



Development of SOLWEIG-LEB v1.0: An urban radiation model integrating LAD-based canopy shortwave attenuation and leaf energy balance

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Abstract

Urban trees are widely used to mitigate pedestrian heat stress by providing shade and modifying the surrounding radiative environment. Accurately representing these effects is important for evaluating urban greening strategies, yet simplified treatments of canopy transmission and vegetation temperature can limit pedestrian-level radiation and mean radiant temperature (MRT) estimates. SOLWEIG is a widely used urban radiation model for spatially resolving pedestrian radiative environments, but its conventional vegetation scheme applies a fixed canopy transmissivity and assumes vegetation temperature equals air temperature. To address these limitations, we developed SOLWEIG-LEB v1.0, which combines path-dependent shortwave attenuation based on leaf area density (LAD), the leaf projection function, and radiative path length with a voxel-scale leaf energy balance that diagnoses leaf temperature, vegetation longwave emission, and sensible and latent heat fluxes. The model was evaluated using two field datasets. Against leaf-temperature observations in Mainz, Germany, Pearson correlation coefficients (r) were 0.97 and 0.85 and root mean square errors (RMSEs) were 1.39 and 1.05 °C under clear-sky and fully cloudy conditions, respectively. Against six-directional radiation and MRT observations in Göteborg, Sweden, SOLWEIG-LEB reduced RMSEs for total shortwave radiation from 231.74 to 203.66 W m⁻², total longwave radiation from 83.42 to 78.93 W m⁻², and MRT from 4.76 to 4.38 °C relative to Legacy SOLWEIG. Differences were greatest near canopy edges and partially obstructed locations, highlighting the importance of spatially variable canopy transmission. SOLWEIG-LEB provides a more physically explicit framework for assessing urban-tree radiative effects and pedestrian thermal environments.

Keywords: urban microclimate; SOLWEIG-LEB; leaf energy balance; canopy radiative transfer; mean radiant temperature



1. Introduction

Pedestrian thermal comfort in urban areas is strongly influenced not only by air temperature, humidity, and wind speed, but also by shortwave and longwave radiation received from surrounding buildings, ground surfaces, vegetation, and the sky. Mean radiant temperature (MRT) integrates the three-dimensional radiative exposure experienced by a human body in outdoor environments and is therefore a key input to outdoor thermal comfort indices such as the Physiological Equivalent Temperature (PET) and the Universal Thermal Climate Index (UTCI) (Mayer and Höppe, 1987; Höppe, 1999; Błażejczyk et al., 2010). Under clear-sky conditions with strong solar forcing, MRT can vary substantially over short distances depending on direct solar exposure, surface reflectance, surface temperature, and sky view factor. Differences in MRT between sunlit and shaded urban spaces can be substantial; for instance, Lau et al. (2015) reported variations of up to approximately 30 °C within urban environments. Direct measurement of such three-dimensional radiative environments requires observations of shortwave and longwave radiation fluxes in six directions, which is often constrained by instrumentation, installation logistics, observation duration, and spatial representativeness (Thorsson et al., 2007; Johansson et al., 2014). Therefore, radiation models that can spatially estimate pedestrian-level radiative environments and MRT across complex urban geometries are essential for climate-resilient urban design and thermal-environment assessment.

The spatial heterogeneity of urban radiative environments is controlled not only by building morphology but also significantly by green infrastructure. Urban trees are a widely implemented nature-based solution for mitigating pedestrian heat stress. They actively modify the local thermal environment through transpirational cooling, while tree crowns intercept direct shortwave radiation and alter the magnitude and directionality of radiation reaching pedestrians through scattering, transmission, and reflection. Among these processes, the most immediate effect of trees on daytime MRT reduction is the physical interception of direct shortwave radiation. Armson et al. (2012) reported that tree shade can reduce globe temperature by up to 5–7 °C, while Kántor et al. (2018) and Middel et al. (2016) demonstrated that vegetation shading plays a governing role in mitigating summer thermal stress in urban public spaces.

The radiative efficacy of trees depends on canopy architecture, species characteristics, and the distribution of leaf area density (LAD). LAD, describing the one-sided leaf area per unit canopy volume, is a key parameter for shortwave attenuation because it determines the cumulative leaf area and optical depth along any discrete radiative trajectory. Konarska et al. (2014) measured solar-radiation transmissivity through single urban trees in Göteborg, Sweden, and showed that direct shortwave transmissivity through foliated tree crowns was only approximately 1.3–5.3 %. Park et al. (2018) showed that increasing LAD and tree height in a street canyon can substantially reduce MRT, mainly through reductions in downward shortwave radiation. Similarly, Krayenhoff et al. (2014), Ryu et al. (2016), Morakinyo and Lam (2016), and Park et al. (2019) demonstrated that tree LAD, crown dimensions and planting configurations strongly modulate urban radiative environments and pedestrian thermal comfort. These studies collectively highlight the indispensable need to account for both canopy structure and path-dependent optical depth when quantifying shortwave attenuation by urban trees.



Various urban microclimate and radiation models have been developed to calculate outdoor MRT and pedestrian-level radiative fields. ENVI-met and PALM/PALM-4U are high-resolution, three-dimensional prognostic microclimate or urban climate modelling systems that represent complex interactions among urban surfaces, vegetation, and the atmospheric boundary layer, resolving airflow, turbulence, surface energy balance, heat and moisture transport, thermal comfort, and air-quality-related processes (Bruse and Fleer, 1998; Maronga et al., 2020). In contrast, models such as RayMan, SkyHelios, CityComfort+, VTUF-3D, and SOLWEIG are more focused on computationally efficient estimation of pedestrian-level radiation fluxes and MRT (Matzarakis et al., 2007, 2010; Fröhlich and Matzarakis, 2018; Huang et al., 2014; Nice et al., 2018; Lindberg et al., 2008). These models simplify urban morphology, radiative transfer, surface temperature, and vegetation effects to varying degrees depending on their intended applications and computational constraints.

Among these models, SOLWEIG (Solar and LongWave Environmental Irradiance Geometry) is a widely utilized 2.5-dimensional radiation model designed to calculate the spatial distribution of shortwave and longwave radiation fluxes and MRT across complex urban settings with high computational efficiency (Lindberg et al., 2008). In SOLWEIG, high-resolution Digital Surface Models (DSMs) of terrain, buildings, and vegetation, combined with standard meteorological forcing, are used to calculate shadow patterns, sky view factors, ground view factors, and reflected shortwave radiation, ultimately resolving directional pedestrian-level radiative loads. Lindberg and Grimmond (2011) extended SOLWEIG by introducing a vegetation scheme that distinguishes between canopy top height and trunk-zone height, enabling the model to represent shadow patterns cast by urban trees and shrubs. This approach provides a practical framework for evaluating spatial variations in vegetation shading and MRT using relatively simple spatial data.

Recent developments in SOLWEIG have progressively shifted from purely empirical or air-temperature-based surface thermal boundary conditions toward an explicit treatment of surface thermal state based on radiative balance and material properties. Wallenberg et al. (2026) introduced a step-heating parameterization for wall surface temperatures in SOLWEIG using wall thermophysical properties, facet radiation balance, and ambient air temperature. They showed that resolving wall surface temperatures explicitly can lead to differences in MRT of up to approximately 2.5 °C compared with the previous version of SOLWEIG, demonstrating that SOLWEIG can be extended to represent the thermal state of urban surfaces more explicitly. However, while wall surfaces are treated as thermally dynamic facets, the legacy vegetation module in SOLWEIG still relies on a single representative transmissivity and an isothermal assumption. Consequently, LAD-based shortwave attenuation through multi-layered tree canopies and leaf-energy-balance-based calculations of leaf temperature have remained uncoupled with the SOLWEIG framework.

The Legacy SOLWEIG vegetation module thus contains two fundamental simplifications. First, shortwave transmissivity through the canopy is prescribed as a static, bulk representative value for a given vegetation class. While computationally efficient, this treatment cannot explicitly account for the three-dimensional LAD distribution within a canopy, solar path length, canopy-edge partial transmission, or spatial differences between sunlit and shaded foliage. In real tree canopies, shortwave attenuation varies with the cumulative LAD and optical depth along the incoming solar beam;



consequently, transmissivity differs substantially between the dense canopy core, crown edges, and internal gaps even within the same tree. Second, the Legacy SOLWEIG assumes the vegetation surface temperature, or leaf temperature, to be equal to ambient air temperature. Although Lindberg and Grimmond (2011) showed that this simplification is pragmatic for rapid MRT mapping, it prevents the model from resolving intra-canopy leaf temperature variations, thermal differences between sunlit and shaded foliage, transpirational cooling, stomatal responses to microclimatic stress, or voxel-scale sensible and latent heat exchanges. Field observations and canopy microclimate studies have consistently shown that leaf temperature deviates significantly from air temperature, modulated dynamically by incident solar radiation, wind speed, vapor pressure deficit, soil moisture availability, and canopy position (Asawa et al., 2024; Leuzinger and Körner, 2007; Miller et al., 2021).

To overcome these limitations, this study develops SOLWEIG-LEB (Leaf Energy Balance) v1.0, hereafter referred to as SOLWEIG-LEB, an advanced explicit extension of the vegetation representation within the SOLWEIG framework. This new module shifts from the empirical representative-transmissivity approach to an LAD-based path-dependent shortwave attenuation scheme, and explicitly diagnoses leaf temperature and vegetation longwave emission through a voxel-scale leaf energy balance solver. By integrating voxel-resolved LAD information into the 2.5D SOLWEIG framework, the model captures fine-scale canopy attenuation physics while retaining the underlying building and ground geometry of the original radiation model. The objectives of this study are fourfold. First, we develop an LAD-based attenuation scheme where path-dependent shortwave transmissivity is determined by LAI, LAD, the leaf projection function, and solar path length. Second, we couple SOLWEIG with a leaf energy balance module encompassing absorbed shortwave and longwave radiation, leaf thermal emission, sensible heat flux, and latent heat flux, thereby calculating leaf temperature and vegetation longwave emission. Third, we evaluate the leaf energy balance module against in situ leaf-temperature observations in Mainz, Germany (under clear-sky and fully cloudy conditions), and we evaluate the integrated pedestrian-level radiative environment against six-directional radiation fluxes and MRT observations in Göteborg, Sweden. Finally, we analyze how LAD-based shortwave attenuation and leaf-energy-balance-diagnosed vegetation longwave emission drive spatial variations in pedestrian-level MRT and intra-canopy microclimate diagnostics. The remainder of this paper is organized as follows. Section 2 describes the mathematical and computational architecture of SOLWEIG-LEB v1.0, including the LAD-based canopy attenuation scheme, directional radiation modifications, and the leaf energy balance module. Section 3 presents the observational datasets and numerical experimental designs for the Mainz and Göteborg sites. Section 4 presents the model evaluation results, comparative performance against Legacy SOLWEIG, and voxel-scale spatial diagnostics. Section 5 discusses the physical interpretations, computational scope, limitations, and future development, and Section 6 summarizes the main conclusions.

