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A Multi-Layer Model for Transpiration of Urban Trees Considering Vertical Structure

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Abstract: As the intensity of the urban heat island effect increases, the cooling effect of urban trees has become important. Urban trees cool surfaces during the day via shading, increasing albedo and transpiration. Many studies are being conducted to calculate the transpiration rate; however, most approaches are not suitable for urban trees and oversimplify plant physiological processes. We propose a multi-layer model for the transpiration of urban trees, accounting for plant physiological processes and considering the vertical structure of trees and buildings. It has been expanded from an urban canopy model to accurately simulate the photosynthetically active radiation and leaf surface temperature. To evaluate how tree and surrounding building conditions affect transpiration, we simulated the transpiration of trees in different scenarios such as building height (i.e., 1H, 2H and 3H, H = 12 m), tree location (i.e., south tree and north tree in a E-W street), and vertical leaf area density (LAD) (i.e., constant density, high density with few layers, high density in middle layers, and high density in lower layers). The transpiration rate was estimated to be more sensitive to the building height and tree location than the LAD distribution. Transpiration-efficient trees differed depending on the surrounding condition and plant location. This model is a useful tool that provides guidelines on the planting of thermo-efficient trees depending on the structure or environment of the city.

Keywords: urban heat island; urban street tree; transpiration; multi-layer model; urban canopy model; cooling effect

1. Introduction

The urban heat island effect refers to the phenomenon in which urban areas are significantly warmer than surrounding areas due to human activities; this results in higher temperatures, and increases the violence of urban residents, which directly and indirectly affects human health and well-being [1]. The urban heat island effect is becoming more serious due to urbanization and climate change [2–4].

One of the representative ways to solve the problem of the heat island in cities is the cooling effect of trees [5–11]. The cooling effect of trees can be distinguished by radiative heat reduction and transpiration [12,13]. Radiative heat reduction is when the trees reduce the radiant heat reaching the surface of an urban area by blocking or reflecting the radiant heat [10,14]. It is an effective way to cool the space under the trees by generating shadows [15]. Additionally, the surface temperature of

trees can be lower than that of impervious surfaces such as asphalt and concrete, resulting in lower longwave radiation [16], which consequently lowers the temperature. Secondly, transpiration is the process of releasing water absorbed through roots into the atmosphere through the stomata of plant leaves, which reduces the urban sensible heat by increasing the latent heat. These two actions play important roles in relieving urban heat [11,17,18]. Among them, transpiration has been studied to examine the water cycle or manage trees in many studies.

There has been much research on calculating the transpiration at the canopy scale focusing on rural or cropland areas. To describe the fluxes of energy and water, it is necessary to partition the canopy [17]. The method of partitioning the canopy can be summarized in three main ways: big-leaf, two-leaf, and multi-layer. The big-leaf model is the simplest approach, in which the canopy is considered as a single leaf [19]. The Penman–Monteith model is usually adopted to estimate the potential evapotranspiration from a vegetated surface [20]. However, the surface temperature between the leaves exposed to sunlight and those in the shadows varies, resulting in a difference in transpiration [21–23]. Hence, at least two different classes of leaves, sunlit and shaded, must be considered to accurately calculate the transpiration. To reflect this, a two-leaf model was developed and demonstrated that this approach is significantly better than big-leaf models [17,24,25]. Finally, the most accurate and sophisticated model, the multi-layer model, was developed. Here, the tree is divided into multiple layers and all quantities are estimated independently for each layer and subsequently integrated to obtain the flux at the canopy scale [26–28]. Most of the models for calculating transpiration, however, focus on forests and orchards, and do not consider built environments such as buildings.

Recently, a number of urban canopy models have considered the influence of vegetation on the energy and water balances, such as short ground vegetation [29], trees [30,31], deciduous and evergreen shrubs and trees [32], and plant types [33]. However, while there are many urban canopy models that describe plants, there is a lack of research on transpiration that reflects both the vertical structure and physiological processes of plants [30,32,34,35].

In this study, we propose a multi-layer model that considers the vertical structure of trees and buildings to calculate the transpiration of urban trees. This model has been expanded from an urban canopy model, the multi-layer mean radiant temperature (MMRT) model, where the urban environment consisting of buildings and vegetation is divided into multiple layers and the radiation transfer is calculated at each layer. We simulated the tree transpiration by scenarios that consider the building height, tree location, and vertical variation of leaf area density. This study will first describe the model, set up the scenario, and calculate and compare the transpiration according to the scenarios. The results will have implications for urban cooling studies and policies regarding urban trees.

