Solar Shading Effects by Tree Species in an Urban Environment Using Numerical Simulation Tool

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ABSTRACT: Deciduous trees can be used to moderate temperatures and to decrease ultraviolet radiation (UV-B) by reducing the impact of solar radiation in the summer and by allowing more solar radiation in the winter. In this paper, we compared the solar shading effects of five tree species commonly used for urban landscaping in Japan. We used a numerical simulation tool to predict thermal and UV-B levels under tree crowns in summer and winter months. The simulated study site represented an actual urban space in Tokyo with an open space in front of a high-rise building, whose exterior was constructed with high-reflectance materials. To characterize the thermal environment, we simulated the surface temperature in the shade of the tree and the mean radiation temperature (MRT) under the tree. To characterize the UV-B environment, we simulated the UV-B scalar illuminance under each tree. We found that the maximum difference in surface temperature between any two species was 5 degrees and 10 degrees near the trunk in the summer and winter scenarios, respectively. In addition, the UV-B scalar illuminance differed by as much as a factor of two between tree species.

Keywords: solar shading effects, urban greenery, simulation, seasonal change, thermal and ultraviolet environment

INTRODUCTION

In recent years, the use of green spaces in front of high-rise buildings has increased in Tokyo, Japan. Depending on a given building's shape and construction materials, this green space can alter the amount of radiation in the surrounding environment by directly influencing the amount of thermal and ultraviolet radiation (UV-B) that reaches the ground [1]. Therefore, using deciduous trees in these green spaces can create more comfortable and healthier urban environments, and quantitatively simulating the effects of deciduous trees is important for architectural design [2]. In addition, although research has shown that a tree's effect on thermal and UV-B radiation can vary by species [3], few studies have compared these effects by species in an urban space. In this paper, we compare the solar shading effects of five deciduous tree species in an office area in Tokyo, Japan. We used a previously developed numerical simulation tool [4, 5, 6] to model seasonal (i.e., winter and summer) mean radiation temperature and UV-B scalar illuminance under the different tree species.

THERMAL AND UV-B SIMULATOR

Thermal simulation

The numerical simulation system was used to evaluate the effects of spatial forms and materials on the outdoor thermal environment [4]. The thermal component of the simulation system proceeded as follows:

1) Building, ground and tree shapes were drawn using three-dimensional computer-aided design (3D-CAD) software.
2) Material data were selected from a database included in the system.
3) The 3D-CAD model was then transformed into a mesh model, which was used to calculate radiative heat transfer and surface heat balance.
4) Heat balance and one-dimensional heat conduction were determined for each mesh model, where the convective heat transfer calculation assumed that there were no air temperature or wind velocity distributions within the outdoor space.

The 3D-CAD model allowed for the observation of the distribution in surface temperatures from almost any viewpoint and at various times of day to fully evaluate the effects of specific spatial forms and materials.

In addition, we considered solar radiation in the calculation of mean radiation temperature (MRT) [5]. Solar radiation is arguably the most influential factor when comparing the solar shading effects of various tree species in an urban area. To compare MRT under the study trees, our calculation of MRT considered the human body, which is expressed in micro-cubes using surface weighting factors.

UV-B simulation

We modified the thermal simulator [4] to conduct the UV-B simulation [6]. We used the 3D-CAD software to draw the buildings, ground and trees. The calculation mesh models were then created at a resolution of 200 mm to represent relevant architectural elements, such as nearby windows and balconies. We also considered the sky UV-B radiance distribution because sky UV-B radiation comprises a higher percentage of global UV-B radiation compared to solar radiation.

To predict the UV-B environment at the height of the average human body, UV-B scalar illuminance was calculated in a manner similar to the calculation for the short radiation component of MRT [6].

CALCULATION OF RADIATION

Tree shapes and dimensions (tree height, branch spread and height of first branch) were modeled based on the Computer Graphic (CG) tree model created through the architectural model [7] in the 3D-CAD software. Tree crowns were filled with meshes containing solar transmittance data in order to simulate solar transmission as a function of the solar permeating incident angle and the tree species. The solar transmittance data were determined in the manner described in the next two sub-sections. Figure 1 illustrates how the amount of solar radiation in the shade of a given tree was modeled. The surface temperature under a given tree crown was calculated by an empirical formula that incorporated parameters for solar radiation, air temperature, and wind velocity [4].

