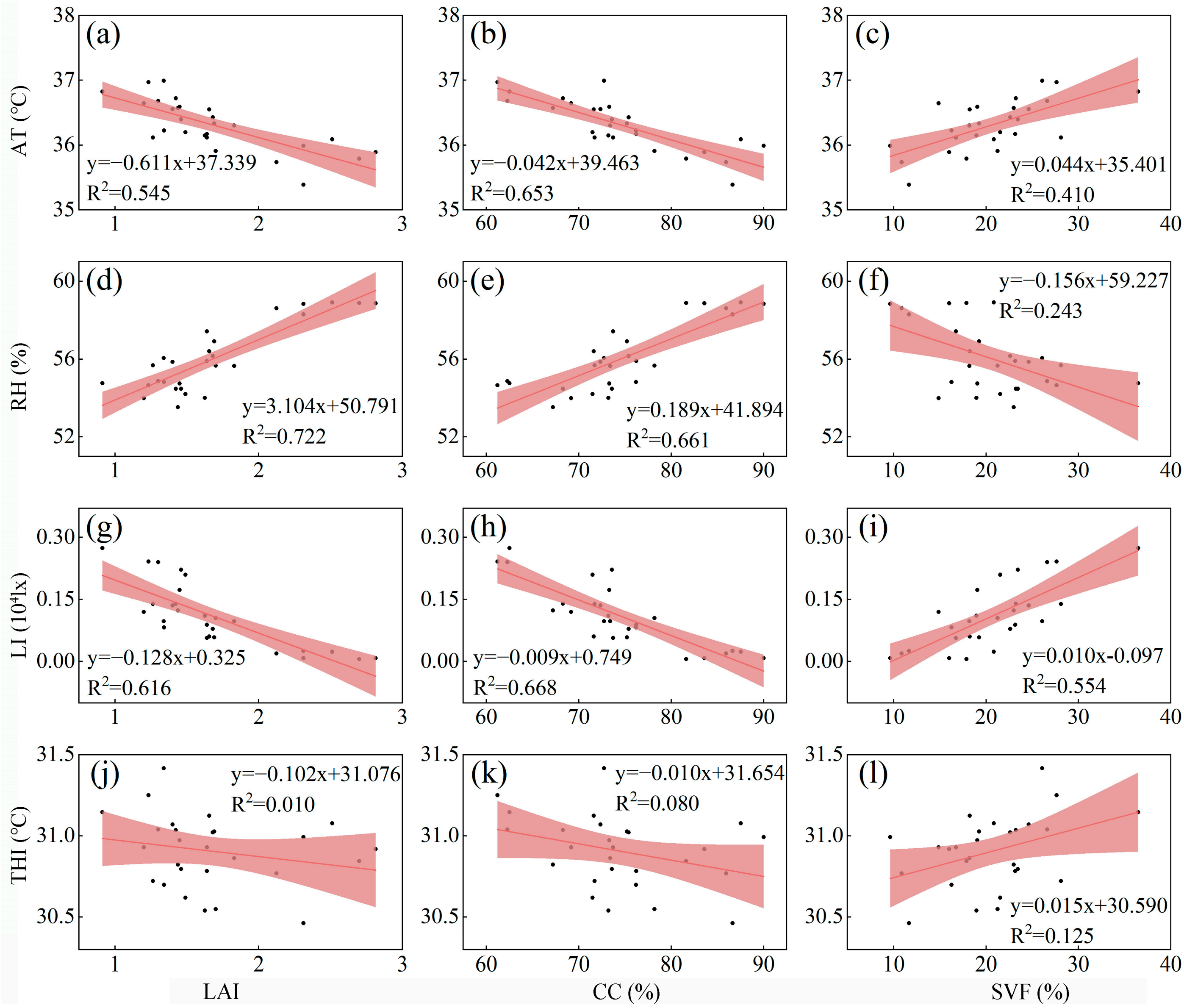

Figure 8. Regression analysis between microclimate factors, THI and the indices of bamboo community canopy structure in summer. Regression analysis between LAI (**a**), CC (**b**), SVF (**c**) and AT; regression analysis between LAI (**d**), LAI (**e**), SVF (**f**) and RH; regression analysis between LAI (**g**), CC (**h**), SVF (**i**) and LI; and regression analysis between LAI (**j**), CC (**k**), SVF (**l**) and THI.