2. Materials and Methods

2.1. Research Framework

This study focuses on developing a multi-layer model to calculate the urban tree transpiration considering the vertical structure of trees and buildings. In the scenario simulation, the transpiration was simulated and compared to scenarios with varying building height, tree location, and leaf area density (LAD) distribution of the tree. Figure 1 shows a flow chart of the model.

First, photosynthetically active radiation (PAR) is calculated using the MMRT model with meteorological and geometric data, and tree properties. Subsequently, the parameter of transpiration is calculated using the input data obtained earlier. To calculate the transpiration and reflect the interaction between transpiration and leaf surface temperature, two strategies are used: (1) simultaneous calculation: calculate the transpiration and leaf surface temperature simultaneously using the resistance values calculated by the parameters; (2) feedback: calculate the surface temperature by temporarily using the atmospheric temperature as the leaf surface temperature, and the resistances and transpiration rate are then calculated.

Figure 1. Model flow for calculating the transpiration.

2.2. Model Description

In this study, the multi-layer model reflecting the vertical structure of a tree consists of n layers of crown area at intervals of 1 m, except for the ground level of a single tree (Figure 2). Among the variables needed to calculate the transpiration, the structural properties (height, trunk height, crown area, and LAD of each layer) are given. PAR are given at each layer through the MMRT model. The multi-layer model calculates leaf surface temperature, three resistances, and transpiration rate at each layer, and finally calculates the total transpiration rate of tree.

Figure 2. Model base domain.

2.2.1. Input Data

The main input data for calculating transpiration are meteorological data and tree properties (Table 1). Meteorological data can be obtained from the surrounding automatic weather station (AWS).

Table 1. Meteorological data and tree properties for input data.

Input Data	Parameter	Units
Air temperature	T_{air}	$^{\circ}\text{C}$
Wind speed	u_a	m s^{-1}
Relative humidity	RH	%
Air pressure	P_{atm}	Pa
Cloud cover	CF	—
Leaf area index	LAI	—
Leaf area density	LAD	m^2m^{-3}
Canopy height	H_c	m
Leaf width	d_{leaf}	cm

2.2.2. Model Processing

The proposed model for calculating transpiration is based on the analogy with Ohm's law, which is used in many leaf energy flux studies [31,36].

$$T_v = \frac{p_a(q_{sat}(T_s) - q_a)}{r_a + r_b + r_s}, \quad (1)$$

where q_a (–) is the specific humidity of the air at the reference height z_{atm} (m), $q_{sat}(T_s)$ (–) is the specific humidity at saturation at the leaf surface temperature T_s (°C), P_a (kgm^{-3}) is the air density, which can be calculated using the ideal gas law, expressed as a function of air temperature T_a (°C) and atmospheric pressure P_{atm} (Pa), and, r_a , r_b , and r_s (sm^{-1}) are the aerodynamic resistance, leaf boundary resistance, and stomatal resistance, respectively.

The specific humidity at saturation and specific humidity of air were calculated from [37]. The air vapor pressure e_a was calculated using the saturation vapor pressure e_{sat} and relative humidity RH (%). The saturation vapor pressure is calculated from the Arden–Buck equation [38,39].

The transpiration model largely consists of calculating (1) PAR ($\mu mol\ m^{-2}s^{-1}$), (2) leaf boundary layer resistance, (3) aerodynamic resistance, (4) stomatal resistance, and (5) leaf surface temperature.

Photosynthetically Active Radiation (PAR)

One of the key parts of the model is the calculation of transpiration using PAR in each layer, which is calculated by the MMRT model [30]. The MMRT model simulates shortwave and longwave radiation exchanges for the view factor between each urban element, including air temperature, dew point, wind speed, cloud cover, and relative humidity. We calculated the shortwave radiation of each layer using the MMRT model to reflect the variation in transpiration caused by different PAR depending on the location within the tree. The detailed algorithm was described in [30]. Because the result of the MMRT model is shortwave radiation SW (Wm^{-2}), we multiply it by 4.57 to convert the unit ($\mu mol\ m^{-2}s^{-1}$, [40]) and by 0.45 again because the proportion of PAR (often defined as 400 to 700 nm) in total solar radiation is approximately 45% [41]; previous studies have used this approach [42–44]

$$PAR = 4.57 \times 0.45 \times SW, \quad (2)$$

Leaf Boundary Layer Resistance

The leaf boundary layer resistance is calculated from the mean plant leaf boundary conductance g_b (ms^{-1}), which is a function of wind speed and therefore of height within the canopy, using Equation (3). We follow Equation (4) from [45] and used by [37,46,47].