Transmittance of direct and mirror-reflected solar (UV-B) radiation, $\boldsymbol{\tau_d(\theta)}$[-]

We used the ray-tracing method [8] to calculate the transmittances from 0 to 90 degrees at intervals of 15 degrees. Each CG tree model was projected as an image representing each tree's shadow on plane with a normal vector pointing along each angle. We used an image resolution of 5 mm to consider the size of leaves and branches. Transmittances along each angle were then obtained from the shadow images by dividing the areas of all shadows by the areas of the voids. Linearly interpolated solar transmittances along each angle were applied to numerical tree models as a function of incident angle.

Transmittance of sky and diffuse reflected solar (UV-B) radiation, $\boldsymbol{\tau_s}$[-]

Transmittance of sky and diffuse reflected solar radiation from surrounding buildings and ground surfaces were assigned an integrated value of $\tau_d(\theta)$ from 0 to 90 degrees according to the following equation.

$$\tau_s = \int_0^{\pi/2} \tau_d(\theta) \sin 2\theta \, d\theta \quad (1)$$

CHARACTERISTICS OF TREE SPECIES

Five deciduous tree species commonly used in urban landscaping in Japan were chosen, including *Zelkova serrate*, *Platanus acarifolia*, *Ginkogo biloba*, *Prunus yedoensis* and *Liquidambar styraciflua*. Each species presented different crown shapes. We created a foliated and a defoliated image of an adult tree for each tree species in the CG software [8]. For comparison, tree height represented around 10 m [9]. Table 1 shows tree dimensions and τ_s for each species, and Figure 2 shows the $\tau_d(\theta)$ value for each species.

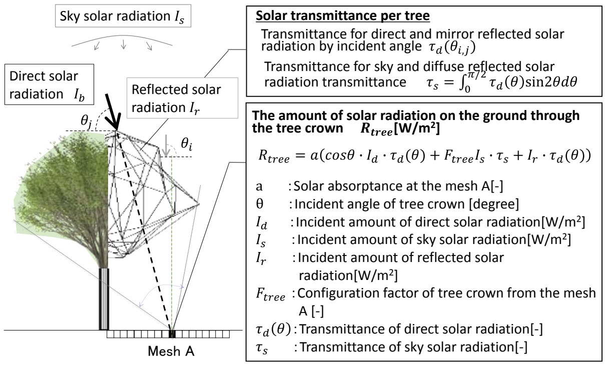
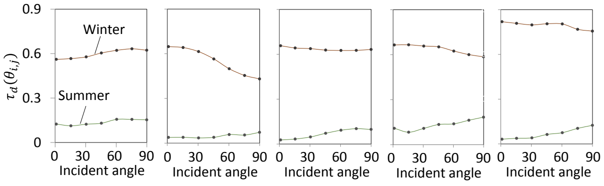


Figure 1: Illustration of the simulation and calculation for the amount of solar radiation that penetrates the tree crown and reaches the ground in the shade of the tree (mesh A).



A) *Ginkgo biloba* B) *Zelkova serrata* C) *Liquidambar styraciflua* D) *Platanus orientails* E) *Prunus yedoensis*

Figure 2: Transmittance of direct and mirror-reflected solar (UV-B) radiation for the five tree species studied as simulated in summer and winter scenarios.

Table 1: Characteristics of tree species modeled in this study.

