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Street trees: The contribution of latent heat flux to cooling dense urban areas

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A R T I C L E I N F O

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A B S T R A C T

Trees are the most important natural factor to alleviate the urban heat island effect and the latent heat flux (LE) they release contributes significantly to urban cooling. In this study, the model ENVI-met was used to study the influence of building geometry on the LE exchanged by trees at the block scale in compact urban areas. The building density (BD), building height (BH) and sky view factor (SVF) were used to characterize building geometry. The sensitivity of LE to building geometry was estimated by multi-linear regression analysis. The following conclusions were drawn:(1) the LE of trees is sensitive to building geometry, higher during daytime than night-time in winter and the higher during night-time than daytime in summer; (2) LE changes as expected across the seasons, with LE larger in summer; (3) The shade affects the LE of a tree by influencing the solar irradiance; (4) In winter the average LE of a single tree is larger with 0.06 than 0.12 fractional vegetation cover (FVC). This study can provide useful leads towards further research to explore latent heat exchanges by trees at the street scale.

1. Introduction

The urban heat island (UHI) affects many millions of people in the world (Mohajerani et al., 2017) and has severe impacts on human health and urban environment (Heaviside et al., 2017). The UHI not only has enormous consequences for health and wellbeing of urban residents, but also increases energy use in urban areas in warm climate conditions (Martilli et al., 2020). Additionally, the UHI is also associated with increasing air pollution(Zheng et al., 2018). How to mitigate the urban excess heat to reduce the UHI concerns both researchers and urban planners.

Urban green space is an important nature-based solution to mitigate urban environmental and human health problems (Krayenhoff et al., 2021). Numerous studies based on remote sensing data and numerical modeling showed that urban green space can reduce urban surface and air temperature (Shiflett et al., 2017; Yang et al., 2022). Krayenhoff et al. (2021) defined the vegetation cooling

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effectiveness as the temperature change caused by the added fractional vegetation cover (FVC). Vegetation mitigates the urban excess heat through transpiration and shading (Mariani et al., 2016). Alexander (2021) showed that where vegetation cover was increased from 0 to 5 % to 95–100 %, median values of land surface temperature (LST) decreased by 4.2 ± 0.8 °C. Zhang et al. (2022) showed that the green space reached the maximum cooling efficiency when building density(BD) was between 0.25 and 0.3. Chapman et al. (2018) showed that mean air temperature may increase by 2.2 °C to 3.8 °C in the absence of vegetation during a hot day in high density area in subtropical city (Brisbane, Australia). Erell and Zhou (2022) showed that mean annual urban air temperature may increase 0.42 °C without vegetation. This means urban vegetation is very important for mitigating urban excess heat, even small vegetation patches. The cooling effect of different vegetation types varies: the cooling effect of trees is a function of intercepted sunlight and background climate, while grass has a smaller effect than trees(Gallay et al., 2023; Smith et al., 2023). Kim et al. (2024) showed that trees are 2–3 times more effective than grass, green roofs and walls to reduce local air temperature. Ouyang et al. (2023) evaluated three urban green infrastructure (GI) typologies, i.e. ground tree, green roof and green wall, showing that ground tree should be prioritized in terms of GI solutions. Liu et al. (2023a) showed that the cooling intensity of ground trees does not change significantly with building form, contrary to green roofs and vertical green walls. This means that urban three-dimensional green objects have beneficial impacts on urban cooling and the cooling effects of different green objects are impacted differently by building forms.

Radiative load in the urban 3D space is higher than in rural areas because of its structure and materials. The received radiative load can be dissipated as sensible and latent heat (Yang et al., 2023). Sensible heat increases surface and air temperature, while latent heat flux(LE) is important for urban excess heat mitigation (Singh et al., 2020). Urban trees increase heat dissipation by LE without increasing air and surface temperature because energy is used for the liquid to vapor phase transition (Ryu et al., 2016). The urban geometry changes the urban surface roughness, thus the turbulent exchange of heat, and this then affects both the sensible heat flux and LE. Narrow streets cast shadows on trees thus reducing solar irradiance and cooling by latent heat exchange (Chen et al., 2023).

However, it is often a challenge to observe a small vegetation patch in densely-built urban areas by using remote sensing images. The thermal infrared signal captured by remote sensing images is the result of surface-atmosphere interactions and it is an instantaneous recording(Li et al., 2020), making it challenging to retrieve information on the overall role of vegetation in urban cooling. Several studies showed that only when vegetation fraction is larger than 0.2, measurements of spectral radiance may reveal its presence(Hou et al., 2014). Yang et al. (2022) showed that vegetation has an impact on land surface temperature when its fractional abundance is higher than 0.2. On the other hand in dense urban areas, the street tree fractional abundance is very low. Such low vegetation fraction is difficult to observe using multi-spectral radiometric measurements. Previous studies have demonstrated that the effect of transpiration of vegetation patches at different sizes in urban areas on temperature changes is between 1 °C and 8 °C (Winbourne et al., 2020). Evapotranspiration can be estimated in large areas by remote sensing data, but its resolution is usually too coarse, given the spatial variability in the urban space at the level of streets or neighborhoods(Zou et al., 2019). The insufficient spatial resolution also causes errors in evapotranspiration estimates(Kowe et al., 2021). Vegetation still releases water vapor from leaves in very dense urban areas and has very important impacts on urban ecology and environment, but it cannot be estimated at low resolution. Liu et al. (2017) showed that even at low FVC, ignoring tree evapotranspiration may lead to a serious underestimation of urban LE. To solve this problem, many studies used on-site monitoring methods to study the cooling efficiency of urban greenery (Gillner et al., 2015; Rashid et al., 2014), but it is difficult and expensive to monitor large areas(Ng et al., 2012). How the trees in densely-built areas exchange energy with the surrounding air is still not clear.

With the development of computer power, numerical simulation has become a popular method to investigate energy exchange between urban landscape elements and atmospheric boundary layer by numerical experiments(Li et al., 2023). Current models of urban climate allow a detailed representation of urban space, so that numerical experiments on the performance of alternate configurations of the urban landscape can be carried out. The latter includes the evaluation of the contribution of urban trees to mitigate urban excess heat. Liu et al. (2020) showed that ENVI-met is the most accurate of three numerical simulation models, i.e. ENVI-met, RayMan, SOLWEIG, in calculating the urban radiation and heat balance. Accordingly, we chose to apply ENVI-met in this study. ENVI-met can simulate biophysical processes related to urban trees at high spatial resolution (Liu et al., 2018; Simon et al., 2018), and estimate the transpiration of trees.

