

## Microclimate regulating functions of urban forests in Changchun City (north-east China) and their associations with different factors

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Microclimate regulating functions of urban trees and their associations with environmental factors and tree-growth characteristics are important for management and ecological evaluations. In this study, a total of 637 trees distributed in the Changchun urban region (ca. 400 km<sup>2</sup>, northeastern China) were sampled in four different types of urban forests (AF: affiliated forests; RF: roadside forests; LF: landscape and relaxation forests; EF: ecological welfare forests). Tree growth-related parameters and environmental factors (inside and outside the forest) were simultaneously measured, and location-dependent differences in shading, cooling and humidifying effects were assessed, along with their associations with the measured variables. We found that urban forests in Changchun reduced the incident sunlight by 74-86% and increased air relative humidity by 3-7%, on average. Air, soil, and upper-canopy temperatures were decreased approximately by 3 °C, <1 °C and 1 °C, respectively, showing a 3-dimensional cooling effect of urban forests on both air and soil. Shading, cooling and humidifying effects significantly differed among the four forest types, with AF stands showing the highest comprehensive scores for all the microclimate regulation functions. Regression analyses and redundancy analysis revealed that urban forests had much stronger effect in terms of microclimate regulation at sunny days with high temperature, and low air humidity. In general, stands with larger trees showed the higher regulating functions, regardless of the stand structure and composition. The results of this study may help urban forest management and planning aimed at maximizing their ecological services.

**Keywords:** Urban Forest Types, Shading Effect, Cooling Effect, Humidifying Effect

### Introduction

The main functions of urban forests is to create favorable habitats for biological survival and provide excellent working, living and relaxing environment for urban residents (Wu et al. 2007, Huang et al. 2008, Lin et al. 2010, Panno et al. 2017). So far, studies on environmental benefits of urban forests have mostly focused on reducing urban heat island effect (Bao et al. 2001, Qin et al. 2006), comparing the cooling effect of different tree species and community types (Wu et al. 2008, Bowler et al. 2010, Liao et al. 2012), exploring their rela-

tions with biodiversity and trees growth (Marziliano et al. 2013, Pesola et al. 2017) or investigating the physiological mechanisms like photosynthesis and leaf transpired water loss (Zheng et al. 2008, Xu et al. 2015), in order to provide suggestions for urban forest management. Remote sensing technology and the corresponding model inversion methods have also been used to assess the environmental benefits of urban green space (Liu & Guo 2009, Imhoff et al. 2010, Gao et al. 2014, Mariani et al. 2016).

In China, urban forests are usually classified into affiliated forests (AF: mainly lo-

cated in schools, institutes, university, residential areas, etc.), roadside forests (RF: forests surrounding the main streets), landscape and relaxation forests (LF: parks, botanical gardens, etc.) and ecological and public welfare forest (EF: mainly distributed in the urban-rural interface area, such as farmland protection forests and other forests of estuarine-coastal areas or water supply areas – He et al. 2004). This kind of functional type division has become the basis of urban forests management in China.

Comprehensive studies focusing on multi-regulation functions (such as shading, temperature cooling, soil and air humidity regulation, etc.) demonstrated that urban forests contribute to optimize local microclimate, although differences among species have been reported (Zhou et al. 2005, Zhang et al. 2008, 2013). Previous studies on the cooling function of urban forests mainly focused on differences in air temperature between inside and outside the forest in horizontal direction (Shashua & Hoffman 2000, Jonsson 2004, Lin et al. 2006), although vertical temperature regulation is becoming more and more a concerning problem in urban areas, due to the increase in building height and the greater use of sky space (Hao et al. 2007). Moreover, leaf transpiration has been de-

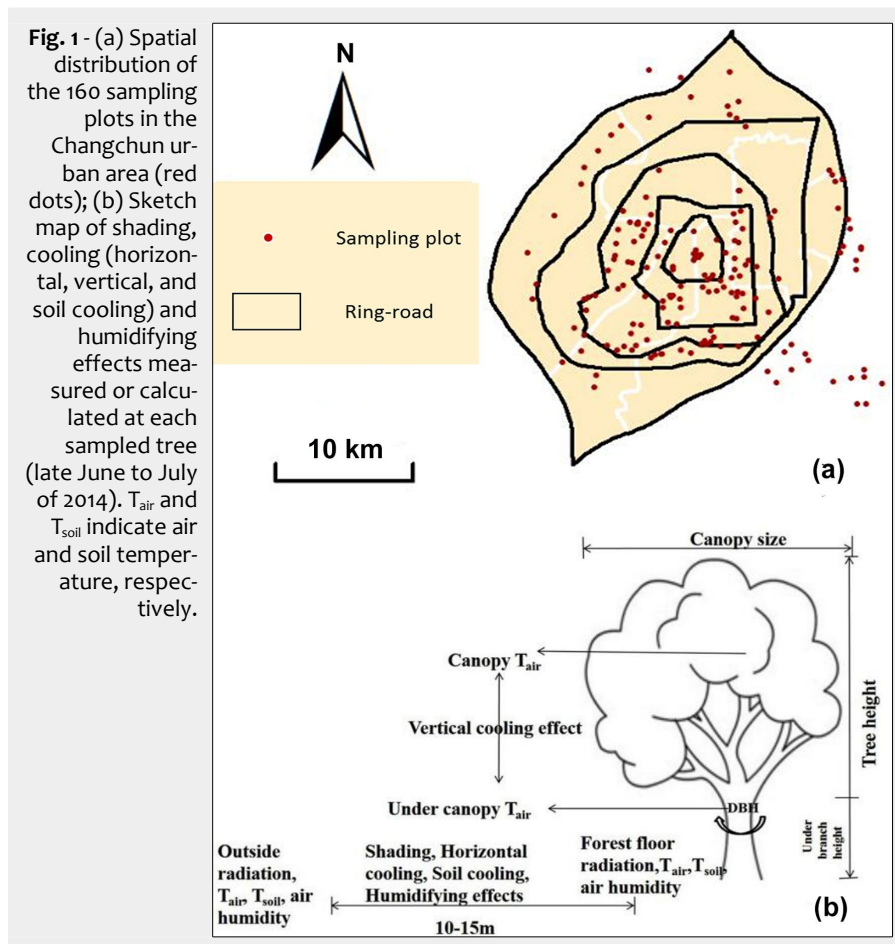
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monstrated to exert a relevant effect on air humidity in arid and semiarid regions of northern China (Liu et al. 2008). Further, the soil of urban forests influences many ecological services, including soil biodiversity and plant growth (Hu et al. 2006), but its cooling effect and the underlying mechanisms have been poorly studied so far.