		A) *Ginkgo biloba*	B) *Zelkova serrata*	C) *Liquidambar styraciflua*	D) *Platanus orientails*	E) *Prunus yedoensis*
CG tree model						
Tree crown shape		cone	invert cone	orb	egg	unform
Height of tree		11m	11m	12m	12m	8m
Branch spread		8m	10m	11m	10.5m	9m
τ_s	summer	0.07	0.02	0.04	0.07	0.04
	winter	0.32	0.30	0.34	0.35	0.43

For the summer scenario, we hypothesized that the maximum difference in direct solar radiation transmittance was approximately 15% between *G. biloba* and *L. styraciflua* at 0 degrees. For the winter scenario, we hypothesized a maximum difference of 30% between *P. yedoensis* and *Z. serrate*. In terms of tree geometry, *P. acarifolia* had the largest crown size, and *P. yedoensis* had the smallest. In addition, *P. yedoensis* reached the shortest adult height, while *Z. serrate* reached the tallest. These differences were calculated in actual urban spaces using the thermal and UV-B environmental simulator.

STUDY CONDITIONS

Area of simulation

We selected an actual urban space in the center of the business district in Ootemachi, Chiyoda-ku, Tokyo as the study area (Fig. 3). Here, there was an open square space east of a major high-rise building with open streets surrounding that building. The open square contained a café and lacked trees. We modeled the use of deciduous trees planted in the spaces shown in Figure 3. The building facade incorporated heat-reflecting glass, which has a high reflectance of solar and UV-B radiation. The reflectance of other building materials used is shown in Table 2.

Weather conditions

Models of the thermal environment incorporated weather data that used the vertical quantity of total solar radiation, air temperature, relative humidity, wind velocity, and cloud coverage from public observation data in Japan [4]. We assumed conditions related to a clear day in both the summer and winter in Tokyo.

Models of the UV-B radiation environment used actual measurements [10]. The amount of horizontal global UV-B radiation and the amount of horizontal sky UV-B radiation were measured using shading bands on sunny days at Shounan, Kanagawa on October 2 and February 21 to represent summer and winter conditions, respectively (Fig. 4). In addition, the amount of UV-B radiation depended on the ozone hole which has a maximum size in September. Therefore, we assumed that UV-B radiation reaching the Earth's surface would still be high during the October observations.

RESULTS

Comparison of thermal environments by tree species

We compared the MRT distribution at 1.5 m above ground under each of the tree species assuming trees

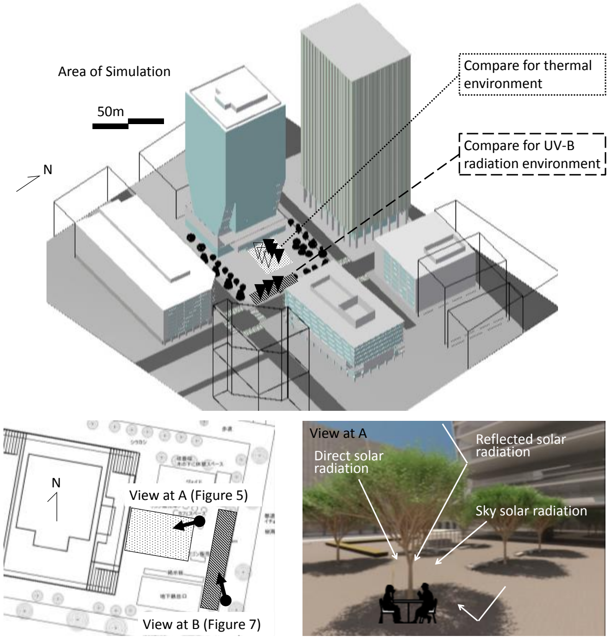


Figure 3: Area of simulation.

Table 2: Reflectance of building materials

	material	UV−B reflectance	Solar reflectance
High rise building	Heat reflecting glass	0.25	0.24
Middle rise building	Concrete	0.19	0.3
Side walk	Asphalt	0.04	0.2