2. Model description

This section describes the mathematical formulation, computational architecture, and implementation of SOLWEIG-LEB. Figure 1 illustrates the overall computational framework. The model extends the radiation-geometry framework of

Legacy SOLWEIG and comprises input data processing, shadow and view-factor calculations, shortwave and longwave radiation-field calculations, a leaf energy balance module, and the final MRT calculation.

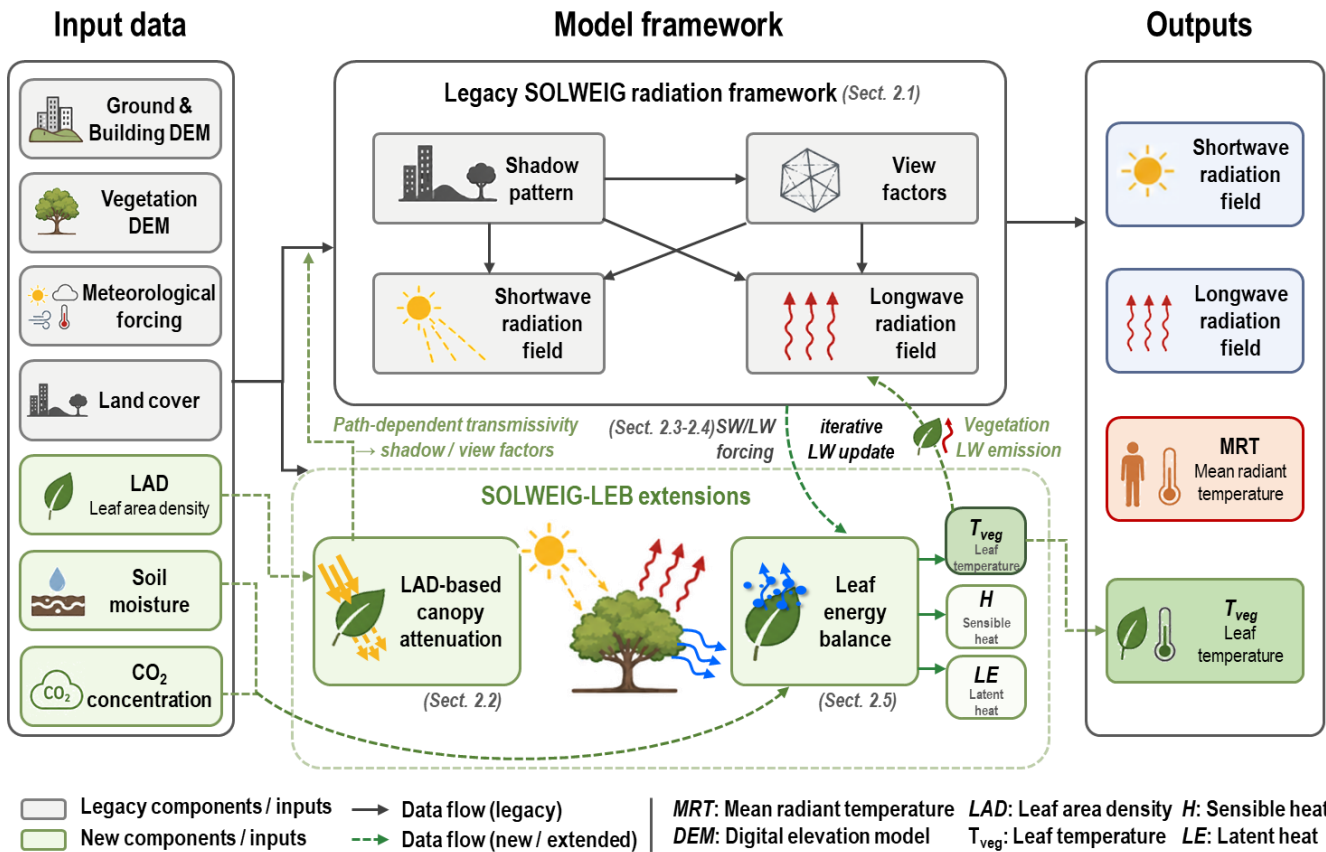


Figure 1. Schematic workflow of SOLWEIG-LEB v1.0. Grey components represent the Legacy SOLWEIG radiation framework, while green components indicate the newly introduced LAD-based canopy attenuation and leaf energy balance modules.

2.1. Legacy SOLWEIG radiation framework and MRT calculation

Throughout this study, Legacy SOLWEIG refers to the QGIS-based SOLWEIG v2025a. It calculates the six-directional radiative environment using terrain, building, and vegetation height data, land-cover information, and meteorological forcing. Specifically, SOLWEIG calculates shadow patterns produced by buildings and vegetation, sky view factors (SVF), ground view factors (GVF), reflected shortwave radiation, and longwave radiation at the pedestrian level. The final target variable of SOLWEIG, mean radiant temperature (MRT), is derived from the mean radiant flux density, which integrates the shortwave and longwave radiation fluxes received by a pedestrian from six orthogonal directions (upward, downward, east, south, west, and north). The mean radiant flux density (R) is defined as follows:



$$R = a_k \sum_{i=1}^6 K_i F_i + \varepsilon_p \sum_{i=1}^6 L_i F_i, \quad (1)$$

where i indexes these six directions, and K_i and L_i are the shortwave and longwave radiation fluxes incident on the human body from direction i , respectively. F_i represents the angular factor between the human body and the surrounding environment. For a standing or walking person, Legacy SOLWEIG uses an angular factor of 0.22 for each of the four horizontal directions and 0.06 for the upward and downward directions, following Lindberg and Grimmond (2011). a_k and ε_p are the shortwave absorption coefficient and longwave emissivity of the human body, set to 0.70 and 0.95, respectively, in this study (Table 1). MRT (T_{mrt}) is then calculated using the Stefan–Boltzmann law as

$$T_{mrt} = \sqrt[4]{\frac{R}{\varepsilon_p \sigma}} - 273.15, \quad (2)$$

where σ is the Stefan–Boltzmann constant ($= 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). Eqs. (1) and (2) are retained in SOLWEIG-LEB. Thus, the objective of this study is not to modify the MRT formulation itself, but to provide a more physically based and spatially explicit calculation of the vegetation-related K_i and L_i terms used in Eq. (1).

Table 1. Model configuration and vegetation treatment in Legacy SOLWEIG and SOLWEIG-LEB.

Model setting	Legacy SOLWEIG (v2025a)	SOLWEIG-LEB
Canopy transmissivity	Fixed transmissivity ($\tau = 3 \%$)	Path-dependent transmissivity calculated from LAD, radiative path length, and the leaf projection function
Leaf projection function	Not explicitly represented	Spherical leaf angle distribution ($G_{proj} = 0.5$)
Vegetation temperature	$T_{veg} = T_{air}$	Calculated for each vegetation voxel using the leaf energy balance
Vegetation longwave emission	Calculated using $T_{veg} = T_{air}$	Calculated using vegetation-voxel T_{veg}
Sensible and latent heat fluxes	Not calculated	Calculated diagnostically for each vegetation voxel
Human-body representation	Six-directional box representation*	
Human posture	Standing	
Calculation height	1.1 m above ground	
Human shortwave absorptivity	0.70	
Human longwave emissivity	0.95	
Diffuse shortwave sky model	Anisotropic (Wallenberg et al., 2020)	
Longwave radiation model	Anisotropic directional parameterization (Wallenberg et al., 2023)	
Wall surface-temperature scheme	Simple step-heating approach (Wallenberg et al., 2026)	



Model setting	Legacy SOLWEIG (v2025a)	SOLWEIG-LEB
Land-cover scheme	Enabled (Lindberg et al., 2016)	

* The six-directional box representation was used to match the radiation observations in Göteborg.

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The vegetation module in Legacy SOLWEIG represents the three-dimensional structure of trees and shrubs by distinguishing between canopy top height and trunk-zone height. This structure distinguishes between the canopy region that casts shadows and the non-vegetated space below the canopy through which solar radiation can pass. However, in the legacy vegetation module, shortwave attenuation by vegetation is not calculated directly from the leaf area distribution within the canopy or from radiative path length. Instead, vegetation shadows are first calculated as a Boolean shadow field that represents only whether a pixel is sunlit (= 1) or shaded (= 0), and a single bulk representative transmissivity (τ), prescribed for specific vegetation types (typically set to 0.03 for dense summer crowns), is then uniformly applied during the shortwave radiation calculation. While computationally efficient, this approach cannot explicitly represent path-dependent shortwave attenuation that varies within the same tree canopy according to the canopy core, canopy edge, canopy gaps, and the direction of incoming solar radiation. Legacy SOLWEIG also simplifies the thermal state of vegetation in the longwave radiation calculation. In the legacy vegetation module, vegetation surface temperature (or leaf temperature) is assumed to be equal to ambient air temperature, and longwave radiation emitted from vegetation is calculated based on this isothermal air-temperature assumption. This approach can be a practical simplification for efficient MRT-oriented radiation modelling, but it does not directly resolve temporal variations in leaf temperature, temperature differences between sunlit and shaded foliage within the canopy, transpirational cooling, stomatal responses to microclimatic stress, or sensible and latent heat fluxes between vegetation and the atmosphere.

SOLWEIG-LEB retains the efficient radiation-geometry framework of Legacy SOLWEIG, while extending the vegetation-related radiation terms in two ways. First, instead of using a fixed representative transmissivity (τ), SOLWEIG-LEB computes the shortwave radiation fluxes (K_i) reaching a pedestrian or vegetation voxel using a path-dependent transmissivity determined from the canopy LAD and the radiative path length. Second, for the vegetation-related longwave radiation fluxes (L_i), the vegetation emission is explicitly driven by the leaf temperature (T_{veg}) calculated from the leaf energy balance module, thereby replacing the conventional air-temperature-based assumption.