Urban forests management will greatly benefit from better understanding the relationships between microclimate regulation functions, urban forest structure, and local environmental conditions (Zhang et al. 2013, Wang et al. 2017b). Recent studies have demonstrated that higher trees have a better regulation capacity in terms of sunlight interception, air temperature and humidity (Giannico et al. 2016).

Changchun, the capital city of the Jilin Province (northeast China), has a 100-yr urban settlement history and is currently surrounded by a system of 5-ring roads in its suburbs (Fig. 1a). Recently, a large development of urban forests and green spaces has taken place in Changchun (Zhang et al. 2016), but a large-scale survey of their regulating effect on local microclimate is still missing.

In this study, a field survey was carried out with the aim of testing whether the different forest types have different microclimate regulating functions, and whether these differences were associated with local climatic conditions and/or with tree characteristics. We will answer the follow-

ing questions: (i) is there any difference among the four forest types (AF, EF, LF, and RF) in their shading, cooling and humidifying effects? (ii) Which are the relations between these regulating functions, environmental factors, and tree growth characteristics? (iii) What suggestions can be put forward for urban forests management?

The results of this study could provide a useful basis for policymakers, urban planners and forest managers to better manage and plan different urban forest types.

## Materials and methods

### Study site

The study sites were located in the Changchun urban area ( $43^{\circ} 05' - 45^{\circ} 15' N$  and  $124^{\circ} 18' - 127^{\circ} 02' E$ ), Jilin Province (northeast China). The climate is a continental monsoon climate of the North Temperate Zone. The annual average temperature is  $4.8^{\circ} C$  and the average annual precipitation is 567 mm. Our study area is primarily located within the 5<sup>th</sup>-ring road of Changchun (Fig. 1a). The main tree species occurring in urban forests are *Populus cathayana*, *Salix babylonica*, *Picea* spp., *Syringa* spp., and *Pinus thunbergii* (Ren 2014, Zhang et al. 2016). A stratified sampling method was adopted to ensure a balanced survey of all urban forests over the City. The spatial distribution of the 160 plots in-

cluded in the survey is shown in Fig. 1. In AF and LF stands,  $20 \times 20$  m plots were established for field measurements, while in RF and EF stands measurements were carried out within belts of 50-100 m, depending on the forest characteristics; in the latter cases, several rows of trees were measured, and all the existing trees were sampled when the forest width was less than 20 m.

### Measurement of microclimate factors and tree growth-related parameters

In each plot, 4 healthy trees belonging to the main tree species were selected. For each tree, we measured tree height and under-branch height (m) using a NIKON® forestry PRO laser tree height meter (Nikon, Japan). Tree circumference was measured by a regular soft tape at 1.3 m height above the ground, and the diameter at breast height (DBH) calculated. Canopy size ( $m^2$ ) was estimated as the elliptic area of the crown projection by measuring its radii in east-west and north-south directions.

Environmental factors (sunlight radiation intensity, air temperature, air humidity, soil temperature, under-canopy temperature and canopy temperature) were simultaneously measured during plot inventory measurements. These data were used for computing cooling effect, shading effect, and humidifying effect due to trees. The point where that measures were taken for each variable is reported in Fig. 1b. Air temperature and relative humidity were recorded with a handheld temperature and humidity meter (Victor 231, Victory Hi-tech Co., Shenzhen, China). Solar radiation was recorded using a digital radiation meter (Tes-1330a, Tai Electronic Industry Co., China). Soil temperature was measured with a thermometer (Wanyunshan, Fuzhou, China) with a needle thermometer at 5 cm soil depth. Canopy temperature and under-canopy temperature were recorded by an infrared hand-held temperature measurement gun (303b Victor, Victory Hi-tech Co., Shenzhen, China). Three measurements were averaged for each variable. According to local sunrise and sunset time (4:30-19:30), all data were collected from 8:00 to 18:00 in sunny days to guarantee their precision. A preliminary statistical analysis did not reveal significant diurnal differences (between morning and afternoon) for any of the recorded variables.