$$r_b = 1 / g_b, \quad (3)$$

$$g_b = a \left(u(H_k) / d_{leaf} \right)^{1/2}, \quad (4)$$

where $a = 0.01$ ($ms^{-1/2}$) is an empirical coefficient [46], d_{leaf} (m) is the characteristic leaf dimension, often referred to as the leaf width, and $u(H_k)$ (ms^{-1}) is the wind speed at each layer height H_k . The wind speed profile is assumed to be logarithmic above the urban canopy and exponential within the urban canyon using Equations (5) and (6) [35,48,49]

$$u_{H_c} = u_a \frac{\ln\left(\frac{H_c - d_0}{z_0}\right)}{\ln\left(\frac{z_{atm} - d_0}{z_0}\right)}, \quad (5)$$

$$u_{H_k} = u_{H_c} \exp\left(-\beta\left(1 - \frac{H_k}{H_c}\right)\right), \quad (6)$$

where u_a (ms^{-1}) is the wind speed at reference height, and β (–) is the light extinction parameter, which is calculated from [50]; d_0 (m) and z_0 (m) are the zero displacement height and aerodynamic roughness length, respectively, which are calculated according to the approach developed by [51] and modified by [52] as follows, using Equations (7) and (8):

$$d_0 = (1 - \alpha_A^{-\lambda^p} (\lambda^p - 1)) H_c, \quad (7)$$

$$z_0 = H_c \left(1 - \frac{d_0}{H_c}\right) \exp \left[- \left(\frac{1}{k^2} 0.5 \beta_A C_{Db} \left(1 - \frac{d_0}{H_c}\right) \frac{\{A_{f,b} + P_v A_{f,v}\}}{A_{tot}} \right)^{-0.5} \right], \quad (8)$$

where $k = 0.4$ (–) is the von Karman constant, and $\alpha_A = 0.43$ (–), $\beta_A = 1$ (–), and $C_{Db} = 1.2$ (–) are parameter values for staggered arrays [51]. H_c (m) is the canopy height, λ^p (–) is the plan area index of the urban roughness elements, $A_{f,b}$ (m) is the actual frontal area of buildings, $A_{f,v}$ (m) is the actual frontal area of vegetation, A_{tot} (m) is the total urban plan area, and P_v (–) is the ratio between vegetation drag C_{Dv} and building drag C_{Db} . These parameters were calculated from [35,52–54] using the height of trees and buildings. For volumetric/aerodynamic porosity, the light extinction parameter is calculated as given by [17], assuming a spherical leaf angle distribution.

Aerodynamic Resistance

The aerodynamic resistance is calculated by a simpler method [37], which assumes a neutral condition as follows using Equations (9) and (10):

$$r_a = \frac{1}{k^2 u_{H_k}} \left[\frac{\ln(z_{atm} - d_0)}{z_0} \right] \left[\frac{\ln(z_{atm} - d_0)}{z_{oh}} \right], \quad (9)$$

$$z_{oh} = 0.1 z_0, \quad (10)$$

Here, z_{oh} (m) is the roughness length for heat.

Stomatal Resistance

As the reciprocal of stomatal conductance is stomatal resistance, stomatal conductance g_s ($\text{mol m}^{-2} \text{s}^{-1}$) is calculated first. Many studies have reported that stomatal conductance is closely coupled with leaf photosynthesis [55,56]. In the proposed model, the stomatal conductance is calculated as a function of leaf photosynthesis A_n ($\mu\text{mol m}^{-2} \text{s}^{-1}$) using Equation (11) from [57] used by [55,58].

$$g_s = \frac{m A_n h_s}{C_s} + g_0, \quad (11)$$

where m (–) is the slope, g_0 ($\text{mol m}^{-2} \text{s}^{-1}$) is the zero intercept, and h_s and C_s (ppm) are the relative humidity and CO_2 concentration at the leaf surface, respectively. In this model, a modified equation is used from [59], by using the CO_2 concentration C_a (ppm) and relative humidity rh (–) in the air as follows, using Equation (12):

$$g_s = \frac{m A_n rh}{C_a} + g_0, \quad (12)$$

Leaf photosynthesis was simulated according to [60]. The version of the model proposed by [59] was used, which calculates photosynthesis without including the potential limitation arising from the triose phosphate utilization, and is used by [36].