A small change in low vegetation cover may only cause a small change in surface and air temperature. How the latent heat changes in response to a change in FVC and in background geometric characteristics is still not clear. Thus, this study will focus on changes in the LE exchange caused by a change in FVC under different geometry conditions, addressing the difficulty of observing street trees in compact urban areas. Considering the challenges in observing the low fraction of vegetation in dense urban areas, this study will explore urban geometry effects on LE of street trees relying on numerical experiments with ENVI-met. We evaluated two types of changes in LE: the ones due to building geometry and the ones due to changes in FVCs.

Using ENVI-met to simulate tree transpiration and its effects on the atmospheric boundary layer at high spatial resolution, this study aims to determine: (1) how the urban geometry affects the street-level tree LE? (2) how the street-level cooling effect of trees change with the vegetation fraction?

2. Methods

2.1. Study area

Hong Kong is located in a subtropical climate zone with hot and humid summers. Urban vegetation in Hong Kong is predominantly evergreen broad-leaved forest. The urban area of Hong Kong is concentrated in just 25 % of the total land area with very little FVC, and approximately 31 % of building heights are in the range of 20-60 m, with the street layout being regular in some areas. Hong Kong is one of the highest urban density and population density in the world(Ouyang et al., 2020), making the urban heat island effect significant. Urban greenery (i.e. ground trees, green roofs and walls) is a good way to mitigate the urban heat island.

2.2. ENVI-met model

ENVI-met is a prognostic three-dimensional microclimate model, based on the fundamental laws of fluid dynamics and thermodynamics. ENVI-met simulates the interactions of the various elements in an urban space scenario with high spatial (0.5-10 m) and temporal (10s) resolution and it is widely used in urban micro-climate modeling(Sinsel, 2022). The vegetation canopy in ENVI-met is defined by using sub-grid elements having different leaf area density. In ENVI-met three core models connect with each other, including vegetation model, soil model and atmosphere model. ENVI-met can output heat fluxes, such as sensible heat flux and LE, and the details of how ENVI-met simulates the elements can be found in Simon (2016).

Many studies have used ENVI-met to study the cooling efficiency of trees, mainly as regards cover, type, and morphological characteristics(Wang et al., 2023).The vegetation model makes it possible to accurately simulate vegetation transpiration during a short or long period of time. Simon et al. (2018) compared transpiration rate between simulation and the actual measurement, showing that ENVI-met can evaluate transpiration accurately, thus the cooling efficiency of trees. Liu et al. (2018) showed that the tree model performs well in subtropical hot-humid climates. Thus, this study investigated the impacts of urban geometry on urban street trees cooling effects based on LE modelled by ENVI-met 5.6.1.

2.3. ENVI-met scenario setting and simulation

In this study, we selected 22.28°N and 114.17°E as the center of model scenarios of the study area. The weather forcing was defined using the meteorological data from the Hong Kong Observatory. According to data collected by the Hong Kong government, the average tree height in the Kowloon District of Hong Kong is 8.05 m and the crown diameter is 4.79 m (Wang et al., 2022), and most trees are evergreen broad-leaved. Basing on this information, we chose Ginkgo/Fan Leave Tree(young) in Albero as tree in the scenarios, because its height is 8.45 m, and the crown diameter is about 4.6 m. We did not apply tree calendar in all scenarios, thus it can be assumed the trees to be evergreen broad-leaved. Most roofs are made of concrete and walls are made of tiles, the road surface is mostly made of concrete in urban areas, and building materials were selected from the options available in ENVI-met 5.6.1 (Table 1).

We built 60*59*26 grid cells with 5 m resolution and added 4 boundary nesting grids in each horizontal direction to ensure the stable operation of the model, thus the total simulated grids were 68*67*26, but nesting grids are not included when the result data are analyzed in study area. To avoid buildings being too close to the boundaries of the scene, we defined some grids around the scene without buildings and trees, but this causes the sky view factor (SVF) to be high, so these grids were not included in the regressions with SVF.

We simulated LE in summer and winter to compare the seasons. Two vegetation patterns were considered in the scenes, one with 436 trees and the other with 216 trees with different FVC. The impacts of building geometry on the LE of trees were investigated by changing the geometry of the buildings. 12 buildings were placed in the scenes, ranging in building height (BH) from 20 to 60 m, length from 30 to 70 m and width from 10 to 50 m, decreasing in steps of 10 m (Fig. 1). To better explain the impact of building geometry on LE of trees, the parameters of each building and street width in the same scene were the same, and four scenes without buildings were created. Totally 104 scenes were built in this study.

In this study, BD, BH and SVF were used to account for building geometry. For the 100 scenarios with buildings, we established

Table 1
Parameters applied in the scenarios evaluated in the numerical experiments by ENVI-met.

Parameters	Input
Simulation start day in summer	2015-07-11
Simulation start day in winter	2015-12-28
Simulation duration	37 h
Start time	12:00(UTC + 8)
Boundary condition	Full Forcing
Clouds	0
Initial air temperature in summer	31.5 °C
Initial air temperature in winter	17.3 °C
Soil humidity	65 % (0-20 cm) 70 % (20-50 cm) 75 % (50-200 cm) 75 % (below 200 cm)
Soil temperature	20 °C(0-20 cm) 20 °C(20-50 cm) 19 °C(50-200 cm) 18 °C(below 200 cm)
Roof	concrete wall
Wall	roof: tile
Road	concrete pavement gray
Tree	Ginkgo/Fan Leave Tree(young)