### Calculation of shading, cooling and humidifying effects

The shading effect ( $\Delta E$ , expressed as kLux) was calculated as the difference between outside-forest radiation and under-canopy radiation. Shading degree (in percentage) was also calculated as  $\Delta E$ /outside radiation. The horizontal cooling effect ( $\Delta T_1$ ,  $^{\circ}C$ ) was estimated as the difference in air temperature between outside the forest and the forest floor ( $\Delta T_1 = \text{outside forest } T_{air} - \text{forest floor } T_{air}$ ). The vertical cool-

ing effect ( $\Delta T_2$ , °C) was calculated as the difference in air temperature between canopy and under-canopy ( $\Delta T_2 = \text{canopy } T_{\text{air}} - \text{under-canopy } T_{\text{air}}$ ). The soil cooling effect was expressed as  $\Delta T_3$  (°C), being  $\Delta T_3 = \text{outside forest } T_{\text{soil}} - \text{forest floor } T_{\text{soil}}$ . Finally, the humidifying effect was quantified as  $\Delta RH$  (%), where  $\Delta RH = \text{forest floor RH} - \text{outside forest RH}$  (Zhang et al. 2013).

#### Data analysis

ANOVA was performed using the software package SPSS® ver. 17.0 (SPSS Inc. Chicago, IL, USA). According to the statistics of multiple comparisons, shading, cooling and humidifying of the four forest types were signed with different letters for indicating significant differences. A comprehensive score was recomputed according to the significant differences; for example, a score value of 3, 2, 1 was given to differences labelled with *a*, *b*, *c*, respectively, while differences including double letters took average score, e.g., *ab* score =  $(3 + 2)/2$  (see Tab. 1). All scores for different microclimate regulations were added in order to obtain a comprehensive score for each forest type. Using this method, higher scores indicate higher microclimate regulation functions. Data standardization and the comprehensive scoring method were adopted from Lu et al. (2016) and Wang et al. (2017a).

A regression analysis using environmental factors and tree growth parameters as predictors of microclimate regulation functions was performed using the software JMP® ver. 10 (SAS, Cary, NC, USA). Best-fit coefficient of determination ( $R^2$ ) was used to quantify the proportion of the total variance accounted for by each tested climatic or tree structural factor used as predictor. Mean  $R^2$  and its standard deviation was calculated both for environmental and tree growth variables and then compared. Furthermore, redundancy analysis (RDA) was used to graphically represent the associations of microclimate regulating function with outside-forest climatic conditions and tree growth characteristics. CANOCO ver. 5.0 (Biometrics, Netherlands) was used for RDA analysis.

## Results

### Differences in microclimate regulation among forest types

The shading percentage across the four different forest types was 80%, on average. No significant differences were found in horizontal cooling effect ( $\Delta T_1$ ) among the four forest types ( $p > 0.05$ ). As shown in Tab. 1, the vertical cooling effect ( $\Delta T_2$ ) is higher (2 °C) in RF and EF stands than in the other forest types. The soil cooling effect ( $\Delta T_3$ ) of AF stands (1.27 °C) was the highest, followed by RF (0.83 °C). The humidifying effect ( $\Delta RH$ ) of AF and LF stands was 6-7% in relative humidity, which was significantly higher than that (3-4%) recorded for RF and EF types (Tab. 1). Data standardization

**Tab. 1** - Differences and scores in shading, cooling and humidifying effects of four different types of urban forests. Different lowercase letters indicate significant differences between different forest types after Duncan's post-hoc test ( $p < 0.05$ ). (AF): Affiliated forests; (RF): roadside forests; (LF): landscape and relaxation forests; (EF): public welfare forests.

Microclimate regulation functions	Forest types			
	AF	RF	LF	EF
Shading degree (%)	84.98 <sup>a</sup>	86.22 <sup>a</sup>	82.39 <sup>ab</sup>	73.86 <sup>b</sup>
Score in shading effect	2	2	1.5	1
Horizontal $T_{\text{air}}$ differences ( $\Delta T_1$ , °C)	3.85 <sup>a</sup>	3.51 <sup>a</sup>	3.16 <sup>a</sup>	3.43 <sup>a</sup>
Score for $\Delta T_1$	1	1	1	1
Vertical $T_{\text{air}}$ differences ( $\Delta T_2$ , °C)	-0.68 <sup>b</sup>	-1.39 <sup>a</sup>	-0.81 <sup>ab</sup>	-1.36 <sup>a</sup>
Score for $\Delta T_2$	1	2	1.5	2
$T_{\text{soil}}$ differences ( $\Delta T_3$ , °C)	1.27 <sup>a</sup>	0.83 <sup>ab</sup>	-0.18 <sup>bc</sup>	-0.03 <sup>c</sup>
Score for $\Delta T_3$	3	2.5	1.5	1
RH differences ( $\Delta RH$ , %)	6.69 <sup>a</sup>	3.38 <sup>c</sup>	5.94 <sup>ab</sup>	4.32 <sup>bc</sup>
Score for $\Delta RH$	3	1	2.5	1.5
<b>Comprehensive score sum</b>	<b>10</b>	<b>8.5</b>	<b>8</b>	<b>6.5</b>

scoring showed that the AF stands had the highest score (10), which was much higher than the other three forest types (average of 7.6).

### Shading effect

The shading effect  $\Delta E$  (i.e., the difference in radiation between outside and under-canopy) was closely associated with outside light intensity. All the four different types of urban forests showed a similar trend, i.e., a positive correlation was found between the shading effect and outside radiation. Compared with outside radiation, shading effect was less associated with under-canopy radiation (Tab. 2a). In the case of AF type, the  $R^2$  obtained using outside-forest radiation as predictor was over 7.5-fold higher than that obtained using under-canopy radiation ( $R^2 = 0.98$  vs. 0.13, respectively). RF and EF stands had an  $R^2$  as high as 100%, indicating that almost all the varia-

tion in the shading effect could be explained by the outside radiation (Tab. 2a).