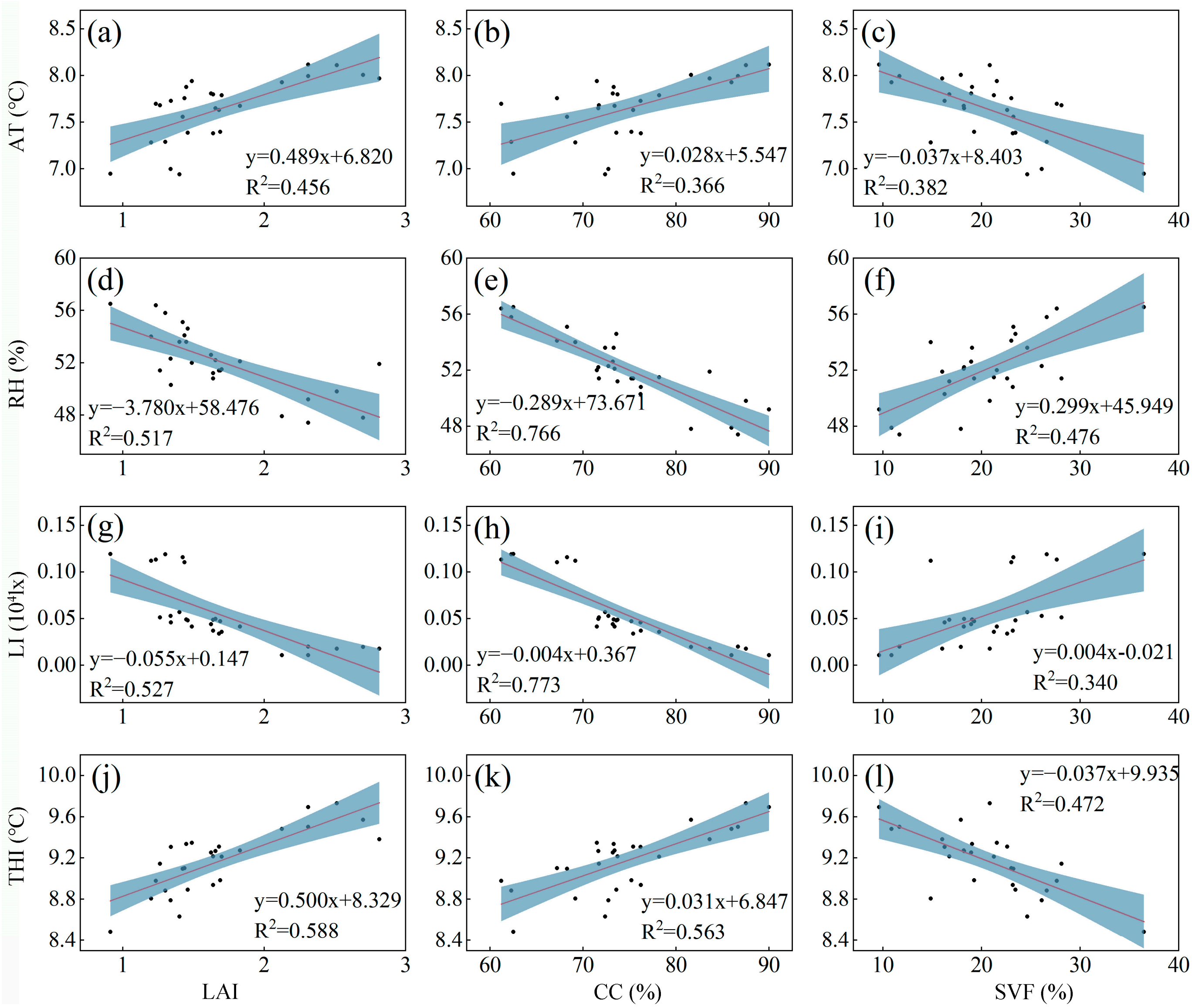

Figure 9. Regression analysis between microclimate factors, THI and the indices of bamboo community canopy structure in winter. Regression analysis between LAI (**a**), CC (**b**), SVF (**c**) and AT; regression analysis between LAI (**d**), LAI (**e**), SVF (**f**) and RH; regression analysis between LAI (**g**), CC (**h**), SVF (**i**) and LI; and regression analysis between LAI (**j**), CC (**k**), SVF (**l**) and THI.