$$A_n = \left[1 - \frac{0.5 O}{\tau C_i} \right] \min(W_c, W_j) - R_d, \quad (13)$$

where W_c ($\mu\text{mol m}^{-2}\text{s}^{-1}$) is the carboxylation rate when the ribulose biphosphate (RuBP) is saturated, W_j ($\mu\text{mol m}^{-2}\text{s}^{-1}$) is the carboxylation rate when the RuBP regeneration is limited by the electron transport, τ is the specificity factor for RuBisCO [61], R_d ($\mu\text{mol m}^{-2}\text{s}^{-1}$) is the rate of CO_2 evolution in light that results from processes other than photorespiration, and O and C_i (Pa) are the partial pressures of O_2 and CO_2 in the interior leaf, respectively. In the proposed model, $C_i/C_a = 0.7$ is used, where C_a (Pa) is the partial pressure of CO_2 in air typically observed with C3 plants under favorable conditions [56,62,63].

W_c obeys competitive Michaelis–Menten kinetics with respect to CO_2 and O_2 as follows, using Equation (14):

$$W_c = \frac{V_{cmax}C_i}{C_i + K_c\left(1 + \frac{O}{K_o}\right)}, \quad (14)$$

where

V_{cmax} ($\mu\text{mol m}^{-2}\text{s}^{-1}$) is the maximum rate of carboxylation, and K_c and K_o (Pa) are the Michaelis constants of RuBisCO for carboxylation and oxygenation, respectively.

W_j is controlled by the rate of electron transport, J ($\mu\text{mol m}^{-2}\text{s}^{-1}$), which depends on PAR. They are calculated as follows, using Equations (15) and (16):

$$W_j = \frac{JC_i}{4\left(C_i + \frac{O}{\tau}\right)}, \quad (15)$$

$$J = \frac{\alpha \times \text{PAR}}{\left(1 + \frac{\alpha^2 \text{PAR}^2}{J_{max}^2}\right)^{1/2}}, \quad (16)$$

where J_{max} ($\mu\text{mol m}^{-2}\text{s}^{-1}$) is the light-saturated rate of electron transport and α is the quantum yield, indicating the efficiency of light energy conversion on an incident light basis.

The coefficients for V_{cmax} , J_{max} , K_c , K_o , R_d , and τ are strong, non-linear functions of temperature [64,65]. One temperature function used for K_c , K_o , R_d , and τ is given by Equation (17) from [59]:

$$\text{Parameter}(K_c, K_o, R_d, \tau) = \exp(c - \Delta H_a / RT_{s'}), \quad (17)$$

where c (–) is a dimensionless, scaling constant, ΔH_a (J mol^{-1}) is the activation energy, R ($8.3143\text{J K}^{-1}\text{mol}^{-1}$) is the gas constant, and $T_{s'}$ (K) is the leaf surface temperature. The temperature dependence of V_{cmax} and J_{max} is expressed by Equation (18) from [59,66]:

$$\text{Parameter}(V_{cmax}, J_{max}) = \frac{\exp(c - \Delta H_a / RT_{s'})}{1 + \exp[(\Delta ST_{s'} - \Delta H_d) / (RT_{s'})]}, \quad (18)$$

Here, ΔH_d (J mol^{-1}) is the energy of deactivation and ΔS ($\text{J K}^{-1}\text{mol}^{-1}$) is an entropy term. Linear relationships were commonly observed between the leaf photosynthetic capacities and amount of leaf nitrogen on an area basis N_a (g m^{-2}) [59,67–69]. To account for linear relationships, the scaling factors c for V_{cmax} , J_{max} , and R_d and are calculated by Equation (19) from [70].

$$c = a_N + b_N \ln(N_a), \quad (19)$$

In the proposed model, the amount of leaf nitrogen is estimated from the mean daily PAR intercepted by the leaves, PAR_i ($\text{mol m}^{-2}\text{d}^{-1}$), by an empirical linear relationship; Equation (20) from [71]:

$$N_a = a_{Na} + b_{Na} \text{PAR}_i, \quad (20)$$

The stomatal resistance through the stomatal conductance of Equation (11) is expressed in biochemical units of $\text{m}^2\text{s mol}^{-1}$. The conversion to common units (s m^{-1}) for Equation (1) is obtained as follows, using Equation (21) from [72].

$$r_s(\text{sm}^{-1}) = \frac{T_f P_{atm}}{0.0224 T_s' P_{atm,0}} r_s(\text{m}^2\text{s mol}^{-1}), \quad (21)$$

Here, $T_f = 273.15$ (K) is the freezing temperature and $P_{atm,0} = 101325$ (Pa) is a reference atmospheric pressure.