The under-canopy radiation of different types of urban forests (Tab. 2b) was significantly related with the tree-growth characteristics, but the best-fit  $R^2$  was much smaller than those obtained for the environmental factors. Moreover, a significant relationship between under-canopy radiation and tree growth parameters was only found in the LF and EF forest types. Tree height accounted for only 10-15% of the total variance in under-canopy radiation, while the other tree growth variables had even smaller  $R^2$  (less than 0.08 – Tab. 2b).

### Horizontal cooling effect

As expected, the horizontal differences in air temperature ( $\Delta T_1$ ) were associated with outside  $T_{\text{air}}$ , radiation, and humidity. The four different forest types showed a similar trend. Overall, the horizontal cooling differ-

**Tab. 2** - Relationships between shading differences and environmental factors (a), as well as between under-canopy radiation and tree growth factors (b) in different urban forest types (non-significant relationships are not listed). (Ind. Var.): independent variable in the regression analysis.

Ind. Var.	Forest types	Regression equation	$R^2$	<i>p</i> -value	N
(a) Shading effect ( $\Delta E$ )	AF	= -3.199 + 0.949 × Outside radiation	0.98	<0.0001	108
		= 20.795 + 10.504 × Log(Under-canopy radiation)	0.13	<0.0001	108
	RF	= -2.474 + 0.963 × Outside radiation	1	<0.0001	112
		= 19.449 + 6.62 × Under-canopy radiation	0.23	<0.0001	112
	LF	= -1.542 + 0.893 × Outside radiation	0.97	<0.0001	273
		= 20.192 + 2.338 × Under-canopy radiation	0.21	<0.0001	273
	EF	= -10.92 + 1.003 × Outside radiation	1	<0.0001	144
	All kinds	= -5.61 + 0.99 × Outside radiation	0.996	<0.0001	637
		= 16.33e 0.1049 × Under-canopy radiation	0.24	<0.0001	637
		= -3.926 + 2.8484 ln(Under-canopy radiation)	0.32	<0.0001	637
(b) Under-canopy radiation	LF	= 9.989 - 0.45 × Tree height	0.15	<0.0001	273
		= 7.016 - 0.302 × Under branch height	0.03	0.0019	273
		= 7.074 - 0.045 × Canopy size	0.05	0.0002	273
	EF	= 16.179 - 0.599 × Tree height	0.1	<0.0001	144
		= 12.711 - 0.038 × DBH perimeter	0.05	0.002	144
		= 12.647 - 0.89 × Under branch height	0.06	0.0038	144
		= 12.787 - 0.099 × Canopy size	0.08	0.0008	144

**Tab. 3** - The relationship between horizontal air temperature differences and environmental factors (a), as well as between the forest floor  $T_{air}$  and tree growth parameters (b) in different urban forest types. Non-significant relationships are not listed. (Ind. Var.): independent variable in the regression analysis.

Ind. Var.	Forest types	Regression equation	R <sup>2</sup>	p-value	N
(a) Horizontal $T_{air}$ differences ( $\Delta T_1$ )	AF	= 0.109 + 0.082 × Outside radiation	0.71	<0.0001	108
		= -11.313 + 0.469 × Outside forest $T_{air}$	0.51	<0.0001	108
		= 12.301 - 0.158 × Outside air humidity	0.49	<0.0001	108
		= 11.532 - 0.13 × Forest floor humidity	0.17	<0.0001	108
	RF	= 0.684 + 0.047 × Outside radiation	0.44	<0.0001	112
		= 1.653 + 0.342 × Under-canopy radiation	0.11	<0.0001	112
		= -11.712 + 0.48 × Outside forest $T_{air}$	0.63	<0.0001	112
		= -4.401 + 0.273 × Forest floor $T_{air}$	0.08	<0.0001	112
		= 9.037 - 0.103 × Outside air humidity	0.28	<0.0001	112
		= 12.079 - 0.145 × Forest floor humidity	0.34	<0.0001	112
	LF	= 1.784 + 0.032 × Outside radiation	0.15	<0.0001	273
		= -8.02 + 0.36 × Outside forest $T_{air}$	0.37	<0.0001	273
		= 5.482 - 0.042 × Outside air humidity	0.04	<0.0001	273
		= 6.661 - 0.056 × Forest floor humidity	0.04	<0.0001	273
	EF	= 1.522 + 0.182 × Under-canopy radiation	0.39	<0.0001	144
		= -11.302 + 0.447 × Outside forest $T_{air}$	0.62	<0.0001	144
= -5.237 + 0.294 × Forest floor $T_{air}$		0.11	<0.0001	144	
= 10.541 - 0.125 × Outside air humidity		0.29	<0.0001	144	
All kinds	= 10.351 - 0.113 × Forest floor humidity	0.2	<0.0001	144	
	= -10.207 + 0.432 × Outside forest $T_{air}$	0.47	<0.0001	637	
	= -0.193 + 0.982 × ln (Outside radiation)	0.12	<0.0001	637	
(b) Forest floor $T_{air}$	LF	= 10.304 - 0.123 × Outside air humidity	0.33	<0.0001	637
		= 9.989 - 0.45 × Tree height	0.15	<0.0001	273
		= 7.0157 - 0.302 × Under-branch height	0.03	0.0019	273
	EF	= 7.074 - 0.0448 × Canopy size	0.05	0.0002	273
		= 16.179 - 0.599 × Tree height	0.1	<0.0001	144
		= 12.711 - 0.038 × DBH	0.05	0.002	144
		= 12.647 - 0.89 × Under-branch height	0.06	0.0038	144
		= 12.787 - 0.099 × Canopy size	0.08	0.0008	144

**Tab. 4** - The relationship between vertical differences and environmental factors, as well as between under-canopy  $T_{air}$  and tree growth parameters in four different forest types in urban forests. Non-significant relationships are not listed. (Ind. Var.): independent variable; (a) relations between vertical  $T_{air}$  differences ( $\Delta T_2$ ) and environmental factors; (b) relations between under-canopy  $T_{air}$  and tree growth parameters.

