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

Wenjie Wang (1-2), Hongyuan Wang (1-2), Lu Xiao (1-2), Xingyuan He (2), Wei Zhou (1-2), Qiong Wang (2), Chenhui Wei (2)

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 km², 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 relations 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 located 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-
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 following 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°05′·45°15′ N and 124°18′·127°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 °C and the average annual precipitation is 567 mm. Our study area is primarily located within the 5th-ring road of Changchun (Fig. 1a). The main tree species occurring in urban forests are Populus cathayana, Salix babylonica, Picea spp., S. ringia 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 included in the survey is shown in Fig. 1. In AF and LF stands, 20 × 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 (m²) was estimated as the elliptic area of the crown projection by measuring its radii in east-west and north-south directions.

Environmental factors (solar 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 thermocouple recorder (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 (305B 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 for 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 (ΔE, expressed as klux) was calculated as the difference between outside-forest radiation and under-canopy radiation. Shading degree (in percentage) was also calculated as ΔE/outside radiation. The horizontal cooling effect (ΔT, °C) was estimated as the difference in air temperature between outside the forest and the forest floor (ΔT= outside forest Tair − forest floor Tair). The vertical cool-
ing effect ($\Delta T_v$, °C) was calculated as the difference in air temperature between canopy and under-canopy ($\Delta T_v = \text{canopy} T_v - \text{under-canopy} T_v$). The soil cooling effect was expressed as $\Delta T_s$, (°C), being $\Delta T_s = \text{outside} T_{soil} - \text{forest floor} T_{soil}$. 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 micrometeorological regulations were added in order to obtain a comprehensive score for each forest type. Using this method, higher scores indicate higher micrometeorological regulation functions. Data standardization and the comprehensive scoring method were adopted from Lu et al. (2016) and Wang et al. (2017).

A regression analysis using environmental factors and tree growth parameters as predictors of micrometeorological 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 micrometeorological regulation function with outside-forest climatic conditions and tree growth characteristics. CANOCO ver. 5.0 (Biometrics, Netherlands) was used for RDA analysis.

**Results**

**Differences in micrometeorological 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 ($\Delta T_v$) among the four forest types ($p > 0.05$). As shown in Tab. 1, the vertical cooling effect ($\Delta T_v$) is higher (2 °C) in RF and EF stands than in the other forest types. The soil cooling effect ($\Delta T_s$) of AF stands (1.27 °C) was the highest, followed by RF (0.83 °C). The humidifying effect ($\Delta RH$) of AF and EF 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 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. 2). 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 variation 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 ($\Delta T_v$) were associated with outside $T_v$ radiation, and humidity. The four different forest types showed a similar trend. Overall, the horizontal cooling differ-