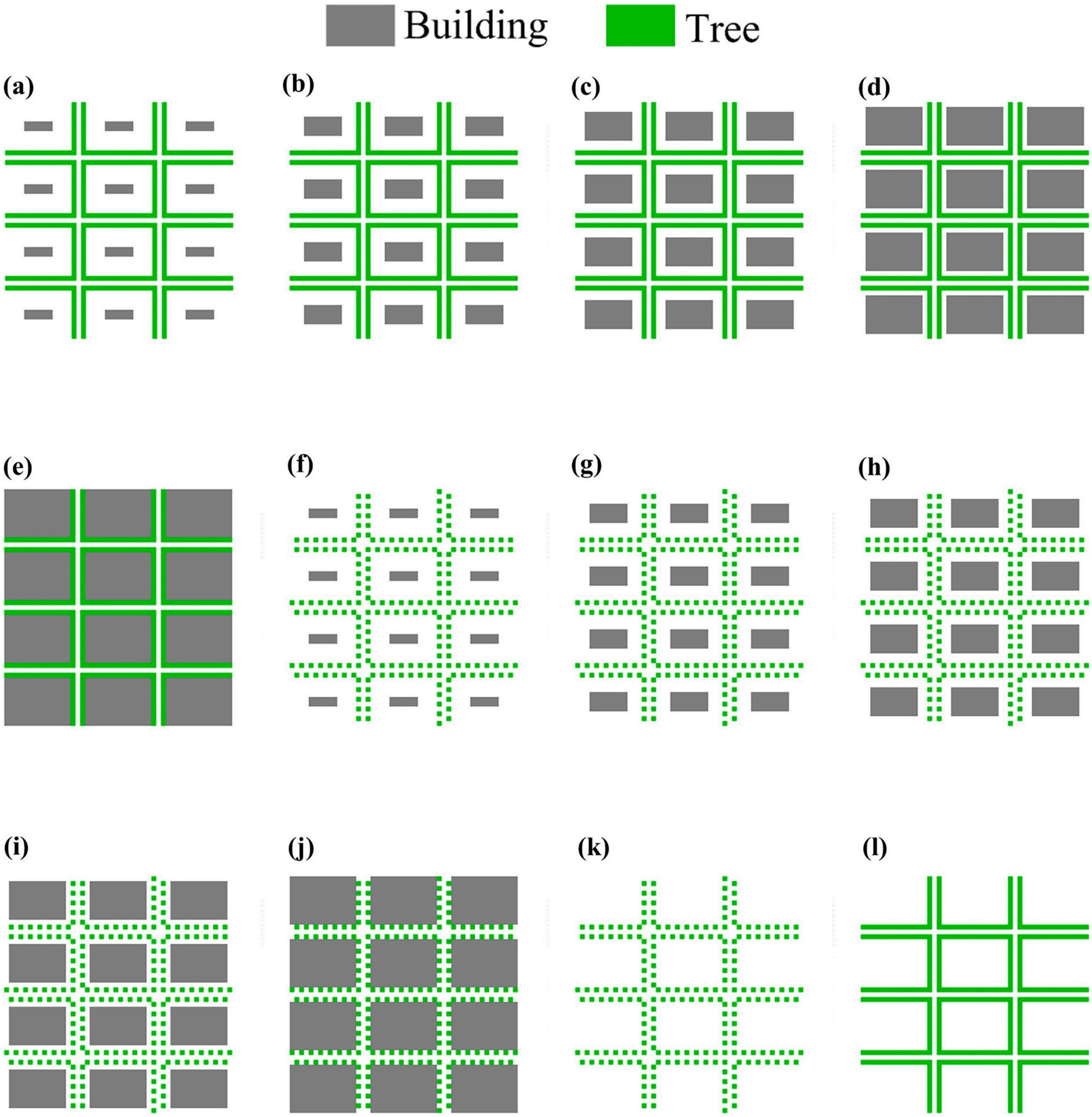

Fig. 1. Based on the BD in scene a to scene j changing the BH (20-60 m, step 10 m), scene k and scene l are without buildings.

multiple linear regressions between LE and the two factors (i.e. BH, BD), and univariate linear regression of LE and SVF to estimate the sensitivity of LE to building geometry. Before the analysis, we also normalized all parameters to facilitate subsequent analysis. We used the slopes of the multiple linear regression equation and the univariate linear regression equation as a metric of the response (sensitivity) of LE to building geometry. When the slope is positive and greater than 0 that the LE increases with the increase of building geometry, while when it is less than 0, it is the opposite.

The input meteorological values for ENVI-met simulation scenarios were the same in the same season, and soil conditions were default in ENVI-met. Tree parameters and urban materials were the same in all scenarios (Table 1). Full forcing was used in the simulations because Hong Kong Observatory provided meteorological data during the simulation times. These avoid differences in output results due to the difference of input meteorological data, urban materials and parameters of tree within the model.

3. Results

3.1. Relationship between LE and LT

The results of the ENVI-met simulations were used to assess the response of LE and leaf temperature (LT) to vegetation cover and the geometry of the urban space. The relationship between LE and LT in daytime shows that LE increases as the temperature increases, but LE reaches the maximum value at about 32.5 °C (Fig. 2(a)). LE reaches the maximum value in winter at 22.5 °C because of net radiation and temperature limitations. This is because the vegetation receives more net radiation in summer which increases the energy available for transpiration and evaporation. Sensible heat flux also increases with higher surface temperature, and increases the air and surface temperature. In summer around noon, the high irradiance makes the sensible heat flux to increase and then the air and surface temperature increase. An increase of LT and vapor pressure deficit (VPD)increases sharply the leaf resistance (r_s) (Fig. 2 (b)). Fig. 2 (b) shows that there is a nonlinear relationship between LT and stomatal resistance. Overall, the stomatal resistance clearly increases with increasing LT up to 50 °C. Fig. 2 (c) shows that r_s is increasing in the morning and it is opposite in the afternoon. This is because with the increase of solar radiation, the sensible heat flux of the trees is increasing, resulting in an increase in leaf surface temperature and air temperature. This also leads to increased stomatal resistance of the leaves. With the increase of stomatal resistance, the LE of trees is reduced, and then LT increases.

3.2. Variation of LE during daytime

Fig. 3 shows that the seasonal variation of LE is similar for both 0.12 and 0.06 FVC, with bimodal and unimodal patterns in summer and winter, respectively. This may be due to the increase of stomatal resistance or even closure due to higher temperature and larger