2.2. LAD-based canopy attenuation

In Legacy SOLWEIG, shortwave radiation fluxes are divided into direct, diffuse, and reflected shortwave components. Because direct shortwave radiation has a single direction determined by the solar position, its obstruction is calculated using building and vegetation shadow factors. In contrast, diffuse shortwave radiation originates from the sky



hemisphere and is therefore controlled by SVF, whereas reflected shortwave radiation is calculated using view factors of surrounding surfaces, such as the ground, walls, and vegetation, together with the wall sunlit/shaded fraction. Thus, in
185 SOLWEIG, the effect of vegetation is represented through the shadow factor (S) for the direct component, and through geometry fields such as the sky view factor (Ψ_{sky}), ground view factor (Ψ_g), and directional angular weighting factor (w_{wall}) for the diffuse and reflected components.

SOLWEIG-LEB retains this existing structure but modifies the vegetation-related geometry fields to incorporate LAD-based transmissivity. Instead of applying a fixed representative vegetation transmissivity (τ) a posteriori, SOLWEIG-
190 LEB calculates the optical depth along each directional ray during the shadow-casting or view-factor calculation and directly integrates the resulting path-dependent transmissivity into the geometry fields. Leaf area density (LAD), defined as the one-sided leaf area per unit canopy volume ($\text{m}^2 \text{m}^{-3}$), determines the cumulative leaf area and optical depth along a radiative path through the canopy. When voxel-scale or vertically resolved LAD data are available, they can be used directly. When only leaf area index (LAI) is available, LAD is estimated by assuming a uniform vertical distribution of leaf area within the canopy
195 layer:

$$LAD = \frac{LAI}{z_{top} - z_{base}}. \quad (3)$$

Here, LAI is the leaf area per unit ground area ($\text{m}^2 \text{m}^{-2}$), and z_{top} and z_{base} denote the canopy-top height and crown-base (trunk-zone) height, respectively. Species-specific or observation-based LAD profiles can therefore be prescribed when available instead of applying the uniform-distribution assumption in Eq. (3). For a specific radiative path p passing through
200 the canopy, the optical depth Ω_p accumulated along the path is calculated as:

$$\Omega_p = \int G_{proj} \cdot LAD(s) \, ds, \quad (4)$$

where $LAD(s)$ is the leaf area density ($\text{m}^2 \text{m}^{-3}$) at position s along the radiative path. G_{proj} is the leaf projection function for the corresponding radiation direction and represents the fraction of leaf area projected onto a plane perpendicular to the incident ray. G_{proj} depends on the leaf angle distribution and the incident direction (Ross, 2012; Campbell, 1986). When the
205 leaf angle distribution of the canopy is not explicitly known, a spherical leaf angle distribution can be assumed, for which $G_{proj} \approx 0.5$ (de Wit, 1965; Campbell and Norman, 2000). In the default configuration of this study, a spherical leaf angle distribution is assumed for all vegetation voxels, and $G_{proj} = 0.5$ is used.

The transmissivity τ_p of shortwave radiation along path p is then calculated using the Beer–Lambert law:

$$\tau_p = \exp(-\Omega_p). \quad (5)$$

210 Thus, τ_p varies with the accumulated optical depth along each radiative path, producing lower transmissivity through dense canopy cores and higher transmissivity near crown edges or canopy gaps. The Boolean vegetation shadow factor used in Legacy SOLWEIG is therefore replaced by a transmissivity-weighted vegetation shadow factor, S_{veg}^* :



$$S_{veg}^* = \begin{cases} 1, & \text{if the ray is blocked by buildings or intersects no vegetation} \\ \tau_p, & \text{if the ray intersects vegetation without being blocked by buildings} \end{cases} \quad (6)$$

Here, S_{veg}^* is a continuous, attenuation-weighted vegetation shadow factor ranging between 0 and 1. Buildings are treated as
 215 opaque obstacles; therefore, the building shadow factor (S_{bd}) remains a Boolean variable as in Legacy SOLWEIG. The same
 integration concept is also applied to the calculation of SVF, GVF, and angular weighting factors. In this study, view-factor
 terms (Ψ^*) and directional angular weighting factors (w^*) with a superscript asterisk (*) do not indicate that a fixed
 transmissivity is multiplied a posteriori. Instead, they indicate that LAD-based canopy attenuation has already been
 dynamically incorporated during the shadow-casting or view-factor ray-tracing process. For example, $\Psi_{sky,veg}^*$, $\Psi_{g,sunlit}^*$, and
 220 w_{veg}^* denote the LAD-transmissivity-weighted quantities for canopy sky obstruction, sunlit-ground visibility, and directional
 vegetation contribution, respectively.

2.3. Modified shortwave radiation fluxes

In SOLWEIG, shortwave radiation fluxes consist of direct, diffuse, and reflected shortwave components (Lindberg
 225 et al., 2008; Lindberg and Grimmond, 2011). Direct shortwave radiation, I , is the direct solar irradiance on a plane
 perpendicular to the solar beam; diffuse shortwave radiation, D , is the sky diffuse component; and G is global shortwave
 radiation. In SOLWEIG, I is estimated from G and D as:

$$I = \frac{(G-D)}{\sin \eta}, \quad (7)$$

where η is the solar elevation angle.

230 SOLWEIG-LEB retains the shortwave radiation calculation structure of Legacy SOLWEIG but uses the
 transmissivity-weighted vegetation geometry terms defined in Section 2.2. Specifically, S_{veg}^* is applied to the direct
 component, whereas LAD-attenuation-weighted view factors, such as $\Psi_{sky,veg}^*$, are used for the diffuse and reflected
 components. The modified downward shortwave radiation, K_d , is expressed as:

$$K_d = I \cdot [S_{bd} - (1 - S_{veg}^*)] \sin \eta + D \cdot [\Psi_{sky,bd} - (1 - \Psi_{sky,veg}^*)] + G \cdot \alpha_s \cdot (1 - f_s) [1 - \{\Psi_{sky,bd} - (1 - \Psi_{sky,veg}^*)\}] \quad (8)$$

235 Here, S_{bd} is the direct-beam shadow factor for buildings, which is 0 when the point is shaded by buildings and 1 when it is
 not. S_{veg}^* is the transmissivity-weighted vegetation shadow factor defined in Eq. (6). $\Psi_{sky,bd}$ is the SVF considering building
 obstruction only, and $\Psi_{sky,veg}^*$ is the vegetation-related SVF including LAD-based canopy attenuation. α_s is the local surface



albedo prescribed according to the surface category, and f_s is the fraction of wall surface that is shaded. The first, second, and third terms on the right-hand side of Eq. (8) represent the direct, diffuse, and reflected components, respectively.

240 The upward shortwave radiation, $K_{\uparrow}$, is calculated as shortwave radiation reflected from the ground surface and reaching a pedestrian or vegetation voxel:

$$K_{\uparrow} = \alpha_s \left[\begin{array}{c} I \cdot \Psi_{g,sunlit}^* \sin \eta \\ + D \cdot \{\Psi_{sky,bd} - (1 - \Psi_{sky,veg}^*)\} \\ + G \cdot \alpha_s \cdot (1 - f_s) [1 - \{\Psi_{sky,bd} - (1 - \Psi_{sky,veg}^*)\}] \end{array} \right]. \quad (9)$$

Here, $\Psi_{g,sunlit}^*$ denotes the attenuation-weighted view factor of sunlit ground surfaces visible from the height of interest. In Legacy SOLWEIG, $K_{\uparrow}$ at pedestrian level is estimated by searching for sunlit areas around the pedestrian height of 1.1 m, with the horizontal search distance limited to 20 times the height of interest for computational efficiency (Lindberg and Grimmond, 2011). In SOLWEIG-LEB, the same principle is extended from pedestrian locations to all individual vegetation voxels. Thus, for each receiver height, the horizontal area corresponding to 20 times that specific height is searched to estimate the sunlit ground contribution, ensuring vertical profiling of reflected shortwave exposure.

250 The sideward shortwave radiation, $K_{\rightarrow,j}$, represents shortwave radiation incident from the four cardinal directions: east, south, west, and north, where $j \in \{E, S, W, N\}$. Each directional component is calculated separately depending on whether direct solar radiation contributes to that specific vertical plane. When direct solar radiation contributes to direction j , the sideward shortwave radiation is calculated as:

$$K_{\rightarrow,j} = I \cdot [S_{bd} - (1 - S_{veg}^*)] \cos \eta \sin \theta_j + D \cdot [1 - (w_{wall,j} + w_{veg,j}^*)] + G \cdot \alpha_s \cdot (1 - f_s) [w_{wall,j} + w_{veg,j}^*], \quad (10)$$

where θ_j is the solar azimuth angle relative to direction j . When direct solar radiation does not contribute to direction j , the direct component is excluded, and only the diffuse and reflected components are considered:

$$K_{\rightarrow,j} = D \cdot [1 - (w_{wall,j} + w_{veg,j}^*)] + G \cdot \alpha_s \cdot (1 - f_s) [w_{wall,j} + w_{veg,j}^*]. \quad (11)$$

Here, $w_{wall,j}$ and $w_{veg,j}^*$ are the attenuation-weighted angular weighting factors for building walls and vegetation visible from direction j , respectively. These weighting factors are utilized to quantify the contribution of shortwave radiation originating from direction j , encompassing secondary reflections from walls, vegetation, sky, and surrounding ground facets. Eqs. (8)–(11) are implemented not only for pedestrian-level MRT calculations but also as boundary conditions for the leaf energy balance calculation in vegetation voxels. However, as described in Section 2.5, the shortwave radiation input to the leaf energy balance is not obtained by simply summing the entire six-directional shortwave radiation field into a single value.



Instead, the direct, diffuse, and reflected components are partitioned and converted into absorbed radiation on an explicit leaf-area basis.