A complete list of the parameters for calculating resistances is presented in Table 2.

Table 2. Values, units, and sources of the parameters for resistances.

Parameter	Value	Unit	Source
d_{leaf}	0.75	m	[73]
m	9.5	—	[31]
g_0	0.081	$\text{molm}^{-2}\text{s}^{-1}$	[59]
a_{Na}	0.46	gm^{-2}	[71]
b_{Na}	0.141	—	[71]
α	0.22	molmol^{-1}	[31]
a_{N_Vcmax}	47.42	—	[70]
b_{N_Vcmax}	1.118	g^{-1}	[70]
a_{N_Jmax}	36.11	—	[70]
b_{N_Jmax}	0.993	g^{-1}	[70]
a_{N_Rd}	−32.85	—	[70]
b_{N_Rd}	−1.027	g^{-1}	[70]
$c(K_c)$	35.79	—	[59]
$c(K_o)$	9.59	—	[59]
$c(\tau)$	−3.9489	—	[59]
$\Delta H_a(K_c)$	80.47×10^3	Jmol^{-1}	[59]
$\Delta H_a(K_o)$	14.51×10^3	Jmol^{-1}	[59]
$\Delta H_a(\tau)$	$−28.99 \times 10^3$	Jmol^{-1}	[59]
$\Delta H_a(R_d)$	84.45×10^3	Jmol^{-1}	[59]
$\Delta H_a(V_{cmax})$	109.5×10^3	Jmol^{-1}	[70]
$\Delta H_a(J_{max})$	79.5×10^3	Jmol^{-1}	[59]
$\Delta H_d(V_{cmax})$	199.5×10^3	Jmol^{-1}	[70]
$\Delta H_d(J_{max})$	201×10^3	Jmol^{-1}	[59]
$\Delta S(V_{cmax})$	650	$\text{JK}^{-1}\text{mol}^{-1}$	[59]
$\Delta S(J_{max})$	650	$\text{JK}^{-1}\text{mol}^{-1}$	[59]

Leaf Surface Temperature

Energy budget for a leaf is Equation (22):

$$R_{net} = H + \lambda E = \rho_a C_p \frac{(T_s - T_a)}{r_a + r_b} + \frac{\rho_a C_p}{\gamma} \frac{(e_{sat}(T_s) - e_a)}{r_a + r_b + r_s}, \quad (22)$$

where γ (Pa K^{-1}) is a psychrometric constant, and Equation (23) is generally used [74].

$$\gamma = \frac{C_p P_{atm}}{\varepsilon \lambda}, \quad (23)$$

where $C_p = 1005$ ($\text{J kg}^{-1}\text{K}^{-1}$) is the specific heat of air at constant pressure,

$\varepsilon = 0.622$ (—) is the ratio of molecular weight of water vapor/dry air, and $\lambda = 1000(2501.3 - 2.351 * T_a)$ (J kg^{-1}) is the latent heat of water vaporization.

To calculate transpiration and leaf surface temperature simultaneously, the slope of the saturation vapor pressure function Δ (Pa) was used from [75].

$$e_{sat}(T_s) - e_{sat}(T_a) = \Delta(T_s - T_a), \quad (24)$$

$$\Delta = 1000 \frac{17.502 \times 240.97 e_{sat}(T_a)}{(240.97 + T_a)^2}, \quad (25)$$

The latent heat term can be linearized using the saturation vapor pressure function as follows:

$$\lambda E = \frac{\rho_a C_p}{\gamma} \frac{(e_{sat}(T_s) - e_a)}{r_a + r_b + r_s} = \frac{\rho_a C_p}{\gamma(r_a + r_b + r_s)} (e_{sat}(T_s) - e_{sat}(T_a) + e_{sat}(T_a) - e_a) = \frac{\rho_a C_p}{\gamma(r_a + r_b + r_s)} (\Delta(T_s - T_a) + VPD), \quad (26)$$