4. Discussion

4.1. Outdoor Microclimate Comparison

Significant differences in both AT and RH between vegetated and nonvegetated areas during daytime in summer have been widely confirmed by researchers from different regions [59–64]. In the present study, we found that the nine bamboo communities differed substantially in both AT and RH during the daytime in summer compared to the CK (which was not covered by vegetation). Compared with the CK, the AT of the bamboo communities was lower, with deltaAT of 1.5 to 2.6 °C (with an average of 2.0 °C) and deltaAT% of 4.0% to 6.8% (with an average of 5.3%); in contrast, the RH was generally high, the deltaRH was from 3.0% to 7.9% (with an average of 5.1%), and the deltaRH% was from 6.0% to 15.5% (with an average of 10.0%), indicating that bamboo communities have significant cooling and humidification effects during daytime in summer. This result is consistent with the conclusions drawn from a large number of empirical studies; for instance, in exploring the effect of shade-dominated tree communities on the improvement of urban microclimate conditions, Yan et al. noted that the average daily cooling intensity of tree plant communities was 1.6 to 2.5 °C and the humidification intensity was 2.9% to 5.2% in urban green spaces [65]. In the Beijing Olympic Forest Park, the Populus tomentosa community tended to reduce the air temperature by 1.0–5.0 °C (by an average of 3 °C) and to increase the relative humidity by 4%–15% (by an average of 10%) during the daytime in summer [66]. During the daytime in winter, the RH under the nine tested bamboo communities was generally lower, and the AT was mostly slightly higher than that in the CK (except for in PN and PH), which suggested that the bamboo communities had a moisture-reducing effect and that most of them had a warming effect. Compared with CK, the deltaAT of the bamboo communities ranged from −0.3 to 0.5 °C (with an average of 0.2 °C), and the deltaAT% was from −3.8% to 7.2% (with an average of 2.0%); at the same time, the deltaRH ranged from 2.2% to 10.0% (with an average of 6.3%), and the deltaRH% was from 3.7% to 17.2% (with an average of 10.8%). Furthermore, compared with the cooling effect in summer, the warming intensity of the bamboo community was relatively low, mainly due to the low temperature in winter. In addition, this may be because the solar radiation in winter is not stronger than that in summer, so the transpiration radiation absorbed and utilized by plants is less, resulting in a negligible cooling range and a slight warming phenomenon. Analogous findings have been made in Nagoya, central Japan, as reported in a study by Hamada and Ohta, which established that vegetated areas are still warmer than nonvegetated urban areas in winter compared to summer, but the temperature range between them is narrower [67]. However, Zhang et al. concluded that in winter, greenery planting still brings temperature reduction to the surrounding environment, but the intensity of cooling is much weaker than in summer [63].

Compared with the deltaLI of the CK, the deltaLI of the bamboo communities in summer and winter ranged from 53,361 to 55,805 lx and 23,983 to 24,995 lx, with mean values of 54,790 and 24,611 lx, and the deltaLI% was 98.0% and 97.8%, respectively. The results demonstrated the remarkable shading ability of the bamboo communities. In fact, approximately 50% of the incoming horizontal solar radiation is visible light, and a monolayer of plant leaves can absorb 80% and reflect 10% of visible light through shading and reflecting effects [68,69]. In a study that occurred in Shenzhen, Zhang et al. proposed that in summer and winter, the solar radiation intensity of the plant community was only 6.0% and 6.6% of that of the open field, respectively [63].