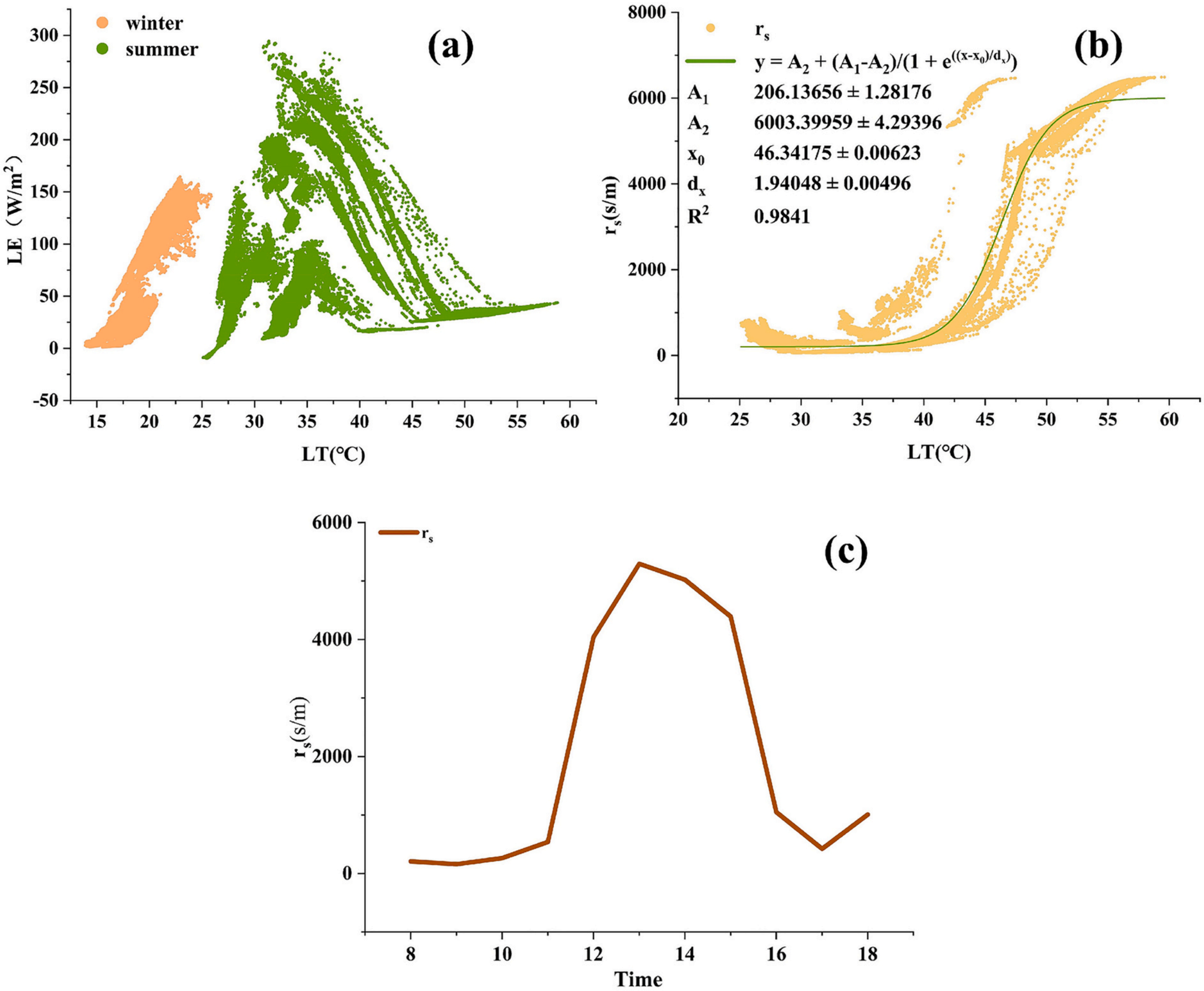

Fig. 2. (a)the relationship between daytime LE and LT in summer(green) and in winter(orange); (b)the relationship between LT and r_s; (c) the average change of r_s from 8:00 to 18:00 in summer.

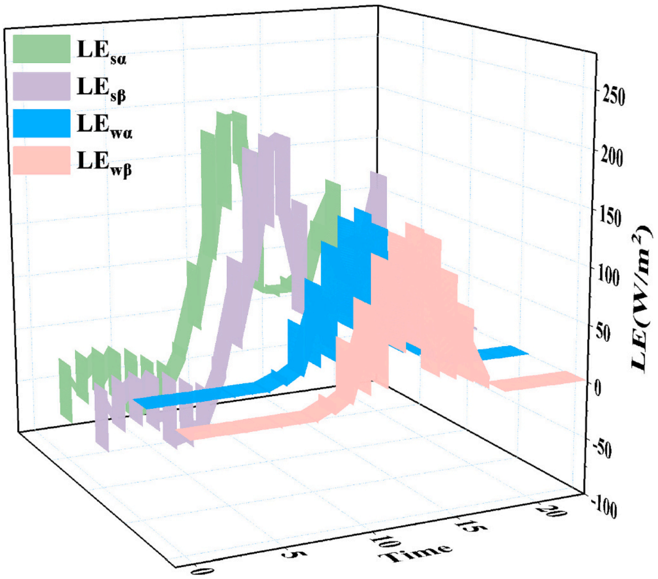

Fig. 3. LE of trees (W/m^2) (a)LE$_{s\alpha}$ is 0.12FVC in summer(green); (b) LE$_{s\beta}$ is 0.06FVC in summer(purple); (c)LE$_{w\alpha}$ is 0.12FVC in winter(blue); (d)LE$_{w\beta}$ is 0.06FVC in winter(pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

VPD in summer after noon (Fig. 2(c)). In summer, the peak occurs after sunrise and a few hours before sunset, and the trough occurs a few hours after noon, which happens to be the peak in winter.

The LE from 0:00 to sunrise is negative in summer (condensation). The diurnal variation of LE in summer is large and may reach the