Using Equations (22) and (26), Equation (27) can be written as

$$R_{net} - \rho_a C_p \frac{(T_s - T_a)}{r_a + r_b} - \frac{\rho_a C_p}{\gamma(r_a + r_b + r_s)} (\Delta(T_s - T_a) + VPD) = 0, \quad (27)$$

Subsequently, Equation (28) can be readily solved for the leaf surface temperature to obtain

$$T_s = T_a + \frac{R_{net} - \frac{\rho_a C_p VPD}{\gamma(r_a + r_b + r_s)}}{\rho_a C_p \left(\frac{1}{r_a + r_b} + \frac{\Delta}{\gamma(r_a + r_b + r_s)} \right)}, \quad (28)$$

2.3. Scenario Simulation

We simulated PAR, leaf surface temperature, and transpiration to evaluate and compare various scenarios including the height of surrounding buildings, location of tree, and LAD distribution of each layer. The parameters of the MMRT model are listed in the Table A1.

The domain for the simulation is presented in Figure 3. In the domain, two buildings, two sidewalks, one road, two trees, and the width and height of each are denoted. The tree height is 12 m, tree crown width is 6 m, and tree vertical layer thickness is 1 m.

Figure 3. Domain for simulation. (a) Geometric settings (b) Tree settings. The darker the color, the higher the leaf area density.

2.3.1. Tree Location

Transpiration can vary by tree position in relation to buildings because of the solar radiance absorption. To evaluate the differences depending on the location of the tree, an E–W street is set so that two trees are located north and south (Figure 3a).

2.3.2. Building Height

The building environment surrounding trees affects the transpiration [76]; for example, by reflecting radiation, intercepting shortwave radiation, emitting longwave radiation, and changing the urban

canopy height. The intensity of the urban heat island changes with the height/width ratio [77]. To evaluate the effect of various building environments, we controlled the building height in three cases (1H, 2H, and 3H). Case 1H is an urban canyon with 12 m buildings; case 2H is an urban canyon with 24 m buildings; and case 3H is an urban canyon with 36 m buildings. H denotes the tree canopy height.

2.3.3. LAD Distribution

A higher leaf area index (LAI) of trees must lead to higher transpiration. However, the LAD distribution can vary in the same LAI. We evaluated the transpiration for four vertical structure cases: (1) constant density (C.D), (2) high density, few layers (H.D), (3) high density in the middle layers (M.H.D), and (4) high density in the lower layers (L.H.D). LAI and tree height were the same in all cases. The crown base height in H.D is 7 m, while in the other cases it is 2 m with the same LAI (3.75) (Figure 3b).

The settings of scenarios are summarized in Figure 4.

Figure 4. Settings of scenarios for simulation. The total number of scenarios is 24.

2.3.4. Other Input Data/Parameters

For the simulation, we selected seven days (213th–219th day of the year, August 1) in 2018 in Seoul (126.9658, 37.57142). August is the hottest and most humid month of the year. Figure 5 presents the 7 day average of climate data for the simulations. For the simulation, O (Pa) and C_a (ppm) were set as 21,000 and 401.91 [78], respectively. Vertical variations in RH and C_a were ignored because they were relatively small and vary with stable air [79,80]. To calculate the amount of leaf nitrogen, the mean daily PAR was simulated for 1 month (182–212th day of the year, July) using the MMRT model.

Figure 5. Meteorological data for the model simulation.

The values of the main parameters and references used in the simulation are presented in Table 2. To compare transpiration in all cases, the parameters for calculating the resistance were fixed and

mainly derived by [59,70]. The leaf width d_{leaf} was set as 7.5 cm of *Ginkgo biloba*, which is planted with the largest proportion of street trees in Seoul [73].

3. Results

3.1. PAR and Leaf Surface Temperature

The results of PAR and leaf surface temperature at 15:00 on the 213th day simulated by the MMRT and transpiration models are shown in Figure 6. Not surprisingly, higher PAR and surface temperature occur when the building is low. PAR showed a decreasing shape depending on the height, but the vertical profile of the surface temperature does not. The highest surface temperature is in the upper layer, but that of the lower layer close to the ground is sometimes greater than that of the middle layer because of the high longwave radiation from the ground. This is similar to higher results, as with the surface temperature of the tree trunk near the surface [81]. The pattern is obvious in the 3H, north tree scenario, where the solar radiation is largely intercepted by the building, resulting in a small difference between the high and low layers.