Ind. Var.	Forest types	Regression equation	R <sup>2</sup>	p-value	N
(a) $\Delta T_2$	LF	= -0.113 - 0.114 × Under-canopy radiation	0.05	0.0001	273
	EF	= 3.609 - 0.081 × Shade air humidity	0.08	0.0007	144
(b) Under-canopy $T_{air}$	LF	= 25.657 - 0.251 × Tree height	0.12	<0.0001	273
		= 24.173 - 0.221 × Under branch height	0.05	0.0003	273
		= 24.93 - 0.028 × DBH perimeter	0.08	<0.0001	273
		= 24.908 - 0.546 × Log (canopy size)	0.03	0.0044	273
	EF	= 25.418 - 0.163 × Tree height	0.1	0.0001	144
		= 24.661 - 0.34 × Under branch height	0.09	0.0003	144
		= 27.03 - 0.808 × Log (DBH)	0.09	0.0005	144

**Tab. 5** - The relationship between soil cooling differences and environmental factors. Non-significant relationships are not listed. (Ind. Var.): independent variable; (a) relations between soil cooling differences and environmental factors (all forest types); (b) relations between forest floor  $T_{soil}$  and environmental factors (all forest types).

Ind. Var.	Regression equation	R <sup>2</sup>	p-value	N
(a) $\Delta T_3$	= -1.96 + 66.417 × (outside forest $T_{air}$ ) <sup>-1</sup>	0.006	0.0038	637
	= 2.023 - 0.032 × Outside air humidity	0.01	0.0002	637
(b) Forest $T_{soil}$	= 26.586 + 0.007 × Outside radiation	0.01	<0.0001	637
	= 30.722 - 0.059 × Forest floor humidity	0.01	<0.0001	637

ences were more strongly related with outside  $T_{air}$  ( $R^2 = 0.47$ ) and outside humidity ( $R^2 = 0.33$ ) rather than outside radiation ( $R^2 = 0.12$  – Tab. 3). Outside  $T_{air}$  explained 37-63% of the variance in horizontal cooling effect across different forest types, and RF stands showed the highest  $R^2$  (0.63). The air humidity was negatively correlated with horizontal cooling differences and the highest correlation was found for AF stands ( $R^2 = 0.49$  – Tab. 3).

The associations between tree growth variables and forest floor  $T_{air}$  were significant; however, they were much weaker than those between horizontal differences and outside environmental parameters.  $R^2$  values were usually less than 0.05 in all the relationships between tree-growth parameters and forest floor  $T_{air}$  (Tab. 3).

#### Vertical cooling effect

As compared with horizontal cooling effect, the vertical  $T_{air}$  differences ( $\Delta T_2$ ) were less associated with environmental factors. Significant relationships between vertical cooling differences and environmental factors were only found in LF and EF types ( $R^2 < 0.1$ ). Under-canopy  $T_{air}$  of LF and EF stands showed a close association with tree height with  $R^2 > 10\%$ , which was much larger than that observed for the horizontal cooling effect. This shows that higher trees were associated with a significant vertical cooling effect (Tab. 4, Fig. S1a, Fig. S1b, Fig. S1c, Fig. S1d in Supplementary material).

#### Soil cooling effect

The soil cooling effect ( $\Delta T_3$ ) in all the four different types of urban forests was significantly correlated with air temperature and air humidity ( $p < 0.05$  – Tab. 5). Forest floor  $T_{soil}$  was correlated with outside forest radiation and air humidity ( $p < 0.05$  – Tab. 5). However, the  $R^2$  was as small as 0.01 or less, showing that the relationship was much weaker than air cooling effects (horizontal and vertical cooling).

#### Air humidifying effect

As expected, differences in  $\Delta RH$  among the four types of urban forests were mainly associated with air humidity (inside and outside forest). Forest floor RH (relative humidity) was mainly associated with the outside forest RH, explaining 66% of the total variation in the data. A higher outside forest  $T_{air}$  is usually related to a lower RH under-canopy ( $R^2 = 0.32$  – Tab. 6).

#### $R^2$ differences between environmental and tree-growth predictors

Based on the  $R^2$  values obtained from regression analysis (Tab. 2 to Tab. 6), we compared the proportion of the total variance in microclimate effects explained by environmental factors and tree growth parameters (Fig. 2a and Fig. 2b, respectively). Shading effect ( $\Delta E$ ) was mainly associated with environmental factors, that explained 8-fold more variance than tree growth pa-

rameters. Likewise,  $\Delta T_1$  (horizontal cooling effect) and  $\Delta RH$  (humidifying effect) were also mainly associated with environmental variables. Contrastingly,  $\Delta T_2$  (vertical cooling effect) was mainly associated with tree growth parameters, rather than environmental factors, as displayed in Fig. 2a.

Environmental factors explained the largest amount of variation in floor microclimate parameters, except vertical cooling ( $\Delta T_2$ ). Indeed, the fairly large variation explained by under-canopy  $T_{air}$  suggests that tree growth is important in regulating vertical cooling through the canopy (Fig. 2b). However, other microclimate effects had more close relations with outside forest environmental factors, compared to tree growth characteristics (Fig. 2a, Fig. 2b).