4.2. Human Thermal Comfort Comparison

A large number of empirical studies and numerical simulations have demonstrated that vegetation generally has a regulating effect on human thermal comfort [18,24,70]. For example, in the residential area of Freiburg in southwestern Germany, Lee et al. applied the ENVI-met model to simulate four different urban green coverage scenarios and noted a maximum reduction in PET of 17.4 K for trees on grasslands and only 4.9 K for grasslands [70]. According to the results of one-way analysis of variance (ANOVA), we found that most bamboos were capable of significantly improving thermal comfort, and the smaller deltaAT led to less variability in winter than in summer. However, from the evaluation level, the THI is still at the "extremely hot" level in summer and at the "cold" level in winter. Compared with the conclusions some researchers have reached, the improvement effect is not obvious. Lee et al. summarized the results of previous mitigation studies and noted that daytime PET in the canopy was reduced by 16 K compared with conditions in which there were no trees [71]. This may be explained by the fact that the index evaluating thermal comfort (THI) used in this experiment does not take into account the effects of radiation and wind, so it is easy to underestimate the improvement effect of bamboo on thermal comfort. Compared with THI, common indicators such as PET and predicted mean vote (PMV), also consider radiation, wind and individual factors, which may prompt a large number of researchers to use these more practical and applicable evaluation indicators [57,72]. In this experiment, higher thermal discomfort in some bamboo communities appeared from 10:00–16:00 in winter, presumably because at midday in winter, solar radiation generated more heat, increased AT and enhanced human thermal comfort to some extent. Instead, compared to the area without vegetation cover, the evergreen plant community screened a large amount of solar radiation by shading [41,72].

4.3. Effect of Canopy Structure on Microclimate and Thermal Comfort

During this experiment, the effects of the bamboo communities on AT, RH and LI differed compared to the effect of the CK. In summer and winter, the microclimate regulation intensity of ST and PA was larger, and that of PN and PH were relatively smaller, which could be closely linked to the canopy structure of the different bamboo communities. During the daytime in summer, ST and PA had higher effect rates (deltaAT% were 6.4% and 6.8%, deltaRH% were 15.5% and 15.0%, deltaLI% were 99.9% and 99.6%, respectively), their LAI were 2.61 and 2.32, CC were 85.1% and 86.7%, respectively, and SVF was 0.145. Therefore, LAI, CC and SVF significantly affected deltaAT, deltaRH and deltaLI. de Abreu-Harbich et al., in their research on the impacts of planting and tree species on human comfort, reached a similar conclusion that canopy characteristics influence ambient temperature by affecting the attenuation function of plants on solar radiation, with a smaller SVF and higher plant area index, producing relatively greater tree cover and a stronger cooling effect [25]. Peters and McFadden found that trees possess a larger leaf area and canopy and consequently provide a greater cooling effect than open lawns provide [73]. The bamboo canopy absorbs most of the solar radiation, and the unabsorbed part causes the temperature to rise, so the higher the LAI and CC are, the smaller the SVF is, and the weaker the radiation is that reaches the bamboo community, so the temperature increases less. Meanwhile, with the higher LAI, more water vapor was generated by transpiration, while the enhancement of the CC of the bamboo community led to the difficulty of dissipation and increased the relative humidity of the bamboo community. Similar to the daytime in summer, in winter, ST and PA had higher effect rates (deltaAT% were 7.2% and 7.0%, deltaRH% were 15.0% and 17.2%, respectively, and deltaLI% was 99.4%), their LAI were 2.61 and 2.32, CC were 85.1% and 86.7%, respectively, and SVF was 0.145. In other words, the higher the LAI is, the higher the CC is and the lower the SVF of the bamboo community is, the higher the AT is that is obtained. This finding was attributed to the relatively weak solar radiation in winter, which produced less heat. When the LAI was higher, the plant leaves generated more heat by absorbing solar radiation, while the increase in CC offered a relatively stable and warming environment. The plant canopy exerts a cooling effect on the environment in the bamboo communities through shading and evapotranspiration during the midday hours when solar radiation is stronger, resulting in a slightly lower AT in the bamboo communities than in the CK. In addition, lower temperatures in winter brought about a reduction in evapotranspiration within the bamboo community, causing a relatively lower RH [21]. Furthermore, bamboo communities with greater LAI and CC strengthened the absorption and reflection of solar radiation, resulting in low LI reaching within the interior of the bamboo community. In summary, the reflection and absorption effects of plant leaves on solar radiation are mainly related to leaf characteristics and canopy coverage. This was similar to the conclusion reached by Irmak et al., who noted that the canopy structure of the tree reflected this light from the sun back before converting it into heat [74]. In terms of these indices, LAI and CC contributed more to the improvement of microclimate. Hardwick et al. also reached a similar conclusion: in Malaysia, for every 1 m^2 m^{-2} decrease in LAI, the average daily maximum AT increased by 2.45 °C [75].