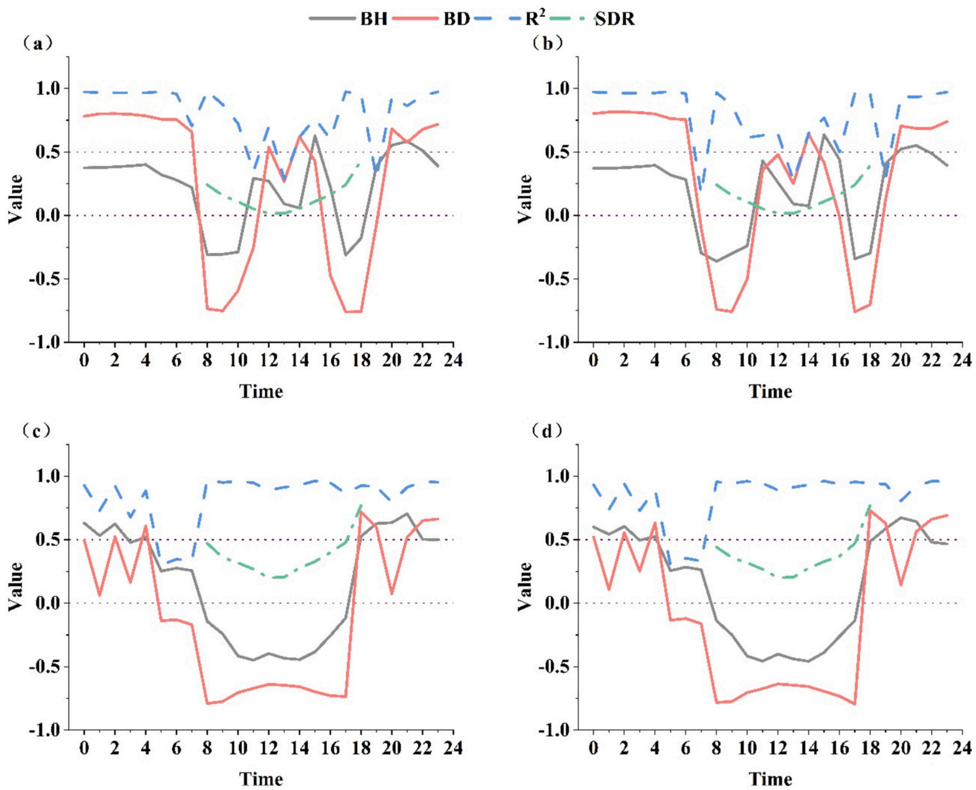

Fig. 4. Multiple linear regression slope of BH (gray) and BD (red), R^2 (blue)and shades to scene area ratio (SDR) (green)at daytime (a)LE$_{s\alpha}$; (b) LE$_{s\beta}$; (c)LE$_{w\alpha}$; (d)LE$_{w\beta}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maximum of 269 W/m^2 and 259 W/m^2 for the two FVCs, respectively, while the maximum LE is only 143 W/m^2 and 147 W/m^2 in winter. Irradiation is greater in summer than in winter, which causes seasonal differences in LE of trees.

3.3. The relationship between building geometry and LE

The daily change in the sensitivity of summer LE to BH and BD shows a 'W' shape (Fig. 4(a) and (b)). This is due to the high irradiance in the daytime of summer, which causes the increase of LT and the closure of leaf stomata. The scenarios for the two FVCs at nighttime show a positive correlation between LE and BH/BD, and the change in the sensitivity of LE is smooth. There is a difference in the sensitivity of LE in daytime compared to nighttime. During the daytime, this trend is clear, especially between 12:00 and 16:00. From 8:00 to 11:00 and 16:00 to 18:00, there is a negative correlation between LE and BH/BD, and the rate of change gradually decreases and transitions to a positive correlation. From 12:00 to 16:00, there is a positive correlation, but the rate change of LE is fluctuant (Fig. 4 (a)). Fig. 4 (a) shows that R^2 between LE and BD/BH, which is below 0.5 at 11:00,13:00 and 19:00. R^2 is below 0.5 at 7:00,13:00,16:00 and 19:00(Fig. 4 (b)). LE may be influenced by stomatal resistance and meteorological disturbances in response to fast changes in forcing variables at fast sunrise and sunset.

Fig. 4(c) and (d) show that the daily change in the sensitivity of winter LE to BH and BD shows a 'U' shape. It is clear that the change in the sensitivity of LE at daytime is smoother in winter than in summer, due to lower irradiance and temperature. There is a negative correlation at daytime and the opposite at nighttime (Fig. 4 (c) and (d)). The change in the sensitivity of LE is smooth at daytime and fluctuant at nighttime. There is a positive correlation between LE and BH, but a negative correlation between LE and BD, and R^2 is lower than 0.5 at 5:00–7:00(Fig. 4(c) and (d)). LE may be influenced by low temperature.

Fig. 5 (a) and (b) show that the daily evolution of the sensitivity of summer LE to SVF has an "M" shape. It is clear that high irradiance and temperature cause instability in summer daytime LE. The sensitivity of LE fluctuates sharply during daytime and fluctuates smoothly during nighttime. Fig. 5(a) shows that there is negative correlation at nighttime and from 12:00 to 15:00, but is reversed at other times. The sensitivity rate of summer LE with SVF fluctuates sharply from 12:00 to 15:00. There is negative correlation during nighttime and from 11:00 to 16:00, but reversed at other times (Fig. 5(b)). R^2 is below 0.5 mainly at 13:00, 15:00–16:00, 19:00 at 0.12 FVC, and at 7:00,13:00, 15:00–16:00, 19:00 at 0.06 FVC. SVF plays little role in LE during the day because of stomatal resistance. LE is influenced by meteorological disturbances in response to fast changes in forcing variables at sunrise and sunset, and stomatal resistance in the afternoon.

Fig. 5 (c) and (d) show that the daily evolution of the sensitivity of winter LE to SVF has an inverted "U" shape. Without the limitation of high irradiance, the sensitivity of LE would be more stable after noon. In winter, there is a positive correlation at daytime and the opposite at other times (Fig. 5(c) and (d)). Fig. 5(d) shows a positive correlation at 5:00. The sensitivity of LE does not fluctuate

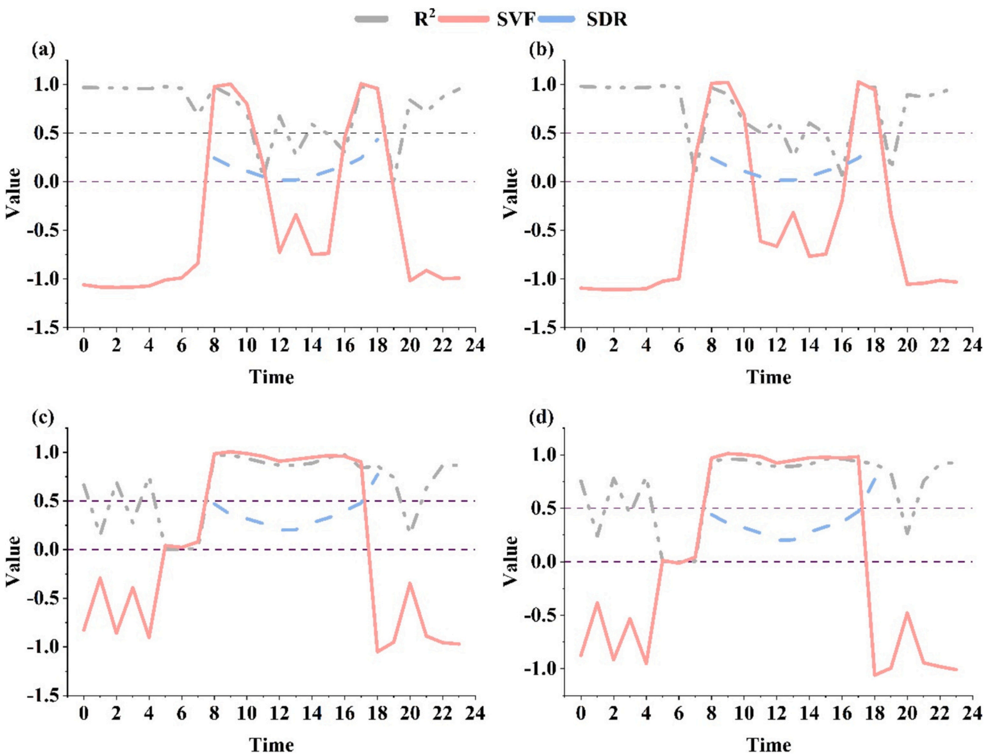

Fig. 5. Univariate linear regression slope of SVF (red), R^2 (gray)and SDR (blue) at daytime(*a*)$LE_{s\alpha}$; (b) $LE_{s\beta}$; (c) $LE_{w\alpha}$; (d)$LE_{w\beta}$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during daytime, but it is the opposite during nighttime. R^2 is below 0.5 for two FVCs settings at 1:00, 3:00, 5:00–7:00, and 20:00. LE may be influenced by low temperature in the evening and the unstable changes before sunrise.