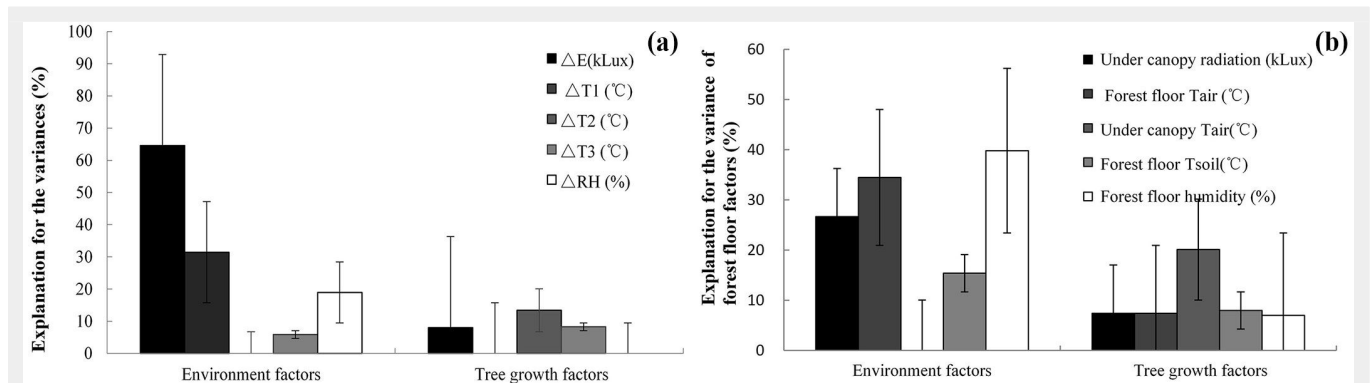
**Redundancy analysis**

Redundancy analysis revealed that tree growth variables and environmental factors accounted for 38.6% of the total variance in the microclimatic regulation effects. Radiation and RH outside forest ex-

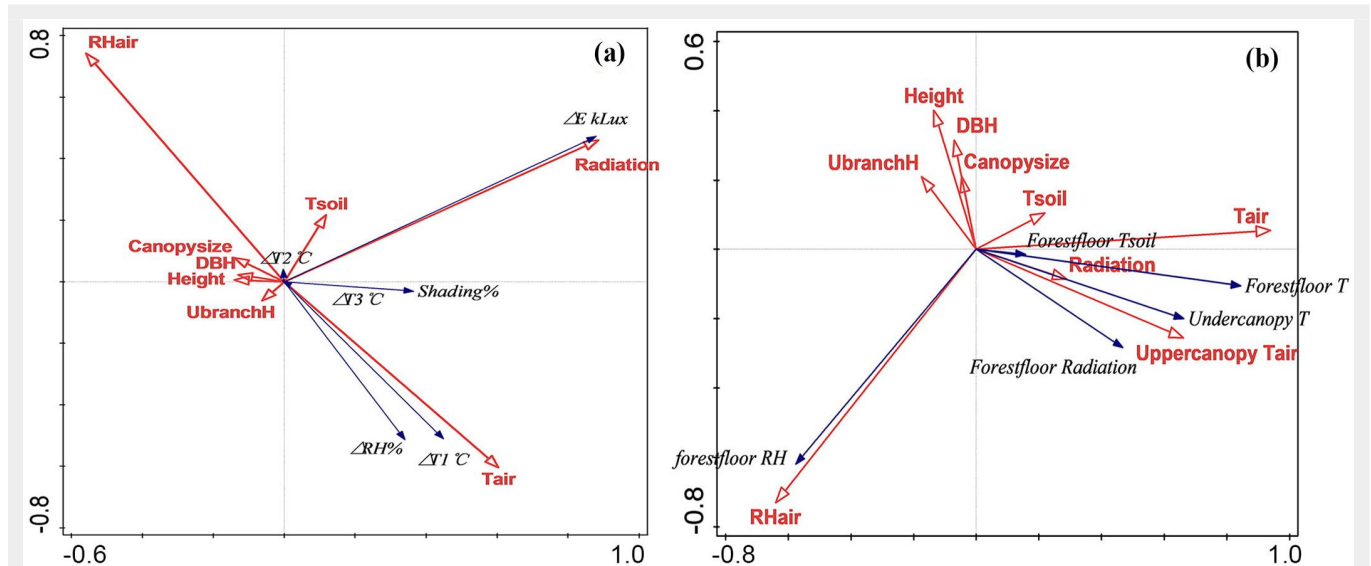
**Tab. 6** - The relationship between RH differences ( $\Delta RH$ ) and environmental factors, as well as between forest floor RH and both environmental factors and tree growth parameters. Non-significant relationships are not listed. (a) Relations between  $\Delta RH$  and environmental factors (all forest types); (b) relations of forest floor RH with environmental factors and tree growth parameters (all forest types).