Figure 6. Vertical profile of photosynthetically active radiation (PAR) (a) and leaf surface temperature, (b) of the 213th day according to the tree location/building height (1H,3H). (Leaf area density (LAD) distribution: C.D).

3.2. Temporal Variation of Transpiration

Leaf surface temperature and photosynthetically active radiation are the main factors affecting the transpiration rate. Figure 7 shows the hourly transpiration rate of the tree along with the PAR and leaf surface temperature of the top layer. Despite the temperature dependence of plant transpiration, PAR is regarded as a dominant factor for the change in transpiration rate. Leaf surface temperature rather decreases because of the latent heat loss by transpiration. On the 219th day, the transpiration rate is relatively small, despite the high leaf surface temperature. Low PAR of the 219th day induces a low carboxylation rate (W_j), which is limited by the electron transport. Therefore, the transpiration rate is high when the surface temperature and PAR are simultaneously high.

Figure 7. Temporal variation of the tree transpiration rate (bar) with PAR (orange line), and surface temperature (red line) of the top layer (building height: 1H, tree location: north, LAD distribution: C.D).

3.3. Scenario Simulations

In all the tree location scenarios, the lower the height of the surrounding buildings, the higher the transpiration rate (Figure 8). The difference in transpiration rate mainly occurs during the day. However, the variation of the south tree is higher than that of the north tree according to the building height. In the C.D case, the difference in tree transpiration is up to 12.9% (south) and 7.3% (north) depending on the building height. The south tree is more sensitive to the height of the building, because it is close to the building forming the shadow. A similar tendency is shown for every LAD distribution scenario (11.3% of south and 6.4% of north in all scenarios). This can be amplified when the distance between the tree and building is lower.

Figure 8. Change of transpiration rate with building height (1H, 2H, 3H). (a) South tree, (b) north tree. (LAD distribution: C.D).

The results show that the change in transpiration rate by tree location is larger in the high building case than the others, as shown in Figure 9 (blue and brown lines). The rate averages of each building height case are 5.3% (1H), 9.3% (2H), and 10.1% (3H) because of the sensitivity of the south tree to building height, as mentioned earlier. In comparison to the location condition, the LAD distribution condition shows less of an effect.

Figure 9. Change in transpiration rate with LAD distribution and tree location (blue lines are south trees and brown lines are north trees). (a) 1H, (b) 2H, (c) 3H.

Figure 10 shows the mean transpiration rate during the days according to all scenarios for four LAD distributions, two tree locations, and three building heights. Depending on the scenarios, the LAD distribution calculated with the highest transpiration rate trees differed. For example, transpiration rate was high in order of the C.D case, H.D case, M.H.D case, and L.H.D case in the south tree, 1H

condition, whereas the order was the H.D case, C.D case, M.H.D case, and L.H.D case in the south tree, 3H condition. The tree that showed the highest transpiration rate was the C.D case or H.D case. Meanwhile, the case of L.H.D showed the lowest transpiration rate in all scenarios. The differences of transpiration between cases are small, in which the maximum rate difference is 4.6% in the south tree, 3H condition, while the minimum is 2.2% in the north tree, 2H condition.

Figure 10. Mean change of transpiration rate with LAD distribution, tree location, and building height scenarios.

4. Discussion

4.1. Variation of Transpiration Across Different Scenarios

This study proposes a multi-layer model that considers the vertical structure of trees and buildings to calculate the transpiration rate of urban trees. It is not surprising that the lower the building heights and the further north the trees are located, which also indicates that they are relatively further away from buildings, the higher the transpiration rate. However, in the case of trees located near high buildings (3H) or at the south side, the transpiration was more sensitive to other factors, due to insufficient light conditions caused by building interception of shortwave radiation (Figures 8 and 9).

In this study, the LAD distribution of trees is a relatively less important factor for the transpiration rate than other factors, such as the tree location and building height. The maximum rate differences were 12.9% by the building height, 10.1% by the tree location, and 4.6% by the LAD distribution. Nevertheless, this result is meaningful because LAD distribution may be the only one that can be improved or changed for urban cooling among the three factors.