---

**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 (%)**           |              |    |    |    |    |
| Score in shading effect          |              |    |    |    |    |
| Horizontal $T_v$ differences ($\Delta T_v$, °C) | 3.85a | 3.51a | 3.16a | 3.43a |
| Vertical $T_v$ differences ($\Delta T_v$, °C) | -0.68a | -1.39a | -0.81a | -1.36a |
| Score for $\Delta T_v$           |              |    |    |    |    |
| $T_{soil}$ differences ($\Delta RH$, %) | 1.27a | 0.83a | -0.18a | -0.03a |
| RH differences ($\Delta RH$, %)   |              |    |    |    |    |
| Comprehensive score sum          |              |    |    |    |    |
| Score for $\Delta RH$            |              |    |    |    |    |
| Score for $\Delta RH$            | 6.69a | 3.38a | 5.94a | 4.32a |
| P-value                           | 0.08 | 0.05 | 0.05 | 0.05 |
| **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 | R² | p-value | N |
|-----------|--------------|---------------------|----|---------|---|
| (a) Shading radiation ($\Delta E$) |              | -3.199 + 0.949 × Outside radiation | 0.98 | <0.0001 | 108 |
|          |              | 20.795 + 10.504 × Log(Under-canopy radiation) | 0.13 | <0.0001 | 108 |
| (b) Under-canopy radiation ($\Delta E$) |              | -2.474 + 0.963 × Outside radiation | 1 | <0.0001 | 112 |
|          |              | 19.449 + 6.62 × Under-canopy radiation | 0.23 | <0.0001 | 112 |
|          |              | -1.542 + 0.893 × Outside radiation | 0.97 | <0.0001 | 273 |
|          |              | 20.192 + 2.338 × Under-canopy radiation | 0.21 | <0.0001 | 273 |
|          |              | -10.92 + 1.003 × Outside radiation | 1 | <0.0001 | 144 |
|          |              | -5.61 + 0.99 × Outside radiation | 0.996 | <0.0001 | 637 |
|          |              | 16.336 × 0.1049 × Under-canopy radiation | 0.24 | <0.0001 | 637 |
|          |              | -3.926 + 2.8484 × In(Under-canopy radiation) | 0.32 | <0.0001 | 637 |
|          |              | 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 |
|          |              | 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 | R² | p-value | N  |
|-----------|--------------|---------------------|----|---------|----|
| (a) Vertical differences (ΔT) | | | | | |
| AF | = 0.109 + 0.082 × Outside radiation | 0.71 | <0.0001 | 108 |
| RF | = 0.684 + 0.047 × Outside radiation | 0.44 | <0.0001 | 112 |
| EF | = -11.313 + 0.469 × Outside forest T_{air} | 0.51 | <0.0001 | 108 |
| LF | = 1.784 + 0.032 × Outside radiation | 0.15 | <0.0001 | 273 |
| EF | = 5.482 - 0.042 × Outside air humidity | 0.04 | <0.0001 | 273 |
| (b) Horizontal T_{air} differences | | | | | |
| AF | = 12.301 - 0.158 × Outside air humidity | 0.49 | <0.0001 | 108 |
| RF | = 11.532 - 0.13 × Forest floor humidity | 0.17 | <0.0001 | 108 |
| LF | = 8.02 + 0.36 × Outside forest T_{air} | 0.37 | <0.0001 | 273 |
| EF | = 6.661 - 0.056 × Forest floor humidity | 0.04 | <0.0001 | 273 |
| EF | = -11.302 + 0.447 × Outside forest T_{air} | 0.62 | <0.0001 | 144 |
| EF | = -5.237 + 0.294 × Forest floor T_{air} | 0.11 | <0.0001 | 144 |
| EF | = -10.541 - 0.125 × Outside air humidity | 0.29 | <0.0001 | 144 |
| LF | = -10.027 + 0.432 × Outside forest T_{air} | 0.47 | <0.0001 | 637 |
| EF | = -0.193 + 0.982 × ln (Outside radiation) | 0.12 | <0.0001 | 637 |
| LF | = 9.989 - 0.45 × Tree height | 0.15 | <0.0001 | 273 |
| EF | = 7.0157 - 0.302 × Under-branch height | 0.03 | <0.0019 | 273 |
| EF | = 7.074 - 0.048 × Canopy size | 0.05 | <0.0002 | 273 |
| EF | = 16.179 - 0.599 × Tree height | 0.1 | <0.0011 | 144 |
| EF | = 12.711 - 0.038 × DBH | 0.05 | <0.002 | 144 |
| EF | = 12.647 - 0.89 × Under-branch height | 0.06 | 0.0038 | 144 |
| EF | = 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 (ΔT_{air}) and environmental factors; (b) relations between under-canopy T_{air} and tree growth parameters.

| Ind. Var. | Forest types | Regression equation | R² | p-value | N  |
|-----------|--------------|---------------------|----|---------|----|
| (a) ΔT_{air} | | | | | |
| 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 |
| LF | = 25.657 - 0.251 × Tree height | 0.12 | <0.0001 | 273 |
| EF | = 24.173 - 0.221 × Under branch height | 0.05 | 0.0003 | 273 |
| LF | = 24.93 - 0.028 × DBH perimeter | 0.08 | <0.0001 | 273 |
| LF | = 24.908 - 0.546 × Log (canopy size) | 0.03 | 0.0044 | 273 |
| EF | = 25.418 - 0.163 × Tree height | 0.1 | 0.0001 | 144 |
| EF | = 24.661 - 0.34 × Under branch height | 0.09 | 0.0003 | 144 |
| EF | = 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_{air} and environmental factors (all forest types).

| Ind. Var. | Regression equation | R² | p-value | N  |
|-----------|---------------------|----|---------|----|
| (a) ΔT_{soil} | | | | | |
| AF | = -1.96 + 66.417 × (outside forest T_{air})³ | 0.006 | 0.0038 | 637 |
| LF | = 2.023 - 0.032 × Outside air humidity | 0.01 | 0.0002 | 637 |
| LF | = 26.586 + 0.007 × Outside radiation | 0.01 | <0.0001 | 637 |
| EF | = 30.722 - 0.059 × Forest floor humidity | 0.01 | <0.0001 | 637 |

Vertical cooling effect
As compared with horizontal cooling effect, the vertical T_{air} differences (ΔT_{air}) were less associated with environmental factors. Significant relationships between vertical cooling differences and environmental factors were only found in LF and EF types (R² < 0.1). Under-canopy T_{air} of LF and EF showed a close association with tree height with R² > 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 (ΔT_{soil}) 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_{air} was correlated with outside forest radiation and air humidity (p < 0.05 – Tab. 5). However, the R² 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 ΔRH 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 (R² = 0.32 – Tab. 6).