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2.4. Modified longwave radiation fluxes and vegetation longwave emission

In SOLWEIG, longwave radiation fluxes (L) are calculated as the sum of longwave radiation emitted and reflected from the sky, buildings, surfaces, and vegetation. This calculation uses the SVF considering building obstruction only, $\Psi_{sky,bd}$, the vegetation-related SVF representing the obstruction of open sky by vegetation, $\Psi_{sky,veg}$, and an auxiliary view-factor term, $\Psi_{sky,veg-bd}$, used to isolate the vegetation layers located directly in front of building walls. In Legacy SOLWEIG, the vegetation surface temperature is assumed to be equal to air temperature, and the longwave contributions from vegetation and walls are calculated in a simplified manner (Lindberg and Grimmond, 2011). SOLWEIG-LEB retains the fundamental longwave radiation framework of the legacy model but dynamically updates the longwave radiation emitted from vegetation based on the diagnostic equilibrium leaf temperature, T_{veg} , calculated by the leaf energy balance module described in Section 2.5. The downward longwave radiation received by vegetation voxels in SOLWEIG-LEB, $L_{\downarrow}$, is formulated as:

$$\begin{aligned}
 L_{\downarrow} = & \{ \Psi_{sky,bd} - (1 - \Psi_{sky,veg}^*) \} \cdot \varepsilon_{sky} \cdot \sigma \cdot T_{air}^4 \\
 & + \{ (1 - \Psi_{sky,veg}^*) + (1 - \Psi_{sky,veg-bd}^*) \} \cdot \varepsilon_{veg} \cdot \sigma \cdot T_{veg}^4 \\
 & + \{ (1 - \Psi_{sky,bd}) - (1 - \Psi_{sky,veg-bd}^*) \} \cdot \varepsilon_{wall} \cdot \sigma \cdot T_{wall}^4 \\
 & + \{ [(1 - \Psi_{sky,veg}^*) + (1 - \Psi_{sky,veg-bd}^*)] (1 - \varepsilon_{veg}) \\
 & + [(1 - \Psi_{sky,bd}) - (1 - \Psi_{sky,veg-bd}^*)] (1 - \varepsilon_{wall}) \} \cdot \varepsilon_{sky} \cdot \sigma \cdot T_{air}^4
 \end{aligned} \quad (12)$$

Here, ε_{sky} , ε_{veg} , and ε_{wall} are the emissivities of the sky, vegetation, and wall surfaces, respectively, in the vegetation-voxel radiation calculation. ε_{sky} is estimated empirically from air temperature and humidity, while ε_{veg} and ε_{wall} are prescribed as 0.98 and 0.90, respectively (Oke, 2002; Lindberg et al., 2008; Jones et al., 2003). T_{air} , T_{veg} , and T_{wall} represent the air temperature, leaf temperature, and building wall temperature, respectively, with all temperatures expressed in Kelvin (K). The first term on the right-hand side of Eq. (12) represents direct longwave radiation from the sky, the second term denotes the explicit vegetation longwave emission, the third term accounts for the longwave radiation emitted from wall surfaces not obscured by vegetation, and the fourth term captures the reflected sky longwave radiation from both vegetation and wall facets.

The upward longwave radiation received by a vegetation voxel, $L_{\uparrow}$, includes the longwave radiation emitted from the ground surface and the longwave radiation emitted from vegetation visible in the downward direction from the receiver height:

$$\begin{aligned}
 L_{\uparrow} = & (1 - \Psi_{g,veg}^*) \varepsilon_g \cdot \sigma \cdot \{ T_{air} + \Psi_{g,sunlit}^* \cdot (T_{sur} - T_{air}) \}^4 \\
 & + \Psi_{g,veg}^* \cdot \varepsilon_{veg} \cdot \sigma \cdot T_{veg}^4
 \end{aligned} \quad (13)$$



Here, ε_g is the ground emissivity prescribed for each land-cover category (Table 2). T_{sur} represents the surface temperature of sunlit ground, while shaded ground pixels are assumed to have the same temperature as T_{air} , as in Legacy SOLWEIG.

290 $\Psi_{g,veg}^*$ is the view factor of vegetation canopy visible in the downward direction from the receiver. The sideward longwave radiation, $L_{\rightarrow,j}$, incident from the four cardinal directions (east, south, west, and north; $j \in \{E, S, W, N\}$), follows the multi-layered structure of Legacy SOLWEIG. At vegetation voxels, the vegetation-originating longwave radiation terms are explicitly driven by the diagnosed T_{veg} rather than the ambient air temperature, and the vegetation-related view-factors utilize the updated canopy geometry representation defined in Section 2.2. For these voxel-level radiation fields, the numerical

295 integration follows Lindberg and Grimmond (2011), with the vegetation longwave source temperature updated from T_{air} to T_{veg} .

Table 2. Surface radiative properties used in the simulations.

Surface category	Albedo	Emissivity
Dark asphalt	0.18	0.95
Roofs	0.18	0.95
Unmanaged grass	0.16	0.94
Walls	0.20	0.90
Bare soil	0.25	0.94

2.5. Leaf energy balance module

300 In SOLWEIG-LEB, leaf temperature (T_{veg}) is calculated by solving a steady-state energy balance for each vegetation voxel. The module adopts the CANOAK leaf energy balance framework (Baldocchi, 1992, 1994; Baldocchi and Harley, 1995). Absorbed radiation is partitioned into longwave emission, sensible heat flux, and latent heat flux. All terms are expressed per unit one-sided leaf area. Longwave emission and sensible heat exchange include both leaf surfaces, whereas transpiration occurs from one surface under the hypostomatous broadleaf assumption. The leaf energy balance is expressed as:

$$\begin{aligned}
 R_{net} &= Q_{rad,in} - L_{emit} \\
 &= K_{abs} + L_{abs} - 2\varepsilon_{veg}\sigma T_{veg}^4. \\
 &= H + LE
 \end{aligned}
 \tag{14}$$

305

Here, $Q_{rad,in}$ is the total radiative energy absorbed by the leaf ($Q_{rad,in} = K_{abs} + L_{abs}$), where K_{abs} and L_{abs} represent the absorbed shortwave and longwave radiation, respectively. L_{emit} ($= 2\varepsilon_{veg}\sigma T_{veg}^4$) accounts for the longwave radiation emitted from both sides of the leaf. H is the sensible heat flux between the leaf and the surrounding air, and LE is the latent heat flux governed by transpirational cooling. The shortwave radiation input to the leaf energy balance is derived from the shortwave



310 radiation fields calculated in Section 2.3. The leaf projection function G_{proj} , defined in Section 2.2, is applied strictly to the direct shortwave component. Thus, the shortwave radiation absorbed by leaves within a vegetation voxel (K_{abs}) is calculated as:

$$K_{abs} = (G_{proj} \cdot K_{dir} + K_{dif} + K_{ref}) \cdot (\alpha_{PAR} \cdot f_{PAR} + \alpha_{NIR} \cdot f_{NIR}). \quad (15)$$

Here, K_{dir} is the direct shortwave radiation component reaching the vegetation voxel, and $G_{proj}K_{dir}$ represents the amount of direct solar beam incident on a unit leaf area. K_{dif} and K_{ref} are the diffuse and reflected shortwave radiation components reaching the vegetation voxel, respectively; these components are not scaled by G_{proj} because they lack a single beam direction. In Eq. (15), α_{PAR} and α_{NIR} are the leaf absorptivities for photosynthetically active radiation (PAR, 400–700 nm) and near-infrared radiation (NIR), respectively, while f_{PAR} and f_{NIR} represent the respective spectral fractions of broadband shortwave radiation. PAR is directly utilized for photosynthesis, whereas NIR contributes primarily to the leaf thermal load. Following the CANOAK configuration, α_{PAR} , α_{NIR} , f_{PAR} , and f_{NIR} are prescribed as 0.795, 0.31, 0.45, and 0.55, respectively. The longwave radiation absorbed by leaves is calculated using the total incoming longwave radiation for the vegetation voxel, L_{total} , calculated in Section 2.4:

$$L_{abs} = \alpha_{LW} \cdot L_{total}, \quad (16)$$

where α_{LW} is the longwave absorptivity of the leaf. Assuming leaves to be gray bodies in the thermal infrared region and applying Kirchhoff's law, the longwave absorptivity can be considered equal to the longwave emissivity. Therefore, for leaf absorption and emission, $\alpha_{LW} = \varepsilon_{veg} = 0.98$ is used.

The sensible heat flux from leaves, H , is treated as heat exchange from both leaf sides:

$$H = 2\rho_{air}c_p \frac{T_{veg}-T_{air}}{r_{b,heat}}. \quad (17)$$

Here, ρ_{air} is air density, c_p is the specific heat capacity of air at constant pressure, and $r_{b,heat}$ is the leaf boundary-layer resistance for heat transfer. The factor of 2 represents the two-sided leaf assumption for sensible heat exchange.

The latent heat flux, LE , is treated as one-sided transpiration under the broadleaf hypostomatous assumption:

$$LE = \frac{0.622 \cdot \rho_{air} \cdot \lambda_{vap}}{P \cdot (r_{b,vap} + r_{stom})} \cdot \{e_s(T_{veg}) - e_{air}\}. \quad (18)$$

Here, λ_{vap} is the latent heat of vaporization, P is atmospheric pressure, and $r_{b,vap}$ is the leaf boundary-layer resistance for water-vapor transfer, and r_{stom} is the stomatal resistance to water-vapor diffusion. $e_s(T_{veg})$ is the saturation vapor pressure at leaf temperature, and e_{air} is the vapor pressure of the surrounding air. The leaf boundary-layer resistance for water-vapor transfer ($r_{b,vap}$) is calculated from wind speed, leaf characteristic length, air viscosity, and the leaf–air temperature difference, accounting for both forced and free convection. In contrast, the stomatal resistance (r_{stom}) represents physiological regulation



driven by coupled photosynthesis, leaf-surface humidity and CO₂ diffusion; increasing PAR generally promotes stomatal opening such that r_{stom} decreases, whereas under very low radiation conditions, the stomata approach a closed state and r_{stom} becomes large. The boundary-layer resistances ($r_{b,heat}$, $r_{b,vap}$) in Eqs. (17) and (18) are expressed as

$$r_{b,heat} = \frac{\ell}{D_h N_u}, \quad (19)$$

$$r_{b,vap} = \frac{\ell}{D_v S_h}, \quad (20)$$

where ℓ is the characteristic leaf dimension (set to 0.1 m), and D_h and D_v are the thermal and water-vapor diffusivities, respectively. The dimensionless Nusselt (N_u) and Sherwood (S_h) numbers characterize convective heat and water-vapor transfers across the leaf boundary layer. Leaves are approximated as flat plates, with boundary-layer resistances calculated using forced- and free-convection correlations implemented in CANOAK (Schuepp, 1993; Baldocchi and Bowling, 2003). The stomatal resistance in Eq. (18) is obtained from the water-vapour stomatal conductance:

$$r_{stom} = \frac{1}{g_{s,w} V_m}, \quad (21)$$

Here, $g_{s,w}$ is stomatal conductance to water vapor (mol m⁻² s⁻¹), and V_m is the molar volume of air (m³ mol⁻¹) at leaf temperature and ambient pressure, giving r_{stom} in s m⁻¹. For positive assimilation, $g_{s,w}$ follows the Ball–Berry relation used by Baldocchi (1994):

$$g_{s,w} = g_0 + m_{eff} \frac{A h_s}{C_s}, \quad (22)$$

where g_0 is residual conductance, m_{eff} is the effective conductance slope, A is net CO₂ assimilation rate (μmol m⁻² s⁻¹), h_s is leaf-surface relative humidity (0–1), and C_s is leaf-surface CO₂ mole fraction (μmol mol⁻¹). Assimilation and stomatal conductance are coupled through the CANOAK C3 photosynthesis formulation (Farquhar et al., 1980; Baldocchi, 1994). The physiological parameters and photosynthesis equations are presented in Appendix A. Soil-water limitation is represented by scaling the Ball–Berry slope following Baldocchi (1997):

$$m_{eff} = m_0 f_w, \quad (23)$$

where m_0 is the slope under non-limiting soil-water conditions and f_w is a water-availability factor. We calculate f_w from relative extractable water (REW) by adapting the linear soil-water response of Granier et al. (1999):

$$f_w = \min(1, \frac{REW}{REW_{crit}}), \quad (24)$$

where $REW_{crit} = 0.4$. REW is prescribed directly or calculated as $REW = \min[1, \max(0, \frac{\theta - \theta_{wilt}}{\theta_{fc} - \theta_{wilt}})]$, where θ , θ_{wilt} , and θ_{fc} are the root-zone volumetric soil water content, wilting-point water content, and field capacity (m³ m⁻³), respectively.