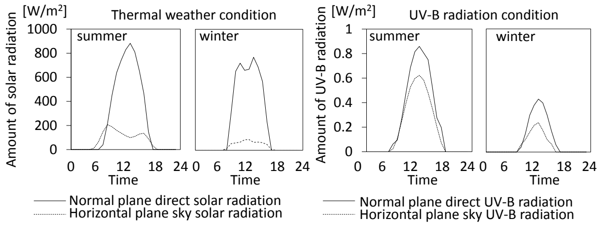
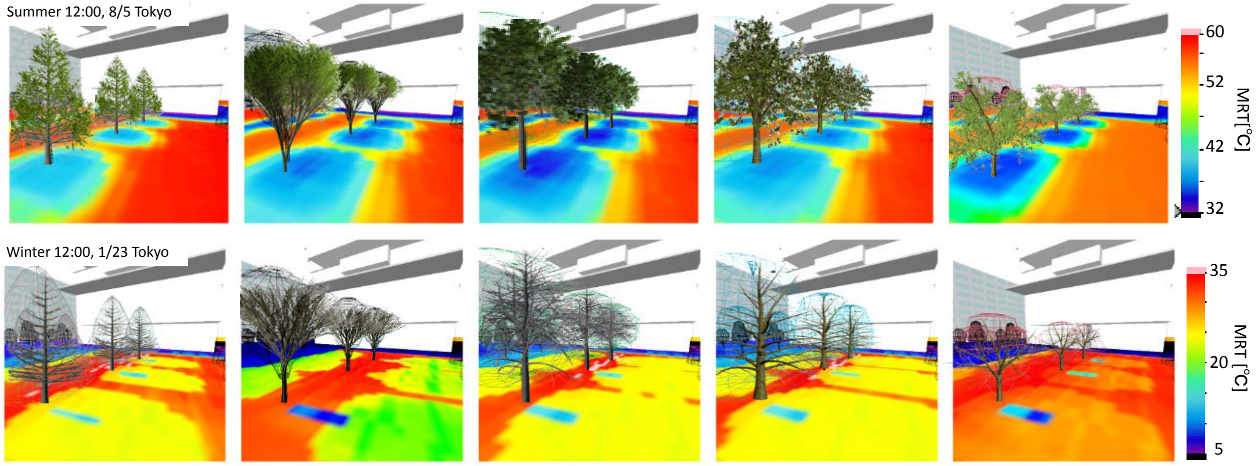


Figure 4: Measurements for solar and UV-B radiation in the summer and winter scenarios.



A) *Ginkgo biloba* B) *Zelkova serrata* C) *Liquidambar styraciflua* D) *Platanus orientails* E) *Prunus yedoensis*

Figure 5: MRT distribution of distribution at 1.5m above the ground in summer and winter at noon.

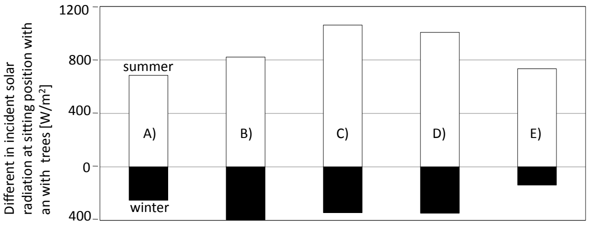


Figure 6: Incident solar radiation at 1.5 m above the ground for human body in summer and winter noon

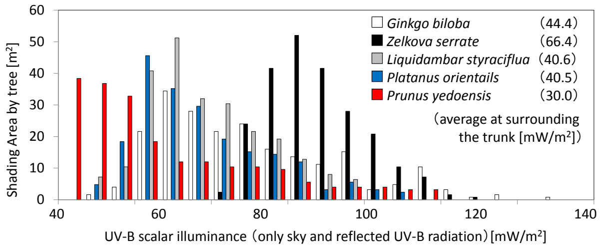
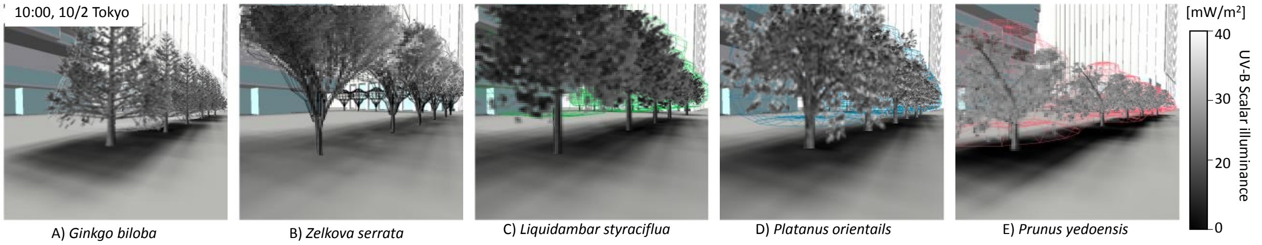


Figure 8: MRT distribution of distribution at 1.5m above the ground in summer noon.