R² differences between environmental and tree-growth predictors
Based on the R² 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 (ΔE) was mainly associated with environmental factors, that explained 8-fold more variance than tree growth parameters were more strongly related with outside T_{air} (R² = 0.47) and outside humidity (R² = 0.33) rather than outside radiation (R² = 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 R² (0.63). The air humidity was negatively correlated with horizontal cooling differences and the highest correlation was found for AF stands (R² = 0.49 – Tab. 3).
Microclimate regulation of urban forests in China

...parameters. Likewise, ΔT₁ (horizontal cooling effect) and ΔRH (humidifying effect) were also mainly associated with environmental variables. Contrastingly, ΔT₂ (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 (ΔT₃). Indeed, the fairly large variation explained by under-canopy Tₑ 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 explained 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

| Ind. Var. | Regression equation | R² | p-value | N  |
|-----------|---------------------|----|---------|----|
| (a) ΔRH   |                       |    |         |    |
|           | = - 10.971 + 0.515 × Outside forest Tₑ  | 0.09 | <0.0001 | 637 |
|           | = - 5.8 + 0.393 × Forest floor Tₑ    | 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 Tₑ | 0.32 | <0.0001 | 637 |
|           | = 104.462 - 1.482 × Forest floor Tₑ | 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 |

Fig. 2 – Mean proportion of variance explained (R²) using environmental factors and tree growth parameters as predictors in regression analysis. (a) Predicted variables: horizontal (ΔT₁), vertical (ΔT₂), and soil cooling (ΔT₃), shading effect (ΔE and shading %) and humidifying effect (ΔRH); (b) Predicted variables: radiation, RH, Tsoil, forest floor Tₑ and under-canopy Tₑ. 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 (ΔT₁), vertical (ΔT₂), and soil cooling (ΔT₃), shading effects (ΔE and Shading %) and humidifying effect (ΔRH); (b) biplot of the measured variables vs. forest floor radiation, RH, Tsoil, Tₑ and under-canopy Tₑ.
loadings after multivariate analysis, except for DBH (Tab. S1a).

As expected, the shading effect (both ΔE and Shading’s) was mostly related with the total amount of radiation, and the horizontal cooling (ΔT1) and the humidifying effect (ΔRH) with higher T stands and the lower RH (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 (6-3.70.7%) to outside forest climatic factors (Tm, RH, Tm and upper canopy Tm), 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 (Giancico 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 km² 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 areas have different 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 Tm, 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 (R² 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 forest 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 have 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 m² in 63% of the trees, >50 m² in only 9%. Our results clearly showed that larger trees (higher tree height and underbranch 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).

Acknowledgements
This study was financially supported by the National Science Foundation of China (41703041, 31670609). Key projects from CAS (Y3H1051001, KFDZ-SW-302), basic research funds for national universities from the Ministry of Education of China (2572017DG04, 2572017EA03).