Solving Eq. (14) yields T_{veg} , H , and LE for each vegetation voxel. The diagnosed leaf temperature is used to update
 365 vegetation longwave emission and the surrounding longwave radiation field. Leaf temperature and radiation are updated
 iteratively using a temperature-change criterion of 0.05 K.

3. Evaluation data and experimental design

Two observational datasets were used for complementary evaluations of SOLWEIG-LEB. Leaf-temperature (T_{veg})
 370 observations from Mainz, Germany, were used to evaluate the leaf energy balance module and its ability to reproduce temporal
 variations, whereas six-directional radiation and MRT observations from Göteborg, Sweden, were used to evaluate the
 integrated pedestrian-level radiation framework, including LAD-based canopy attenuation and leaf-temperature-based
 vegetation longwave emission. In addition, a computational benchmark was conducted to quantify the additional computational
 cost associated with the newly introduced model components (Section 3.3).

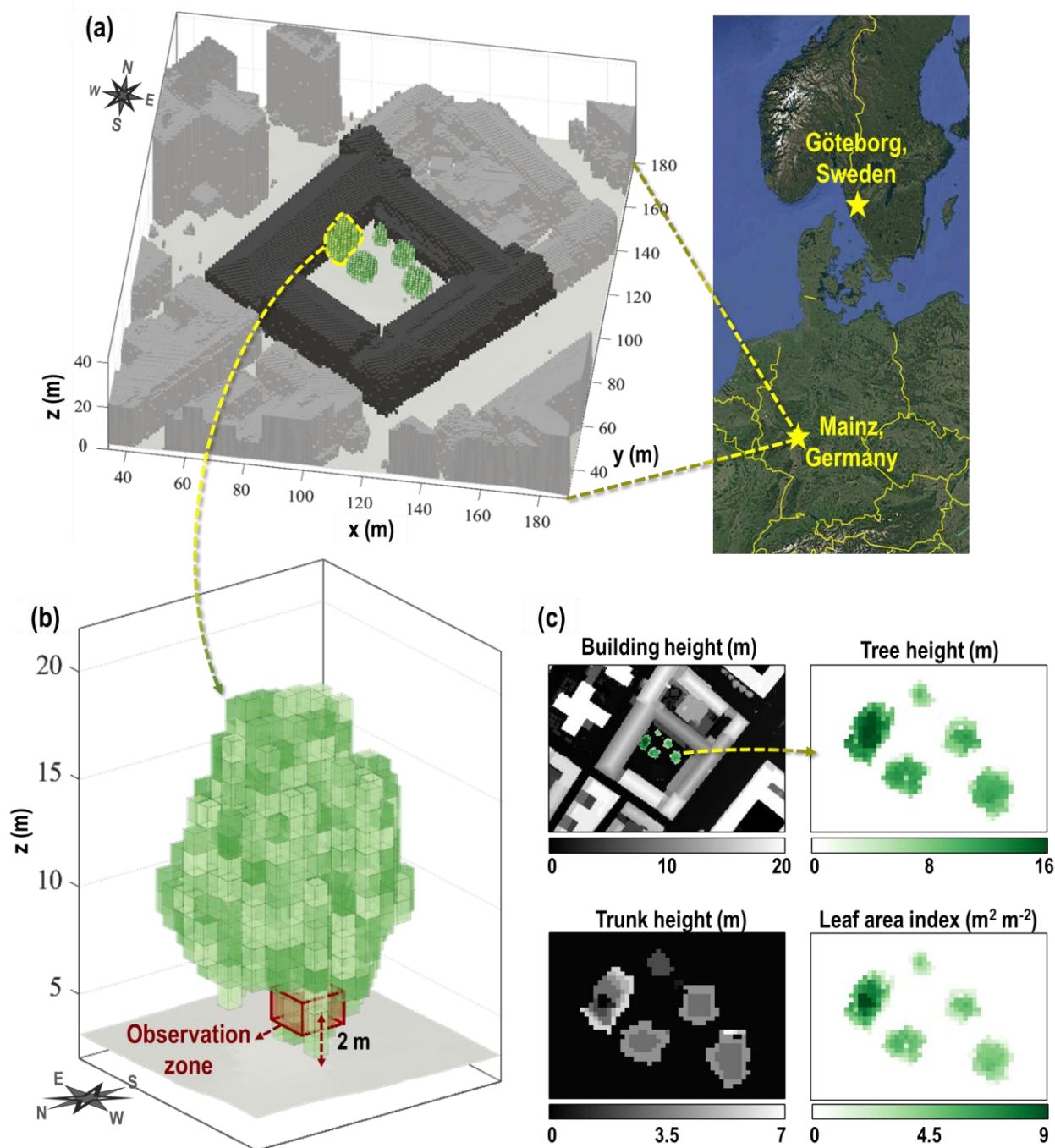
3.1. Leaf-temperature evaluation dataset in Germany

The leaf energy balance module of SOLWEIG-LEB was evaluated using the leaf-temperature observational dataset
 of Simon et al. (2018) from Mainz, Germany. The observations were conducted in the Landesmuseum Mainz courtyard located
 in the city center (50°00'14.0"N, 8°16'03.0"E). The site is an approximately 43 m × 48 m courtyard surrounded by buildings
 380 with heights of 10 to 16 m (Fig. 2a). Several mature *Platanus × acerifolia* trees are present within the courtyard, and Simon
 et al. (2018) measured the leaf surface temperature from one representative large tree among them (Fig. 2b). The leaf
 temperature was measured using an Arduino-based infrared thermometer equipped with a Melexis MLX90614ESF-DCI
 infrared sensor. The sensor was installed on a branch approximately 5 m above ground and was directed toward a dense cluster
 of leaves located approximately 3 m below the sensor. Because the original study did not provide exact three-dimensional
 385 coordinates or a specific grid index that could be directly matched to the SOLWEIG grid, this study compared the observed
 leaf temperature with the mean and range of T_{veg} calculated for the estimated observation area shown in Fig. 2b, namely the
 lower-canopy vegetation cells situated approximately 2 m above ground surface.

The model domain was configured to replicate the Landesmuseum Mainz courtyard and its surrounding buildings and
 vegetation. The numerical simulations were performed at a spatial resolution of 1 m, utilizing building height, vegetation
 390 height, and trunk-zone height as geometric inputs. Following the model setup of Simon et al. (2018), the vegetation LAD was
 prescribed as 0.6 m² m⁻³. Based on the constructed canopy geometry and LAD configurations, the spatial LAI input data were
 derived for the simulation (Fig. 2c). The leaf-temperature evaluation was conducted for two contrasting sky conditions: a clear-
 sky period on 2–3 August 2015 and a fully cloudy period on 16–17 August 2015. These periods exhibited distinctly different
 contributions of direct and diffuse shortwave radiation, allowing the leaf energy balance module to be evaluated under strong



395 direct radiative forcing and predominantly diffuse conditions. Direct and diffuse shortwave radiation components were
extracted from the meteorological dataset used by Simon et al. (2018), which originated from a weather station located
approximately 3 km southwest of the study site. Although Simon et al. (2018) reported air temperature and relative humidity
measurements within the courtyard, the corresponding hourly time series were unavailable for the present evaluation.
Consequently, the synchronous air temperature and relative humidity from the same background weather station were utilized
400 as the meteorological forcing for SOLWEIG-LEB (Fig. 3). The background wind speed was set to 1.3 m s^{-1} . Non-limiting
soil-water conditions were prescribed ($\text{REW} = 1$ and $f_w = 1$). The background CO_2 concentration was set to 420 ppm.
Observed leaf temperatures were compared with SOLWEIG-LEB results and the ENVI-met results reported by Simon et al.
(2018).



405 **Figure 2. Mainz site and model domain used for leaf-temperature evaluation. (a) Site location and three-dimensional model domain, (b) vegetation-voxel representation of the evaluated tree and estimated observation zone, and (c) building height, tree height, trunk-zone height, and leaf area index used as model inputs.**