A) *Ginkgo biloba* B) *Zelkova serrata* C) *Liquidambar styraciflua* D) *Platanus orientails* E) *Prunus yedoensis*

Figure 7: UV-B scalar illuminance distribution at 1.5m above the ground in summer at 10am.

were located at the center of the open square area (Fig. 5). Figure 6 shows a comparison of the differences of simulated incident solar radiation with and without a tree (1.5 m above the ground, i.e., standing position under the tree). The MRT distributions under all trees species were 20 to 25 degrees C and 5 to 10 degrees C lower compared to non-shadow areas in the summer and winter scenarios, respectively at 12.

In the summer scenario, *L. styraciflu* had the lowest MRT distribution near the trunk at 35 degrees because this species' large crown and prevented low direct solar transmittance. In contrast, *G. biloba*, with a smaller crown, had the highest MRT distribution and direct solar transmittance at 40 degrees C near the trunk. The maximum difference in MRT distribution between any two tree species was 5 degrees C.

In the winter scenario, *L. styraciflu* and *G. biloba*, had similar MRT distributions. *P. yedoensis* and *Z. serrate* had the highest and lowest MRT distributions at 30 and 20 degrees C, respectively. *Z. serrate* likely had the lowest MRT distribution because of its large number of branches. However, shadow positions in winter vary widely due to differences in height of first branch because of low solar altitude. Therefore, even under *Z. serrate*, solar radiation would increase near the trunk because of tall height of first branch.

Comparison of UV-B radiation environments by tree species

The UV-B scalar illuminance distribution at 1.5 m above ground was compared for all five tree species along the east street (Fig. 7) between the open square and the public road (Fig. 4) at 10 am, when surrounding buildings and the ground have the highest impacts on reflected UV-B radiation. Figure 8 illustrates examples of the amount of UV-B scalar illuminance and the distribution of shadow areas calculated from diffuse and sky UV-B radiation at 10 am in both the summer and winter.

In the summer scenario, although the crown of *P. yedoensis* is smaller than that of *L. styraciflu*, this species provided the lowest UV-B scalar illuminance because of its low clear length and round, flat crown shape. This species was able to effectively block both reflected and sky UV-B radiation. The UV-B scalar illuminance for *Z. serrate,* which provides a large shade area, was two times higher than that for *P. yedoensis* at their trunks. Because *Z. serrate* has a tall height of first branch and a wedged crown shape, this species was not able to block sky UV-B radiation as effectively from outside of the tree crown.

In the winter scenario, UV-B scalar illuminance under the tree crown was much lower than in summer for all tree species. Depending on the time of day and the direction of the human body, UV-B scalar illuminance in the winter was half that in the summer for some tree species.

CONCLUSIONS

In this paper, we compared the solar shading effects in summer and winter under the crown of five deciduous tree species in an actual urban space in Tokyo, Japan using numerical simulation tool. We found that in the summer scenario at noon, the maximum difference in MRT between species was approximately 5 degrees, while the maximum difference was 10 degrees in the winter scenario. These differences in MRT were due to differences in the transmittance of direct solar radiation through the tree crown for each species. In addition, each species' height of first branch and crown size impacted levels of UV-B scalar illuminance in the summer scenario at midmorning; UV-B scalar illuminance differed by a factor of two for some tree species.

These calculations provide some evidence that different tree species, represented by crown shape, height of first branch and solar transmittance, affect thermal and UV-B environment in both summer and winter differently. A further study of how to create the database about urban tree to support landscape designer and architecture should be conducted.

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