In this study, most of the bamboo communities improved human comfort in both seasons. The difference in the bamboo communities in summer was small, while in winter, PA had the best improvement effect, and PN showed almost no change. This can be explained by different canopy structures. The conclusion was similar to that reached by Taleghani, who stated that the shading effect of trees enhances human comfort, and that this effect is intimately related to the characteristics of trees, including height and canopy [76]. Chow et al. insisted that vegetation canopy characteristics are an important factor affecting outdoor thermal comfort by affecting wind and sunshine [39]. In addition, Morakinyo et al. believed that LAI is one of the most important factors to improve daytime thermal comfort [26]. Indeed, during the daytime in summer, the degree of deltaAT determined the magnitude of variation in THI, and plant canopy structure affected THI indirectly by influencing AT owing to the significant relationship between AT and canopy structure characteristics. In the winter, the differences among PAS, PH, PN and the CK were not significant, which may be related to the weaker solar radiation in winter and the smaller deltaAT between the bamboo communities and CK.

4.4. Bamboo Species Selection in Urban Green Spaces and Future Research

We investigated the effect of bamboo on outdoor microclimate and thermal comfort in summer and winter seasons and quantified the mechanism of the effect of LAI, CC and LI on them. In summary, the magnitude of the effect of canopy structure on improving the thermal environment and thermal comfort varied among bamboo species; for instance, the ST and PA communities with higher LAI and CC were more beneficial in improving the thermal environment and thermal comfort in both seasons, while the effect of the PN and PH communities was relatively small. These findings provide theoretical support for future bamboo species selection in urban green space planning and construction. Notably, in addition to AT and RH, wind speed and thermal radiation were also primary indicators affecting human thermal comfort [52,57,77]. This experiment did not exclude wind speed and thermal radiation, which may have a certain impact on the calculation results of thermal comfort. Therefore, further research will need to consider more factors and, in addition, the time dimension will also need to be extended, such as at night, including an assessment of the changing characteristics of temperature and humidity and thermal comfort provided by the bamboo communities. Furthermore, this paper focused on the related reports on bamboos, and subsequent research can consider comparisons with other plants to explore their similarities and differences, since bamboo plants have some unique characteristics, such as leaves being more layered and the pattern of leaf fall for most bamboos being semideciduous [42]. Moreover, the canopy structure and planting density are also different from those of other trees [78].

5. Conclusions

The effects of the microclimatic environment in nine bamboo communities and the CK in Hangzhou were compared through field measurements. The relative contributions of canopy structural characteristics to the outdoor microclimatic and thermal comfort were quantified. We reached the following conclusions: (1) AT under bamboo communities decreased by 1.5 to 2.6 °C during the daytime in summer and increased from −0.28 to 0.54 °C during the winter daytime; (2) RH increased by 3.0% to 7.6% during the daytime in summer and decreased from 2.2% to 10.0% during the winter daytime; and (3) LI decreased by 95.4% to 99.9% and 95.3% to 99.4% compared with CK (grass with no shade) in the park. Among the different bamboo communities, *Sinobambusa tootsik* var. *laeta* (ST) and *Pseudosasa amabilis* (PA) had better effects on improving microclimate and thermal comfort, so the construction of urban green spaces in the same area could increase the allocation ratio of these two types of the bamboo communities. In contrast, the effects of *Phyllostachys nigra* (PN) and *Phyllostachys heterocycla* 'Pubescens' (PH) were relatively small.

The results of this study confirmed the regulation of canopy structure on outdoor microclimate and thermal comfort in summer and winter. LAI and CC had the greatest impact on the microclimate environment, while AT made the greatest contribution to thermal comfort. The microclimate benefits of bamboo can provide a reasonable choice of bamboo species for different application environments, and provide a more effective way to alleviate urban climate problems by using the ecological benefits of urban green space.

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Visualization, H.Y.; Writing—original draft, X.N.; Writing—review and editing, R.W., N.W., K.W., H.Y. and T.M. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. The standard errors of AT, RH and LI of different bamboo communities at different time points.