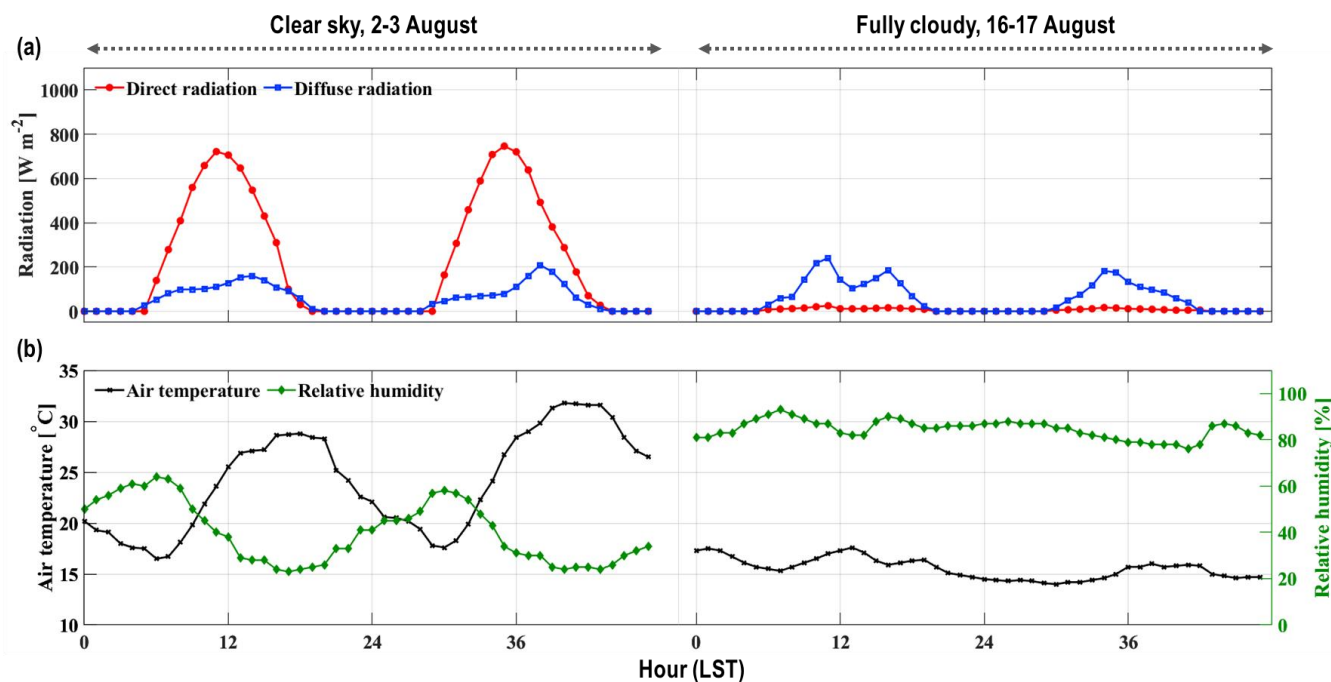


Figure 3. Meteorological forcing used for the Mainz simulations under clear-sky and fully cloudy conditions. (a) Direct and diffuse shortwave radiation and (b) air temperature and relative humidity. Time is expressed in local standard time (LST).

3.2. Pedestrian-level radiation and MRT evaluation dataset in Sweden

The pedestrian-level radiative environment and MRT calculated by SOLWEIG-LEB were evaluated using six-directional radiation observations from Göteborg, Sweden (57°41'22.0"N, 11°58'01.0"E) (Lindberg and Grimmond, 2011; Konarska et al., 2014). The study site is a public square surrounded by two- to three-storey buildings, with a park containing deciduous trees and shrubs to the northwest (Fig. 4a). Shortwave and longwave radiation fluxes were measured in six directions—upward, downward, east, south, west, and north—using CNR1 net radiometers (Kipp & Zonen). For the present study, the two measurement locations were denoted OP1 and OP2 (Fig. 4b). OP1 was located beneath an approximately 13.5-m-high *Aesculus hippocastanum* canopy, whereas OP2 was located north of a row of *Tilia cordata* trees approximately 16.6 m in height. Both locations were therefore strongly influenced by tree-canopy shading. Measurements were available for 23 May 2010 at OP1 and for 7, 10, and 12 July 2010 at OP2.

The model domain was configured to include the observation points and the surrounding buildings and vegetation, with horizontal and vertical spatial resolutions of 2 m and 1 m, respectively. In SOLWEIG-LEB, vegetation LAD or LAI values must be specified to execute the LAD-based canopy attenuation scheme. The LAD values reported in previous literature are approximately $0.6 \text{ m}^2 \text{ m}^{-3}$ for *Tilia cordata* (Scholz et al., 2018; Moser et al., 2015; Helletsgruber et al., 2020). In contrast, *Aesculus hippocastanum* has been reported to exhibit a broader range of approximately $0.2\text{--}0.7 \text{ m}^2 \text{ m}^{-3}$ (Lv et al., 2024; Moser-Reischl et al., 2025). Konarska et al. (2014) reported that the direct shortwave transmissivity beneath the foliated canopy of

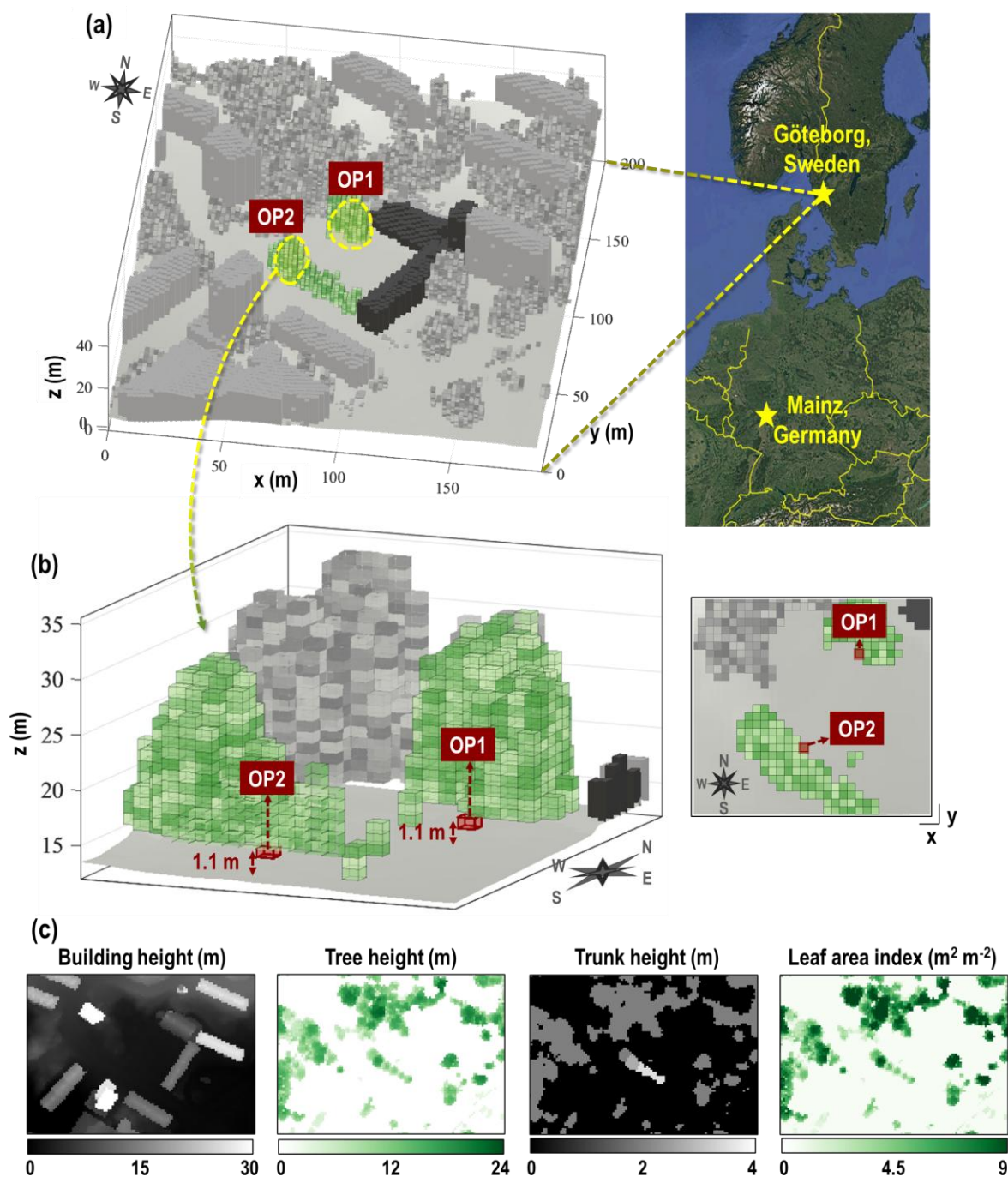


Aesculus hippocastanum at the study site was approximately 1.7 %. Using $G_{proj} = 0.5$, corresponding to a spherical leaf angle distribution, and the Beer-Lambert formulation in Eq. (5), the effective LAI (LAI_{eff}) corresponding to $\tau = 0.017$ is estimated
430 as:

$$LAI_{eff} = \frac{-\ln(\tau)}{G_{proj}} \approx 8.1 \text{ m}^2 \text{ m}^{-2}. \quad (25)$$

Here, LAI_{eff} represents effective leaf area along the radiation path. Guided by the reported literature values, LAD was set to $0.6 \text{ m}^2 \text{ m}^{-3}$ at both OP1 and OP2, and the spatial LAI input was calculated accordingly (Fig. 4c).

In the evaluation using the Swedish dataset, the observed six-directional shortwave and longwave radiation fluxes
435 and MRT were compared with the corresponding outputs from Legacy SOLWEIG v2025a and SOLWEIG-LEB. In both model configurations, a six-directional standing box at 1.1 m above ground was used to match the six-directional radiation observations (Lindberg et al., 2008). The cylindrical human-body representation is also available in SOLWEIG-LEB but was not used in the present evaluation because the observational dataset provides radiation fluxes in six orthogonal directions. An anisotropic diffuse shortwave sky model was applied following Wallenberg et al. (2020), while directional longwave radiation
440 from the sky, vegetation, and sunlit and shaded building surfaces was calculated using the anisotropic longwave parameterization of Wallenberg et al. (2023). Wall surface temperatures were calculated using the simple step-heating approach proposed by Wallenberg et al. (2026). The common radiation-model settings and the differences in vegetation treatment between the two configurations are summarized in Table 1.



445 **Figure 4.** Göteborg site and model domain used for pedestrian-level radiation and MRT evaluation. (a) Site location and three-dimensional model domain, (b) locations and surrounding canopy geometry of OP1 and OP2, and (c) building height, tree height, trunk-zone height, and leaf area index used as model inputs.



To evaluate the combined effect of the newly introduced vegetation schemes, the two simulations differed only in canopy shortwave attenuation and vegetation thermal treatment. Legacy SOLWEIG used a fixed canopy transmissivity of 0.03 and assumed $T_{veg} = T_{air}$, whereas SOLWEIG-LEB used LAD-based path-dependent transmissivity and solved the leaf energy balance for each vegetation voxel to diagnose T_{veg} and vegetation longwave emission. The same site geometry, meteorological forcing (Fig. 5), and prescribed surface properties were used; the configuration files document the settings of the SOLWEIG-LEB runs. Ground-cover surface-temperature parameterization and radiative properties followed Lindberg et al. (2016), and the surface albedo and emissivity values are listed in Table 2. Non-limiting soil-water conditions ($REW = 1$ and $f_w = 1$) and a background CO₂ concentration of 420 ppm were prescribed, as in the Mainz simulations.