4.2. Strategies for Urban Heat Island

Urban planners and designers have paid less attention to the tree's role in cooling effects, particularly evapotranspiration. However, since most of the deep urban canyons are shaded, the importance of cooling effects from evapotranspiration will increase, and the need to consider LAD distribution increases (Figure 10). As shown in the results, the most efficient/inefficient trees vary depending on surrounding building condition and the arrangement of trees (Figure 10). In particular, it is noteworthy that L.H.D cases, with the high density in lower layers, show the worst efficiency in most cases because of relatively lower PAR and wind speed in lower layers around the leaves. The H.D. case, which has a high LAD density and few layers, is the most efficient at 3H scenarios, while the C.D. case is the most efficient at 1H scenarios.

The results of the scenario simulation suggest that the location and shape of trees that are efficient for cooling vary depending on the urban environment. This model can better evaluate the cooling effect

of trees by considering the radiant heat intercepting effect of trees. For example, the shallow canyon can be hotter due to the high exposure of canyon surfaces to intense solar radiation [77,82]. The air temperature with taller buildings is lower due to their shading effect [83]. Therefore, considering the fact that the shallow street canyon needs a higher cooling effect, trees with large crowns could be effective in terms of both transpiration and shading [84,85]. We expect that applying this model will be warranted in future studies to help simulation-informed street tree planning and design.

4.3. Model Limitations and Future Development

During the calculation of transpiration rate, the model generates a difference between the vapor pressure deficit, wind speed, and resistance values, which results in a difference in the result of transpiration depending on the scenarios. Although many parameters that can lead to restrictive results were fixed to simulate transpiration, it is meaningful to compare the relative transpiration rate of each scenario. Future studies need to estimate and verify the parameters of the model to improve accuracy.

In this study, transpiration was calculated assuming a constant C_i/C_a . This implies that the stomatal conductance does not affect the internal CO_2 concentration. To increase accuracy, this limit could be developed through a feedback that calculates

This study only dealt with the transpiration among the tree's cooling effects. Considering the radiative heat reduction of trees in the future will be a more accurate assessment of the cooling effect of trees. Under various conditions, there will be different cooling requirements, along with other thermal environments, and the shadow effects will vary significantly.

The results show LAD distribution of trees is a relatively less important factor for the transpiration rate than other factors. In actual urban space, however, variation in the leaf area distribution will increase dramatically, both vertically and horizontally, resulting in a larger effect on the transpiration rate. The variations include tree height, crown width, crown shape, leaf shape, etc. Future study should consider these variations and suggest the most efficient tree variations for effective tree planting.

5. Conclusions

We propose a multi-layer model for calculating the transpiration of urban trees. The advantage of the model is that it simulates transpiration by considering the vertical structure of trees and buildings. To effectively reflect the vertical structure, PAR was simulated using the MMRT model, which is an urban canopy model. For evaluating the model accuracy, two strategies (simultaneous calculation and feedback) are used in this study. The proposed model includes a detailed representation of the plant biophysical and ecophysiological characteristics and urban conditions.

Simulations were conducted on four LAD distributions of trees with three types of buildings (12, 24, and 36 m) and two types of tree locations (south and north). In this study, the transpiration rate is more sensitive to building height and tree location than to LAD distribution. The results of the scenario simulation suggest that the location and shape of trees that are efficient for cooling effects vary depending on the urban environment. Our results suggest that tree shape and location need to be considered with the surrounding built environment when an urban planner designs planting for the mitigation of the urban heat island. This model will be a useful tool that provides guidelines on the plantation of thermo-efficient trees depending on the structure or environment of the city.

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Appendix A

Table A1. Model parameters of the multi-layer mean radiant temperature (MMRT) model.

Classes	Description	Default	Units/(Type)
Geometric data	Street orientation	0–360	Radian
Computational parameters	Index of rays	-	-
	Number of rays	10,000	-
	Index of ray steps	-	-
	Number of ray steps	-	-
	Ray step size (view factor)	1	m
	Ray step size (direct shortwave radiation)	0.1	m
Radiative parameters	Albedo of walls	0.4	-
	Albedo of roofs	0.15	-
	Albedo of sidewalks	0.2	-
	Albedo of roads	0.1	-
	Albedo of trees	0.18	-
	Emissivity of walls	0.9	-
	Emissivity of roofs	0.9	-
	Emissivity of sidewalks	0.95	-
	Emissivity of roads	0.95	-
	Emissivity of trees	0.96	-

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