References
Akinbode OM, Eludoyin AO, Fashae OA (2008). Temperature and relative humidity distributions in a medium-size administrative town in southwest Nigeria. Journal of environmental management 87: 95-105. - doi: 10.1016/j.jenvman.2007.01.018
Alexandri E, Jones P (2008). Temperature decrease in an urban canyon due to green walls and green roofs in diverse climates. Building and Environment 43: 480-493. - doi: 10.1016/j.buildenv.2006.10.055
Armsden D, Stringer P, Ennos AR (2012). The effect of tree shade and grass on surface and global temperatures in an urban area. Urban Forestry and Urban Greening 11: 245-255. - doi: 10.1016/j.ufug.2012.05.002
Arx GV, Dobbertin M, Rebetz M (2012). Spatio-temporal effects of forest canopy on understore microclimate in a long-term experiment in Switzerland. Agriculture and forest meteorology 166-167: 144-155. - doi: 10.1016/j.agrformet.2012.07.018
Bao CS, Lou JH, Zeng XY, Xiang ZS (2001). Effect of landscaping and greening on microclimate in Hangzhou city. Journal of Zhejiang University, (Agriculture and Life Sciences) 27: 415-418. - doi: 10.13230/j.issn.0001-0466
Berry R, Livesley SJ, Aye L (2013). Tree canopy shade impacts on solar irradiance received by building walls and their surface temperature. Building and Environment 69: 91-100. - doi: 10.1016/j.buildenv.2013.07.009
Bowler DE, Buyung-Alam I, Knight TM, Pullin AS (2010). Urban greening to cool towns and cities: a systematic review of the empirical evidence. Landscape and urban planning 97: 147-155. - doi: 10.1016/j.landurbplan.2010.05.006
Gao MR, Ji BQ, Wang C, Sun CH (2014). Relationship between urban forest canopy cover and heat island effect in Xiamen Island. Scientia Silvae Sinicae 50: 63-68.
Georgi NJ, Zaffirardi K (2006). The impact of park trees on microclimate in urban areas. Urban Ecosystems 9: 195-209. - doi: 10.1007/s11252-006-095-9
Giannico V, Lafortezza R, John R, Sanesi G, Pesola L, Chen JQ (2016). Estimating stand volume and above-ground biomass of urban forests using LIDAR. Remote Sensing 8: 339. - doi: 10.3390/rs8040339
Greene CS, Millward AA (2017). Getting closure: the role of urban forest canopy density in moderating summer surface temperatures in a large city. Urban Ecosystems 20: 141-156. - doi: 10.1007/s11252-015-0358-5
Hamada S, Tanaka T, Ohta T (2015). Impacts of land use and topography on the cooling effect of green areas on surrounding urban areas. Urban Forestry and Urban Greening 14: 426-434. - doi: 10.1016/j.ufug.2015.06.008
Hao XY, Lin YD, Wu XG, Wang J, Liang F, Liang J (2007). Vertical thermal characteristics analysis between different urban green land. Acta Ecologica Sinica 2: 685-692. [In Chinese]. - doi: 10.1002/scej.2007.02.033
He XY, Liu CF, Chen W (2004). Discussion on urban forest classification. Chinese Journal of Ecology 23: 175-178. [In Chinese] [Online] URL: http://www.wanfangdata.com.cn/Periodical/jsexs2002040532
Hu YL, Wang SL, Yan SK (2006). Advances in the study of factors affecting soil microbial activity and community structure. Chinese Journal of Soil Science 37: 170-176 [In Chinese]. - doi: 10.13230/j.issn.0093-0933.2007.02.038
Huang HK, Li JL, Huang LM (2008). Diurnal variation patterns of microclimate and their effects on human comfort degree in Nanjing City. Chinese Journal of Ecology 27: 601-606 [In Chinese]. - doi: 10.13230/j.issn.1000-0933.2006.01.038
Lafortezza R (2017). Linking above-ground biomass to ecosystem services in the subtropical city of Gabo, Southern Italy. Journal of Forestry Research 28: 1307-1322. - doi: 10.1007/s11676-017-0577-1
Lafortezza R, Colangelo G, Davies C, Sanesi G (2015). Vertical thermal characteristics of green land based on urban green space structure. Acta Ecologica Sinica 36: 3339-3346. [In Chinese]. - doi: 10.3724/SP.J.1148.2016.03206.10.025
Lin ML, Chen QB, Deng XG (2010). Remote sensing of the urban heat island in Beijing during increasingly hot summers. Environmental Research 159: 249-256. - doi: 10.1016/j.envres.2009.10.008
Ma N, He XY, Shi XF, Chen W (2011). Evaluation of urban forest economic benefit based on i-Tree model. Chinese Journal of Ecology 4: 810-817 [In Chinese]. - doi: 10.13230/j.issn.1000-4890.2011.01.07
Mariani L, Parisi SG, Cola G, Laforteza R, Colangelo G, Sanesi G (2016). Climatological analysis of the mitigating effect of vegetation on the urban heat island of Milan, Italy. Science of the Total Environment 569-570: 762-773. - doi: 10.1016/j.scitotenv.2016.06.111
Marzilli P, Aider M, Sangrà A, Piroddi C, Sanesi G (2013). Forest cover and temperature in urban areas: a case study in Northern Italy. Urban Forestry and Urban Greening 12: 246-254. - doi: 10.1016/j.ufug.2013.01.006
Panno A, Carrus G, Laforteza R, Mariani L, Sanesi G (2017). Nature-based solutions to promote urban resilience and wellbeing in cities during increasingly hot summers. Environmental Research 159: 249-256. - doi: 10.1016/j.envres.2017.08.016
Penn K, Oettle M, Haas EM, Raiter R (2013). Vertical greening: the key to success in urban greening systems, a process tree for green façades and living walls. Urban Ecosystems 16: 265-277. - doi: 10.1007/s11252-012-0262-3
Pesola L, Cheng X, Sanesi G, Colangelo C, Ella M, Laforteza R (2017). Linking above-ground biomass and biodiversity to stand development in urban forest areas: a case study in Northern Italy. Landscape and Urban Planning 157: 90-97. - doi: 10.1016/j.landurbplan.2016.06.004
Qin YM, Liu K, Wang YJ (2006). Ecological func-
Ren Z (2014). Multi-scale effects of urban forest on urban thermal environment: a study in Changchun. Ph.D. thesis, Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences, Changchun, China, pp. 156 [in Chinese]. [online] URL: http://d.wanfangdata.com.cn/Theiss/Y116236