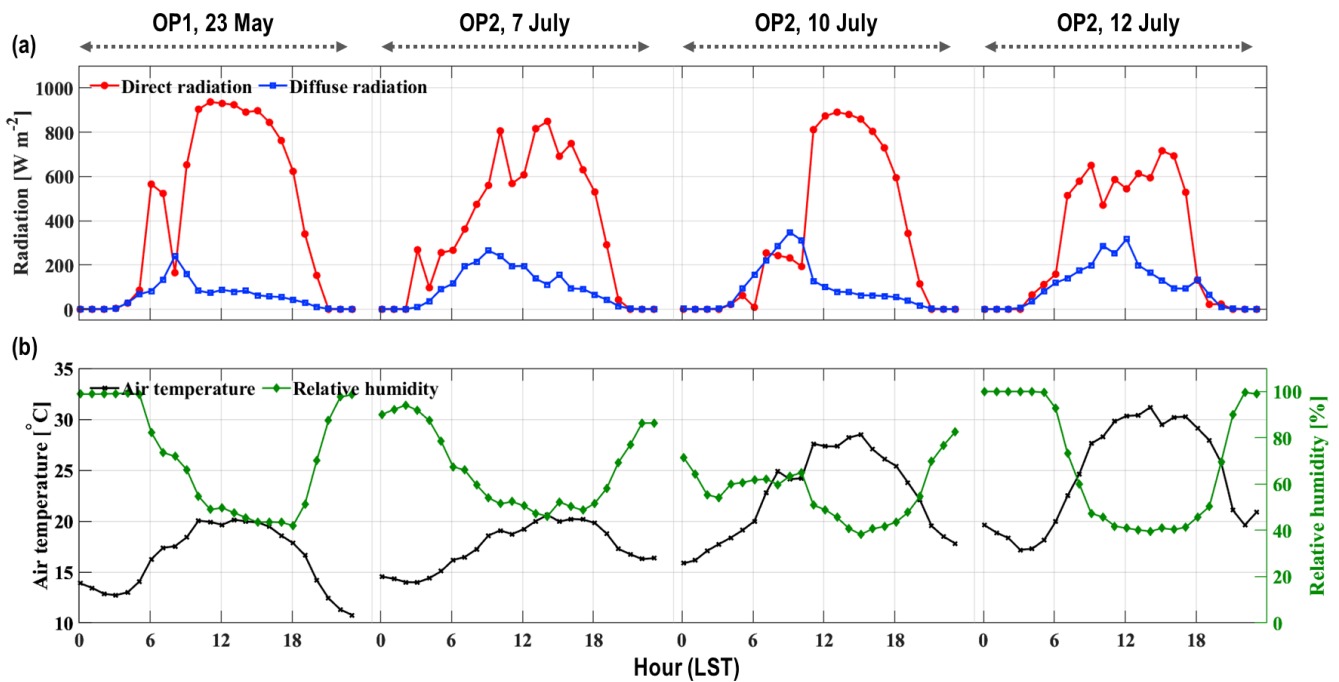


Figure 5. Meteorological forcing used for the Göteborg simulations at OP1 on 23 May 2010 and OP2 on 7, 10, and 12 July 2010. (a) Direct and diffuse shortwave radiation and (b) air temperature and relative humidity.

3.3. Computational benchmark setup

A key advantage of Legacy SOLWEIG is its high computational efficiency and relatively low runtime. SOLWEIG-LEB, however, introduces additional three-dimensional vegetation-voxel calculations for LAD-based canopy attenuation and an iterative leaf energy balance. The benchmark was therefore designed to quantify the computational overhead introduced by these new components and to assess how effectively a GPU-accelerated implementation offsets this additional cost. The benchmark domains were generated based on the spatial data used for the Göteborg evaluation. The horizontal resolution was fixed at 2 m, and the horizontal grid dimensions were systematically scaled from 50×50 to 100×100 , 200×200 , 300×300 ,



400 × 400, 500 × 500, and 600 × 600 grid cells. The larger domains were synthetic domains generated by spatially repeating the same urban morphology and therefore do not represent different real urban areas. The numbers of active vegetation voxels and wall-surface voxels were also quantified for each domain to characterize the scaling of the three-dimensional computational workload.

Four distinct numerical configurations (T1–T4) were compared to isolate and distinguish the computational costs associated with different model components. T1 represents the CPU-based QGIS implementation of Legacy SOLWEIG (v2025a). T2 performs the legacy-equivalent calculation of T1 re-implemented within the GPU framework. T3 activates LAD-based shortwave attenuation within the GPU framework, while T4 represents the full SOLWEIG-LEB configuration with both LAD-based attenuation and the vegetation-voxel leaf energy balance activated. Accordingly, the comparison between T1 and T2 represents the speedup achieved by the GPU-based legacy-equivalent implementation, the comparison between T2 and T3 quantifies the additional overhead of 3D ray-tracing and LAD-based attenuation, and the comparison between T3 and T4 quantifies the additional cost of the iterative leaf energy balance module. Identical terrain, building, vegetation, meteorological inputs, and output settings were enforced across all configurations.

Preprocessing time and per-timestep SOLWEIG runtime were measured separately. Preprocessing included the SVF calculation and wall preprocessing required for the wall-temperature scheme; for the LAD-enabled configurations (T3 and T4), the LAD-weighted vegetation SVF calculation was additionally included. The per-timestep runtime included input-data loading, radiation and thermal-environment calculations, and disk write-out of the common model outputs. The T1–T4 timestep simulations were repeated three times for each domain size, and the mean runtime and standard deviation were evaluated. For the GPU configurations, peak device-memory usage during model execution was also recorded. GPU runtimes were measured after a warm-up execution to eliminate CUDA context initialization overheads.

All benchmarks were performed on a Lenovo ThinkPad P16 Gen 3 equipped with an Intel Core Ultra 9 275HX CPU, 80 GB DDR5 RAM, and an NVIDIA RTX PRO 3000 Blackwell Generation Laptop GPU with 12,227 MiB of device memory. The GPU environment consisted of Python 3.12.9, CuPy 13.3.0, CUDA runtime 12.6, and 64-bit Windows 11.

3.4. Statistical metrics

Model performance was evaluated using the Pearson correlation coefficient (r), root mean square error (RMSE), range-normalized root mean square error (NRMSE), and mean bias error (MBE). These metrics quantify temporal agreement, error magnitude, relative error, and systematic bias, respectively. The Pearson correlation coefficient (r) was calculated as:

$$r = \frac{\sum_{i=1}^N (M_i - \bar{M})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^N (M_i - \bar{M})^2} \sqrt{\sum_{i=1}^N (O_i - \bar{O})^2}} \quad (26)$$



Here, M_i and O_i are the modelled and observed values for data point i , respectively, while $\bar{M}$ and $\bar{O}$ represent their corresponding mean values, and N is the total number of data points. The absolute magnitude of simulation error is quantified by RMSE, while NRMSE provides a relative error scale normalized by the range of observations:

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2}, \quad (27)$$

$$NRMSE = \frac{RMSE}{O_{max} - O_{min}}, \quad (28)$$

where O_{max} and O_{min} denote the maximum and minimum values for the observations, respectively. MBE was calculated as:

$$MBE = \frac{1}{N} \sum_{i=1}^N (M_i - O_i). \quad (29)$$

Positive and negative MBE values indicate model overestimation and underestimation, respectively. The same metrics were applied to leaf temperature, shortwave radiation, longwave radiation, and MRT.

4. Results

4.1. Evaluation of leaf temperature

Figure 6 compares the observed leaf surface temperature at Mainz with T_{veg} calculated by SOLWEIG-LEB. Red triangles and light red shading indicate the mean and minimum–maximum range of T_{veg} within the estimated observation area, respectively. The ENVI-met results reported by Simon et al. (2018) are also shown for comparison.

Under clear-sky conditions, SOLWEIG-LEB reproduced the observed morning warming, afternoon cooling, and daytime maxima on both days (Fig. 6a). The ENVI-met results of Simon et al. (2018) tended to overestimate T_{veg} in the morning and underestimate it in the afternoon, whereas SOLWEIG-LEB generally agreed more closely with the observations. SOLWEIG-LEB slightly underestimated leaf temperature around 07:00–08:00 LST under weak solar radiation. Uncertainty in the air-temperature and humidity forcing from a station approximately 3 km away may have contributed to this early-morning discrepancy.

Under fully cloudy conditions, the diurnal variation in leaf temperature was smaller than under clear-sky conditions, and SOLWEIG-LEB reproduced this reduced variability successfully (Fig. 6b). Under cloudy conditions, the contribution of direct shortwave radiation is minimal, and the influence of diffuse radiation and background meteorological conditions becomes relatively more dominant. SOLWEIG-LEB reproduced the temporal variation of the observed leaf temperature but retained a negative mean bias. Compared with the ENVI-met results, SOLWEIG-LEB generally yielded values closer to the observations. Table 3 presents the quantitative evaluation metrics for the two sky conditions. Under clear-sky conditions, SOLWEIG-LEB exhibited $r = 0.97$, $RMSE = 1.39$ °C, and $NRMSE = 0.10$, indicating an improved performance in terms of



temporal variability and error magnitude compared with the ENVI-met results ($r = 0.90$, $RMSE = 1.63$ °C, and $NRMSE =$
 525 0.11). However, under clear-sky conditions, SOLWEIG-LEB had a negative MBE of -0.57 °C, with a larger absolute
 magnitude than that of ENVI-met (0.28 °C). Under fully cloudy conditions, SOLWEIG-LEB showed $r = 0.85$, $RMSE = 1.05$ °C,
 $NRMSE = 0.36$, and $MBE = -0.88$ °C, showing a higher correlation and lower RMSE, but a larger absolute mean bias, than
 ENVI-met ($r = 0.68$, $RMSE = 1.52$ °C, $NRMSE = 0.52$, and $MBE = 0.58$ °C). Overall, SOLWEIG-LEB reasonably reproduced
 530 that the leaf energy balance module introduced in this study can reasonably diagnose T_{veg} under different radiative regimes.