Fig. 4 and Fig. 5 show that shaded areas decrease in the morning and increase in the afternoon in summer and winter, while shaded areas are small around noon. The shaded areas are greater in winter than summer, meaning that irradiance is higher in summer than winter. Due to high sun altitude angle around summer noon, the higher BH and the greater BD can provide more shades, which is conducive to the increase of LE.

We compared the R^2 of the multiple linear regression with the R^2 of the univariate linear regression analysis. It can be seen that the combined effect of BH and BD is a stronger driver of LE than SVF. Moreover, comparing the absolute values of the slopes for BD and BH in the multiple regression analysis, it was found that the influence of BD is greater than BH. In summer the sensitivity gradually decreases in the morning. Because the sun altitude angle increases with time, the solar radiation received by trees increases. According to the slope of regression analysis, the influence of building geometry on the LE of trees is greater during winter daytime than summer daytime.

3.4. The difference between shadow and no shadow

We paired the shadows with the position of the trees to distinguish between the shaded and the sunlit trees. During the summer day, after sunrise and a few hours before sunset, the LE of trees in the shaded area is lower than that in the sunlit area, and the reverse is true at noon. In winter, the LE of shaded trees is significantly lower than that of sunlit trees (Fig. 6). It shows that solar radiation does indeed affect LE of trees.

3.5. LE of the difference between buildings and no buildings

To study the influence of buildings on LE, it was calculated whether there was a difference related to buildings expressed as:

$$\Delta LE = LE_{wb} - LE_b \tag{1}$$

LE_{wb} is LE without buildings, and $LE_b$is LE with buildings. As can be seen from Fig. 7, during the summer daytime this difference appears to be positive a few hours after sunrise and before sunset, and at noon it is mostly negative. In winter, the difference is positive, which also indicates that the building reduces the LE of trees in winter by reducing the tree absorption of solar radiation through shading caused by the low sun elevation (Fig. 7).

3.6. The impact of FVC on LE

In the cases with the same building geometry, the LE estimated for tree in the 0.12 and 0.06 FVC scenarios at the same location were compared.

$$\Delta LE = LE_{0.12FVC} - LE_{0.06FVC} \tag{2}$$

where $LE_{0.12FVC}$ and $LE_{0.06FVC}$ are average LE of tree with FVC = 0.12 and 0.06 at the same location, respectively. In summer, the average LE of tree for the FVC = 0.12 case is greater than for FVC = 0.06 from 9:00 to 12:00, with the difference exceeding 60 W/m^2 at times. In the afternoon, this difference is much smaller. In winter, this difference is negative in most cases, indicating that the increase in FVC reduced the average LE of tree at the same location (Fig. 8(a)).

In the case of the same building geometry, the difference in average LE in the scenarios was calculated as:

$$\Delta LE = LE_\alpha - LE_\beta \tag{3}$$

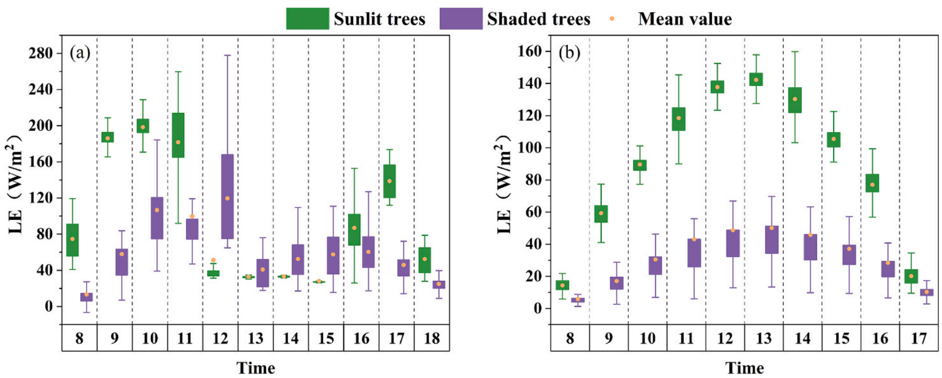

Fig. 6. LE in sunlit trees(green) and shaded trees(purple) (a)summer; (b)winter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

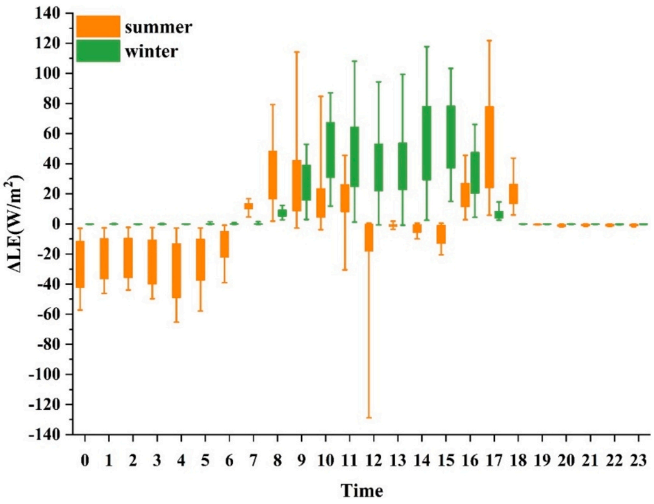

Fig. 7. The difference between LE without buildings and with buildings in summer (orange) and in winter(green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

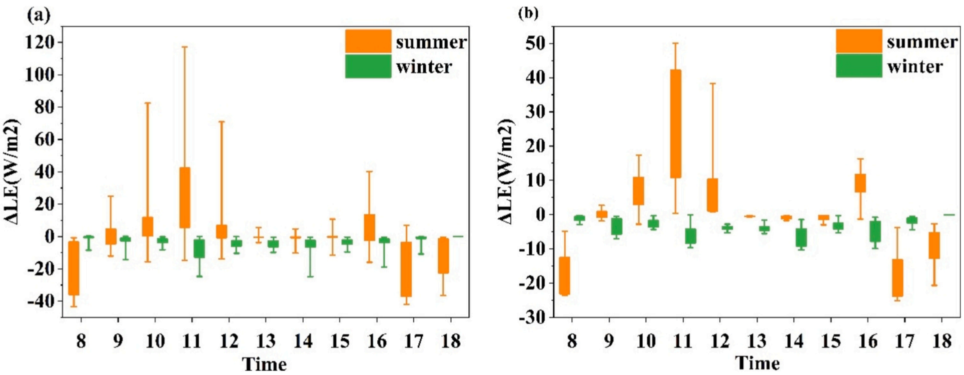

Fig. 8. (a)LE difference at the same location; (b) average LE difference caused by FVC.