Shashua Bl., Hoffman ME (2000). Vegetation as a climatic component in the design for predicting the cooling effect of urban green areas with trees. Energy and Buildings 31: 221-235. - doi: 10.1016/S0378-7788(99)00018-3

Solecki WD, Rosenzweig C, Parshall L, Pope G, Wang W et al. - iForest 11: 140-147

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 (ΔT_h), vertical cooling (ΔT_v), soil cooling (ΔT_s), shading effects (ΔE_shading %) and humidifying (ΔRH).

Tab. S2 - Results of the redundancy analysis of microclimatic regulation functions: radiating, RH, T_air, forest floor T_f, and under-canopy T_c.

Link: Zhang_2466@suppl001.pdf

Li B (2015). Research advance in effect of ecological system in Xi’an. Chinese Journal of Ecology 25: 155-159. [in Chinese with English summary]. [online] URL: http://en.cnki.com.cn/Article_en/CJFD TOTAL-STX200602004.htm

Wang KL, Zhong ZL, Wang Q, Wang HM, Fu YJ, Zhou LC, Shi WY, Xue WJ, Wang TH (2005). Relating none-greening square and lawn on temperature and moisture in urban green space. Journal of Ecology 24: 1102-1105. [in Chinese] - doi: 10.1016/j.chinaes.2005.01.008

Zhang D, Zheng HF, He XY, Ren ZB, Zhai C, Yu XY, Wu F, Li SH, Liu JM (2007). The effects of greening none-greening square and lawn on temperature, humidity and human comfort. Acta Ecologica Sinica 27: 2964-2971. [in Chinese]. - doi: 10.52303/j.issn.0953-2007.07.038

Zhang Z (2007). Study on structure of road greening and the improvement of microclimate in Harbin. Master Thesis, Northeast Forestry University, Harbin, China, pp. 51. [in Chinese] [online] URL: http://d.wanfangdata.com.cn/Theiss/Y116236

Zhang Z, Lv Y, Pan H (2013). Cooling and humidifying effect of plant communities in subtropical urban parks. Urban Forestry and Urban Greening 12: 323-339. - doi: 10.1016/j.ufug.2013.03.010

Wang NH, Yu C (2005). Study of green areas and urban heat island in a tropical city. Habitat International 29: 547-558. - doi: 10.1016/j.habitat.2004.04.008

Wu F, Li SH, Liu JM (2007). The effects of greening none-greening square and lawn on temperature, humidity and human comfort. Acta Ecologica Sinica 27: 2964-2971 [in Chinese]. - doi: 10.3321/j.issn:1000-0933.2007.07.038

Wu Z, Lin YD, Yan HB, Hao XY (2008). Correlation between ecological effect and structure characteristics of urban green areas. Chinese Journal of Eco-Agriculture 16: 1469-1473. - doi: 10.3724/SP.J.1011

Xu S, Chen W, He XY, Huang YQ, Gao JY, Zhao Y, Li B (2015). Effects of urban trees on local outdoor microclimate: synthesizing field measurements by numerical modelling. Urban Ecosystems 18: 1305-1311. - doi: 10.1007/s11252-015-0447-7

Wang WF, Bakker F, Groot RD, Worpthe H, Leemans R (2015). Effects of urban trees on local outdoor microclimate: synthesizing field measurements by numerical modelling. Urban Ecosystems 18: 1305-1311. - doi: 10.1007/s11252-015-0447-7