Category	Season	Community	Time					
			8:00	10:00	12:00	14:00	16:00	18:00
AT	Summer	PP	0.25	0.95	0.05	0.01	0.01	0.77
		PAS	0.05	0.39	0.40	0.30	0.08	0.52
		PN	0.24	0.23	0.24	0.21	0.15	0.52
		ST	0.35	0.00	0.33	0.00	0.09	0.48
		IG	0.53	0.97	0.05	0.15	0.16	0.09
		PB	0.18	0.78	0.21	0.10	0.53	0.51
		OL	0.12	0.47	0.66	0.21	0.05	0.10
		PA	0.51	0.50	0.50	0.11	0.34	0.15
		PH	0.45	0.49	0.77	0.53	0.23	0.18
		CK	0.45	0.77	0.14	0.56	0.56	0.25
	Winter	PP	1.14	1.24	1.19	1.20	0.50	0.59
		PAS	2.08	1.00	1.35	1.59	0.28	0.81
		PN	1.79	0.26	1.59	1.77	1.19	0.12
		ST	1.53	0.88	0.90	1.64	0.69	0.34
		IG	2.00	0.92	1.22	1.32	0.73	0.56
		PB	1.97	0.33	0.42	1.72	1.13	1.01
		OL	1.54	0.37	0.27	1.24	1.33	1.17
		PA	1.37	1.33	1.11	1.56	1.06	1.05
		PH	1.15	0.93	0.89	1.77	1.19	0.90
		CK	1.52	0.50	1.43	1.49	1.26	0.83
RH	Summer	PP	1.93	2.11	1.77	0.76	0.58	1.05
		PAS	1.28	0.45	0.17	0.36	0.10	0.47
		PN	0.02	0.58	0.50	0.40	0.30	0.20
		ST	0.72	1.23	0.29	0.00	0.58	1.24
		IG	0.73	0.68	0.73	0.53	0.42	0.16
		PB	0.73	0.43	0.26	1.04	1.46	1.99
		OL	0.05	0.11	0.29	0.23	0.59	0.70
		PA	1.20	1.24	0.46	0.41	0.25	0.78
		PH	0.81	0.44	1.17	0.76	0.58	1.24
		CK	0.33	0.08	0.72	0.33	0.26	2.29
	Winter	PP	4.32	1.85	6.06	1.53	1.68	0.85
		PAS	3.07	2.05	10.97	5.90	2.54	0.46
		PN	3.80	2.70	3.33	3.27	5.06	2.68
		ST	2.30	1.20	11.53	0.82	11.61	7.74
		IG	5.60	1.44	3.19	2.04	1.46	1.99
		PB	10.97	1.76	13.76	1.15	0.78	1.12
		OL	1.83	0.14	8.07	2.04	0.75	3.03
		PA	2.20	1.31	7.78	1.24	4.61	2.47
		PH	5.57	2.17	10.88	0.95	2.25	2.25
		CK	8.64	1.10	3.92	1.65	3.99	1.05

Table A1. *Cont.*

Category	Season	Community	Time					
			8:00	10:00	12:00	14:00	16:00	18:00
LI	Summer	PP	153.15	173.08	355.58	217.83	272.90	168.70
		PAS	140.00	6.90	652.98	57.10	275.86	156.78
		PN	572.55	359.95	167.01	1121.35	565.60	415.78
		ST	11.26	15.39	38.76	26.22	11.10	4.15
		IG	115.82	492.30	308.82	441.54	154.25	113.10
		PB	11.93	213.62	69.01	180.41	284.25	47.22
		OL	675.67	176.73	560.57	252.88	769.17	273.72
		PA	52.06	194.04	55.98	90.97	29.46	8.11
		PH	243.67	318.28	239.21	548.18	57.52	39.96
		CK	16638.73	36048.09	12601.10	2241.87	8289.48	1878.36
	Winter	PP	16.52	200.27	196.65	213.95	29.26	0.00
		PAS	14.04	327.41	83.33	75.29	44.70	0.00
		PN	14.56	286.26	256.44	238.54	331.57	0.00
		ST	9.82	54.97	107.03	98.83	37.85	0.00
		IG	15.85	159.35	39.40	58.92	77.21	0.00
		PB	13.65	173.81	245.54	130.59	44.61	0.00
		OL	5.02	116.84	138.95	56.42	90.00	0.00
		PA	4.86	38.02	114.39	110.43	38.87	0.00
		PH	5.01	155.99	94.03	194.30	79.13	0.00
		CK	1273.89	1736.57	1364.29	686.86	1359.04	0.00

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