LE_α is the average LE for 0.12 FVC, LE_β is the average LE for 0.06 FVC. As can be seen from Fig. 8(b), LE_α is higher than LE_β several hours after sunrise in summer. As the FVC increases, the LE increases in summer, but the average LE is lower in winter. This means that the effect of increasing tree cover on average LE is different across seasons in different time.

4. Discussion

The cooling effect of trees is mainly determined by two factors: shading and evapotranspiration (Smith et al., 2021), but the factors affecting the evapotranspiration of trees are very complicated (Jin et al., 2022).Tree evapotranspiration is affected by solar radiation, air temperature, humidity, and soil moisture (Mu et al., 2021). These changes will cause changes in LE. The solar radiation in urban areas is affected severely by urban geometry. Additionally, the urban geometry also changes the urban roughness length. Both affect the urban vegetation energy exchange and LE. Additionally, the cooling effects of street trees in dense urban areas are little discussed because they are relatively difficult to observe by thermal infrared remote sensing. Thus, this study focused on the influence of building geometry on LE of street trees using the ENVI-met.

Evaporation from water bodies and swamps, as well as transpiration from forests and grasslands, are natural processes that create LE, providing cooling services in urban areas(Park et al., 2021). Water body can create more LE in the same area, but water is less distributed in high density urban areas(Park et al., 2021). Kong et al. (2023) showed that mean LE is close to 0 in urban areas because of the widespread presence of impervious surfaces. This finding underscores the importance of sources of LE, such as vegetation transpiration, which becomes a significant contribute to the urban LE. Therefore, vegetation transpiration accounts for a significant portion of total urban LE, which may include the contributions of soil and open water evaporation (Ding et al., 2023). The balance of radiative and convective fluxes at leaf level determines the LT (Fig. 2(a)). It is found that the LE reaches the peak when LT reaches around 32.5 °C. This is because LE decreases due to multiple stress factors, thus sensible heat flux increases to dissipate the high net radiation in summer. Then both air and LT increase. Too high LT leads to an increase in stomatal resistance of the leaves and lower LE

(Fig. 2(b)). This means that the cooling effect of the LE of street trees in dense urban areas under extreme high temperature is less than under non-extreme high temperature conditions.

In the process of growing, trees need to absorb water from the soil to ensure high transpiration (Marx et al., 2022). In summer, the transpiration of trees is strong, and soil water uptake increases, which will lead to the decrease of soil moisture (Abdallah et al., 2020; Liu et al., 2023b). Trees transpiration increases and the soil moisture decreases in the morning, which influences transpiration of trees and then may cause low LE in the afternoon. Impervious surface and weather conditions affect the recovery of soil water content (Fini et al., 2022). Therefore, urban trees need adequate irrigation to ensure that the cooling effect of the tree can be better harnessed.

The peak of LE of trees is at different times in the two seasons because trees receive more solar radiation in summer than in winter (Wallenberg et al., 2020). Trees absorb solar radiation for a short period of time and begin to warm, transpiration occurs, peaking a few hours after sunrise. Due to the large sun altitude angle in summer, the building geometry can provide short or even no shade at noon. To avoid losing too much water at noon, trees increase stomatal resistances and transpiration will decrease, but it will lead to high LT (Simon, 2016). Persisting high LT will lead to closure of stomata to prevent further loss of water (Meili et al., 2021), so LE is low after noon. The high transpiration of vegetation during the morning in summer may lead to the decrease of soil water content (Abdallah et al., 2020; Liu et al., 2023b) and the decrease of LE in the afternoon. As the temperature continues to drop and water potential of the trees gradually recovers (Feng et al., 2022), the leaves begin to transpire again, and there is a second peak appearing before sunset, but it is significantly lower than the first peak. On summer nights the LE is negative, meaning that condensation takes place (dew formation) (Meili et al., 2021). In winter, the trees receive less solar radiation, and the leaves warm slowly, so that they reach the highest temperature of the day around noon, when the LE is the largest. However, in winter, trees do not reach the conditions for maximum LE (Feng et al., 2022). The reason is that the solar radiation and net radiation in winter are lower, thus smaller sensible and LE heat flux. Thus, the maximum LE of street trees occurs at around 10:00 to 11:00 in summer (Fig. 3).

Solar radiation is an important factor affecting tree transpiration (Huang et al., 2022), and shade affects the solar irradiance absorbed by a tree. The trend of sun elevation angle increases in the morning and decreases in the afternoon during daytime, the solar irradiance has the same change trend and the shaded areas have opposite trends in summer and winter, but solar irradiance and LE are greater in summer than winter. The building geometry increases will lead to more facades being sunlit, and then larger shadows on the ground. The comparison of shaded and sunlit trees also shows that shade reduces or increases the LE of trees over a certain period of time. Shade can affect the cooling effect of vegetation (Wang et al., 2024), especially a few hours after sunrise in summer. Compared to no shade, shade can cool trees during the summer noon period, since only the diffuse fraction of solar irradiance reaches leaves in shaded areas. However, the short time in the shade cannot bring long-term and effective cooling to the leaves, so the cooling effect brought by transpiration is not large at this time. Due to the lower sun elevation trees are longer in the shade in winter than in summer, which makes them receive less solar radiation than in areas without shade, which also causes trees in shaded areas to transpire more and warm more slowly than trees in areas without shade. Even on a small scale the impact of canopy architectural shading on the LE cannot be ignored. In subtropical regions, trees oriented in a N-S direction receive less solar irradiance in summer than *E*-W trees. In winter, trees oriented in a E-W direction receive less solar irradiance than N-S trees. Therefore, in the layout of the tree, we should consider the orientation of tree lines. To improve the ability to cool in extreme weather, trees should be planted in the pavements to provide shade, and trees can also provide good cooling on summer nights(Wang et al., 2018). Nowadays, there are many reflective materials used in the urban space (Yang et al., 2015), which allow to increase irradiance onto trees in shaded patches.