Ind. Var.	Regression equation	R <sup>2</sup>	p-value	N
(a) $\Delta RH$	= - 10.971 + 0.515 × Outside forest $T_{air}$	0.09	<0.0001	637
	= - 5.8 + 0.393 × Forest floor $T_{air}$	0.03	<0.0001	637
	= 27.22 - 0.382 × Outside air humidity	0.42	<0.0001	637
	= 1.373 + 1.064 × Log (Outside radiation)	0.02	0.0005	637
(b) forest floor RH	= 102.108 - 1.247 × Outside forest $T_{air}$	0.32	<0.0001	637
	= 104.462 - 1.482 × Forest floor $T_{air}$	0.24	<0.0001	637
	= 27.22 + 0.618 × Outside air humidity	0.66	<0.0001	637
	= 63.699 - 0.015 × Outside radiation	0.02	0.0012	637
	= 76.778 - 0.501 × Outside soil temperature	0.04	<0.0001	637
	= 65.591 - 0.326 × Tree height	0.02	0.0003	637
	= 64.855 - 0.036 × DBH	0.02	0.0008	637

plained the highest proportion (18.7% and 12.4%, respectively), while tree height and canopy size explained a lower proportion (1.5% and 0.7%, respectively – see Tab. S1a in Supplementary materials). However, all the measured variables showed significant



**Fig. 2** – Mean proportion of variance explained ( $R^2$ ) using environmental factors and tree growth parameters as predictors in regression analysis. (a) Predicted variables: horizontal ( $\Delta T_1$ ), vertical ( $\Delta T_2$ ), and soil cooling ( $\Delta T_3$ ), shading effect ( $\Delta E$  and shading %) and humidifying effect ( $\Delta RH$ ); (b) Predicted variables: radiation, RH,  $T_{soil}$ , forest floor  $T_{air}$  and under-canopy  $T_{air}$ . Error bars represent the standard deviation.



**Fig. 3** - Redundancy analysis of the effect of environmental variables and tree growth parameters on microclimatic regulation functions. (a) Biplot of the measured variables vs. horizontal ( $\Delta T_1$ ), vertical ( $\Delta T_2$ ), and soil cooling ( $\Delta T_3$ ), shading effects ( $\Delta E$  and Shading %) and humidifying effect ( $\Delta RH$ ); (b) biplot of the measured variables vs. forest floor radiation, RH,  $T_{soil}$ ,  $T_{air}$  and under-canopy  $T_{air}$ .

loadings after multivariate analysis, except for DBH (Tab. S1a).

As expected, the shading effect (both  $\Delta E$  and Shading%) was mostly related with the total amount of radiation, and the horizontal cooling ( $\Delta T_1$ ) and the humidifying effect ( $\Delta RH$ ) with higher  $T_{air}$  and the lower  $Rh_{air}$  (Fig. 3a). Other microclimate effects were poorly explained by the measured variables, as indicated by the much shorter arrows displayed in the RDA biplot (Fig. 3a).

Forest floor microclimate was strongly associated with both outside forest climatic conditions and tree-growth variables (Fig. 3b). The overall variation explained was 57.4% (Tab. S2 in Supplementary material), being mostly due (6.7-30.7%) to outside forest climatic factors ( $T_{air}$ , RH,  $T_{soil}$  and upper canopy  $T_{air}$ ), and much less to tree characteristics (0.3-0.8%). The outside-forest environmental parameters were closely associated with the corresponding variables measured on the forest floor (Fig. 3b).

## Discussion

Current studies on the ecological benefits of urban forests range from small-scale analysis of gardens or single trees (Marziliano et al. 2013), to remote-sensed, large-scale investigations of green spaces (Gianico et al. 2016), to energy-balance modeling (Mariani et al. 2016). In this study we carried out a field survey of different types of urban forests over an area of about 400 km<sup>2</sup> in the urban region of Changchun (northeast China). Our results provide some useful hints that could contribute to a better understanding of urban forest functions.

In general, the four different types of urban forests investigated in this study showed different shading, cooling and humidifying effects. On average, the air temperature in the forest was reduced by about 3 °C in the horizontal direction as compared with the outside-forest environment, though no significant differences were found among the four forest types. Contrastingly, AF and LF types showed a higher humidifying effect than RF and EF stands (6-7% vs. 3-4%). This is particularly important in semi-dry and semi-moist climate regions like Changchun, where people usually suffer from dry air periods. Panno et al. (2017) found that people visiting urban green areas experienced a greater well-being and lower stress associated with higher air temperature.

Wong & Yu (2005) reported that urban forests could reduce the temperature up to 4.01 °C compared to the central business district. Spatial and temporal analysis of urban temperatures has revealed that vegetation-rich areas have lower temperatures (Akinbode et al. 2008, Armson et al. 2012) and the cooling effect was different among different land uses (Hamada et al. 2013). Georgi & Zafiriadis (2006) found that maximum cooling and humidifying effects of urban parks were about 24% and 41%, respectively. Arx et al. (2012) demonstrated that

maximum daily temperature was lower up to 5.1 °C (mean: 1.8 °C) and minimum daily humidity was higher up to 12.4% (mean: 5.1%) in 14 urban forest stands in Switzerland.

Our results on the horizontal cooling effect and humidifying effect of urban forests in semi-arid regions are consistent with those reported in similar studies, and further confirm the importance of urban afforestation for local microclimate regulation. Moreover, our findings support the evidence that forest stands in different urban locations differ in their microclimate regulation efficiency, regardless of their composition and structure.

Several studies on ecosystem services assessment of urban forests have applied complex models (e.g., I-Tree) including environmental, tree-growth, and social variables (Solecki et al. 2005, Ma et al. 2011). In this paper, we successfully applied simple regression analysis to evaluate the microclimatic regulation functions of urban forest stands. For example, we found that shading effect was closely related with outside forest radiation, and different forest types showed quite similar relationships. Using data of solar radiation from local meteorological stations and remote sensing technology to map urban forest coverage, the overall shading effect of urban forest stands in a specific area could be estimated with high accuracy (Ren 2014), regardless of the forest type. However, for some other functions (e.g., cooling and humidifying effect), forest type-related differences should be carefully considered.