Buildings in urban space can create large shades and reduce significantly solar irradiance onto trees in summer several hours after sunrise and several hours before sunset(Fig. 4 and Fig. 5), which gives a large LE and sensible heat flux difference between patches with buildings and those without buildings. At noon in summer, when sun elevation is very high solar radiation is the highest, shaded patch area of buildings is small and surface temperatures, air temperatures and LT gradually increase. High temperature is one reason that forces closure of the stomata, thus reducing the transpiration (Yu et al., 2024). However, there is a time difference between the maximum LE and the maximum solar radiation, at which point the ability to lower the ambient temperature is reduced as LE decreases (Johansson et al., 2013). The sensible heat flux becomes gradually greater than the LE and even dominates, and this is one effect of the low LE after noon (Fig. 3(a) and (b)). In winter, when there is no building, trees get more solar irradiance, while the shielding of trees by buildings reduces solar irradiance onto tree leaves (Jiao et al., 2021). Thus the sensible heat flux and LE of trees without building is higher than when there is a building. Due to the lower temperature in winter, the temperature of the leaves is also relatively low, thus avoiding stomatal closure, but the transpiration effect is less than in summer. It can be seen that the shelter of the building reduces the solar irradiance in winter, and also reduces the sensible heat flux and LE of the trees. Urban buildings on the sunny side absorb a large amount of solar radiation, causing the wall to warm (Nugroho et al., 2022), while the emitted radiation will be absorbed by the surrounding trees, increasing the temperature of the trees. However, in terms of tree cooling efficiency, buildings have a greater impact in summer than in winter.

The influence of different building geometry on LE is different. The influence of BD on LE is larger than BH. The height of the building affects the length of the shade, but when the BH reaches a certain height, even if the BH is increased, it will not have a great impact on solar irradiance onto tree leaves. On streets of different densities, however, trees of different orientations at the right time can also absorb solar irradiance (Loibl et al., 2021). The higher BH and greater BD cast larger shadows around summer noon, then LE is higher (Fig. 4 and Fig. 5). BH, BD, and trees affect SVF, which can demonstrate the effect of building geometry on LE, and large SVF increases solar irradiance compared with small SVF(Kim et al., 2022). The poor correlation between LE and SVF during part of the summer daytime may be due to high temperature and increase of stomatal resistance. High density and tall buildings can cast large shadows on the ground, and the cooling capacity of trees is very weak in these conditions. It is clear that the lower SVF reduces the loss of long-wave radiation(Lin et al., 2010), leading to warming during the night, which increases the LE during the night with the decrease of SVF(Fig. 5). To make the trees play a cooling role, the trees should be kept away from the buildings according to the building layout of the area and the direction of the sun. This allows for good ventilation and allows the tree to receive solar irradiance at the right time.

After understanding the relationship between building geometry and LE of trees, it is necessary to understand the possible reasons for the difference related to vegetation coverage. The increase of FVC in winter increases the total LE, but the average LE decreases. Probably because when vegetation cover is high in winter, the solar irradiance on lower level leaves is reduced (Zhang et al., 2021), with a resulting impact on weakened transpiration. Adding trees reduces the spacing between trees and enhances heat exchange between trees in summer and winter, which may lead to an increase in LE some of the time. The average LE may be different under different FVC, however, and the LE in the whole scenario is still very large. However, multiple studies showed that the increase of trees will reduce the albedo, which may play a role in warming, thus the trees should be rationally arranged (Wu et al., 2024).

Building geometry has important impacts on LE of vegetation, with the value of LE depending on local climate conditions and vegetation type. In this study, airflow is facilitated by the orderly arrangement of buildings. However, high BH and BD will reduce the performance of natural ventilation and decrease airflow(Guo et al., 2023), and there is a difference in the wind speed in the *E*-W direction and the N-S direction in the streets, depending on the prevailing wind direction in the local area. The building geometry affects the distribution of temperature by influencing the distribution of solar radiation and the wind flow and then change the surface energy exchange in urban areas, e.g. LE. Due to the subtropical nature of this study area, with evergreen leaves, it can also be quantified as high latitude summer LE. And the high temperature conditions in summer may not exist in every region.

This study has some limitations. ENVI-met overestimates leaf surface temperature and underestimates water vapor flux at midday in summer (Liu et al., 2018), this is one reason why LE is low at that time. ENVI-met underestimates transpiration in the evening and during night(Simon et al., 2018), this may be one reason why transpiration is low at these times. Cloud cover is an influential factor that affects the amount of solar radiation reaching the ground. In this study, the cloudless setting will cause the solar radiation to be higher than under cloudy conditions. In some scenarios, the building layout may not be realistic. The location of the case-study is in the subtropics, and the values of transpiration of the trees may be different in different regions (i.e. high latitude area). Representing the seasons only by a certain day in summer and winter does not illustrate the variability in LE during the seasons. One type of tree was used in this study, but there are differences in LE among different tree species and crown density conditions. We did not evaluate the results of the numerical experiments with in-situ observations. Sensible heat flux is important for urban energy exchange, and urban geometry also affects sensible heat flux and thus surface energy balance. The impact of urban geometry on the ratio of sensible heat flux to LE (Bowen Ratio), will be further explore in future work.

5. Conclusions

In this study, we used ENVI-met to create 104 scenes to explore the impact of building geometry on the LE of street-scale vegetation, and drew the following conclusions by comparing different seasons.

LE is a crucial factor in the regulation of urban climate. LE exhibits seasonal variability, with a bimodal pattern in summer and a unimodal pattern in winter, and it is higher in summer. However, LE decreases during certain periods in summer, necessitating a rational arrangement of trees and adequate irrigation. Trees significantly enhance their cooling performance in hot summers. Generally, BH and BD reduce LE, while differences in FVC lead to variations in the average LE of trees across scenarios.

This study acknowledges inherent limitations, particularly in its approach to set building geometry, where a regular street layout and same building sizes were employed. However, urban landscapes are inherently diverse, and such irregular may not accurately represent all areas, potentially skewing the results in regions with distinct characteristics. This study was confined to cloudless conditions, which overlooks the impact of varying cloud cover on the outcomes. We will make improvement in future study.

ENVI-met is an important means to investigate the LE of trees at the microscopic scale, which can make up for the insufficient spatial resolution of current thermal infrared remote sensing data. It is to be expected that current model limitations, including underestimates transpiration and overestimates LT in some times, but they will be overcome in the near future.

CRediT authorship contribution statement

Lili Zhu: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Jinxin Yang:** Writing – review & editing, Writing – original draft, Resources, Methodology, Funding acquisition, Conceptualization. **Xiaoying Ouyang:** Writing – review & editing, Methodology, Formal analysis. **Yong Xu:** Writing – review & editing, Visualization. **Man Sing Wong:** Writing – review & editing, Data curation. **Massimo Menenti:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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