Shading, cooling and humidifying effects of urban forests are usually stronger in sunny days with high  $T_{air}$ , and lower air humidity. Our results strongly support this conclusion. Jim (2015) argued that plants play a greater role in cooling when solar radiation is higher. Alexandri & Jones (2008) found that the cooling effect of urban green spaces was remarkable in dry and hot weather. Wang et al. (2015) reported that the cooling effect of trees in clear and hot days was twice as higher than in cloudy and cold days. Zhang et al. (2013) demonstrated that canopy density, canopy area, tree height and solar radiation had a significant influence on temperature reduction and relative humidity increase.

Our findings strongly support previous results from similar studies on microclimate regulation of urban forests. Additionally, we also investigated the vertical air cooling and soil cooling effects, which were rarely analyzed in previous studies. Regression analysis revealed that vertical cooling, soil cooling and humidifying effect had a weak correlation with outside-forest climatic parameters and tree growth characteristics ( $R^2$  was often less than 0.5). This is important as rapid urbanization in China has resulted in a high utilization of sky spaces with taller buildings, and in a dramatic reduction of bare soil areas for plant survival. Li et al. (2011) reported that the vertical

cooling effect of green plant canopy in residential areas was significant above 1.5 m. Moreover, vertical greening vines or roof greening to enhance cooling and humidifying effects along the vertical profile have also been suggested (Alexandri & Jones 2008, Perini et al. 2013, Jim 2015). In this study, using infra-red temperature monitoring techniques, we found that canopy temperature was lower compared with under-canopy. More attention should be paid to both air cooling effect (horizontal and vertical) of trees and the cooling effect of bare soil, aiming to improve the microclimate regulation functions of urban forests.

Surprisingly, we found a weak association between under-canopy radiation and shading effect in all the forest types considered (Tab. 2). Previous studies have shown the importance of forest scale and structure on microclimate regulation functions of urban forests (Zhang et al. 2013). The environmental benefits provided by urban trees has been assessed analyzing tree dendrometric variables (stem diameter, height, and crown width) at different ages (Marziliano et al. 2013). In this paper, the negative correlation between tree size and microclimatic effects (horizontal cooling, shading and humidifying effects) confirmed that a larger tree size is usually associated with lower light intensity and temperature under the tree canopy. Our study also suggested that trees along the roadside (RF), in universities and schools (AF), in gardens and parks (LF) and along farmland or riverbanks (EF) have different microclimate regulation efficiency, regardless of the forest structure and composition. These location-dependent functional differences should be carefully considered in the management and planning of urban forests.

Trees can intercept solar radiation and reduce air temperature through transpiration, thereby absorbing large amounts of heat from the environment and regulating atmospheric humidity (Liu et al. 2008). Urban forests management and planning should take the landscape structure into account to provide maximum ecological benefits. Based on our results, the following recommendations were formulated to improve the urban forest ecosystem services in Changchun city.

Firstly, to protect larger trees in the city and increase their frequency. At present, Changchun has a fairly low percentage of high trees (<10% of total measured trees); based on our field survey, 54% of trees ranged from 3 to 9 m in height, while only 8% are in the range 15-23 m. As for tree circumference, 35% trees ranged from 25 to 50 cm, while larger trees (100-230 cm) were only 10%. Under-branch height was 1-3 m for 54% of the sampled trees, and >6 m for only 6% of trees. Canopy projection area was <20 m<sup>2</sup> in 63% of the trees, >50 m<sup>2</sup> in only 9%. Our results clearly showed that larger trees (higher tree height and under-branch height, larger canopy projection area) can significantly enhance shading,

cooling and humidifying effects under canopy. Moreover, temperature and humidity in forests have proven to be closely related to tree cover and canopy density (Greene & Millward 2017, Zhou et al. 2005). Zhang et al. (2013) revealed the canopy density, crown size, tree height and radiation significantly influence cooling and humidifying effects. Tall tree species had stronger ability to regulate air temperature (Berry et al. 2013). These studies demonstrated the importance of tree structural characteristics rather than environmental factors in microclimate regulation, as well as air purification (Zhang 2007, Zhao 2008). Furthermore, the conservation of old-growth trees in urban areas, besides their cultural and recreational value, may partly balance the loss of the original vegetation due to the rapid urbanization currently occurring in Chinese cities.

Secondly, urban forest management and planning should take into account the differences found among forest types. In this study, AF stands showed better microclimate regulation functions than the other forest types considered. AF stands usually grow close to universities, schools, institutes and government agencies, where intensive management is carried out in terms of watering, fertilizing, and tending. Similar activities, along with rational pruning and the choice of diverse species for afforestation purposes, should be extended also to other urban forest types in other locations to maximize their ecological benefits (Qin et al. 2006).

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## Supplementary Material

**Fig. S1** - The relationships between vertical differences and tree growth characteristics in four different types of urban forests.

**Tab. S1** - Results of the redundancy analysis of microclimate regulation functions: horizontal cooling ( $\Delta T_1$ ), vertical cooling ( $\Delta T_2$ ), soil cooling ( $\Delta T_3$ ), shading effects ( $\Delta E$  and shading %) and humidifying ( $\Delta RH$ ).

**Tab. S2** - Results of the redundancy analysis of microclimatic regulation functions: radiation, RH,  $T_{soil}$ , forest floor  $T_{air}$  and under-canopy  $T_{air}$ .

**Link:** [Zhang\\_2466@suppl001.pdf](mailto:Zhang_2466@suppl001.pdf)