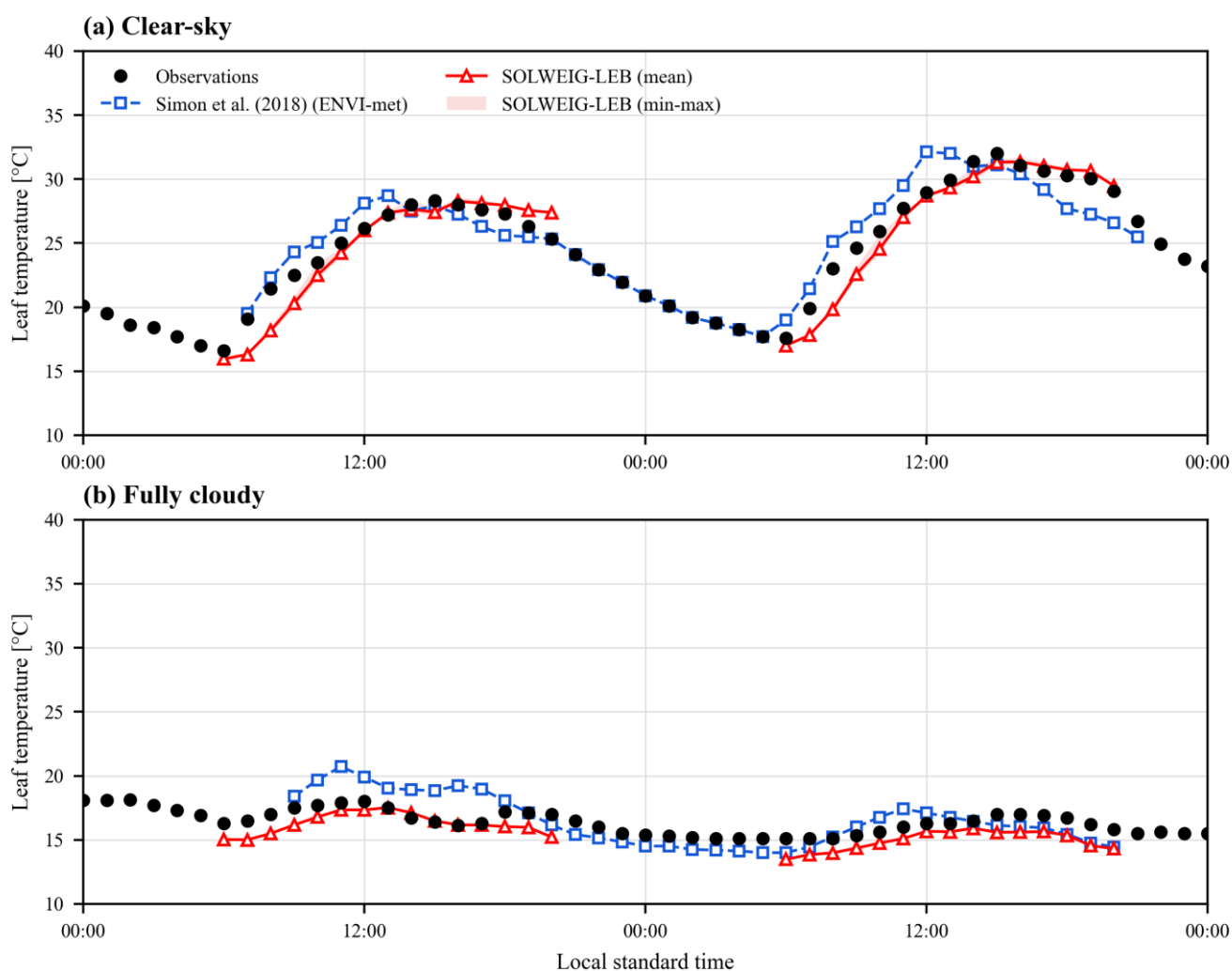


Figure 6. Observed and simulated leaf temperatures at the Mainz site under (a) clear-sky and (b) fully cloudy conditions. Black circles and blue squares indicate observations and the ENVI-met results of Simon et al. (2018), respectively. Red triangles and shading indicate the mean and minimum–maximum range calculated by SOLWEIG-LEB.

535



Table 3. Statistical evaluation of leaf temperature at the Mainz site.

Sky condition	Metric	Simon et al. (2018) (ENVI-met)	This study (SOLWEIG-LEB)
Clear-sky	r	0.90	0.97
	RMSE [°C]	1.63	1.39
	NRMSE	0.11	0.10
	MBE [°C]	0.28	−0.57
Fully cloudy	r	0.68	0.85
	RMSE [°C]	1.52	1.05
	NRMSE	0.52	0.36
	MBE [°C]	0.58	−0.88

4.2. Evaluation of pedestrian-level shortwave, longwave, and MRT

Figure 7 compares the total shortwave radiation (K_{tot}), total longwave radiation (L_{tot}), and MRT (T_{mrt}) observed at the pedestrian height ($z = 1.1$ m) at the Göteborg site with the simulation results from Legacy SOLWEIG and SOLWEIG-LEB. Here, K_{tot} and L_{tot} denote the sums of the six directional shortwave and longwave radiation fluxes, respectively. The comparison was conducted for OP1 on 23 May 2010 and for OP2 on 7, 10, and 12 July 2010. Overall, SOLWEIG-LEB reproduced the temporal variations in observed K_{tot} , L_{tot} , and T_{mrt} well. In particular, K_{tot} and T_{mrt} exhibit rapid increases and decreases associated with direct solar exposure and dynamic changes in tree shading; SOLWEIG-LEB successfully captured these temporal variations in most cases. While Legacy SOLWEIG and SOLWEIG-LEB showed similar overall temporal patterns, distinct differences appeared during specific periods. For example, around 17:00 LST on 23 May 2010 at OP1 and around 11:00 LST on 12 July at OP2, Legacy SOLWEIG tended to underestimate T_{mrt} compared with the observations, whereas SOLWEIG-LEB produced values closer to the observations. These specific periods correspond to microclimatic conditions in which canopy obstruction near the tree-shade boundary exerts a dominant influence. This suggests that the LAD-based path-dependent canopy attenuation scheme in SOLWEIG-LEB represents the actual canopy transmission and attenuation physics more flexibly and realistically than the representative-transmissivity approach utilized in Legacy SOLWEIG. A more detailed analysis of these periods is provided in Section 4.3.

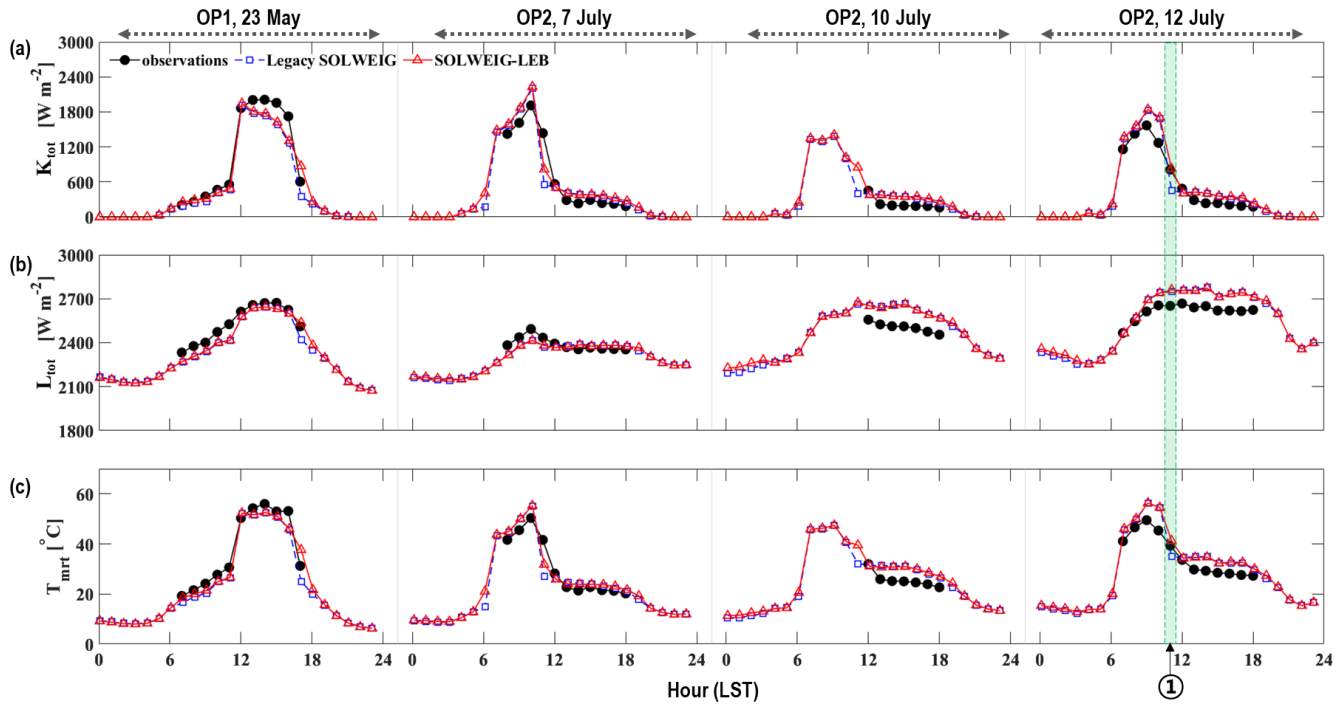


Figure 7. Observed and simulated pedestrian-level (a) total shortwave radiation, (b) total longwave radiation, and (c) MRT at the Göteborg site. Results from Legacy SOLWEIG and SOLWEIG-LEB are compared for the four evaluation periods. The interval marked ① identifies the OP2 case examined in Figs. 9 and 10.

Table 4 presents the quantitative evaluation metrics for K_{tot} , L_{tot} , and T_{mrt} during the observation periods at the Göteborg site. For K_{tot} , SOLWEIG-LEB yielded a higher correlation coefficient and a reduced error magnitude compared to Legacy SOLWEIG. Specifically, the correlation coefficient increased from 0.94 to 0.95, while the RMSE decreased from 231.74 to 203.66 W m^{-2} , and the NRMSE dropped from 0.13 to 0.11. These statistics indicate lower pooled shortwave RMSE for the combined extension in the evaluated sample. However, the MBE increased from 21.90 to 56.78 W m^{-2} , indicating increased mean overestimation of the six-directional shortwave sum. For L_{tot} , SOLWEIG-LEB also showed a slight improvement compared with Legacy SOLWEIG. The correlation coefficients were approximately 0.89 for both models, and the RMSE decreased slightly from 83.42 to 78.93 W m^{-2} . The NRMSE also decreased from 0.25 to 0.23. However, the magnitude of this improvement was smaller than that observed for shortwave radiation, and the MBE decreased from 28.78 to 25.25 W m^{-2} . For T_{mrt} , SOLWEIG-LEB demonstrated an improved predictive performance compared with Legacy SOLWEIG. The correlation coefficient increased from 0.92 to 0.94, the RMSE decreased from 4.76 to 4.38 $^{\circ}\text{C}$, and the NRMSE decreased from 0.13 to 0.12. However, the MBE increased from 1.36 to 1.90 $^{\circ}\text{C}$, indicating that SOLWEIG-LEB tended to slightly overestimate T_{mrt} on average across the simulation steps.



Table 4. Statistical evaluation of total shortwave radiation (K_{tot}), total longwave radiation (L_{tot}), and mean radiant temperature (MRT) at the Göteborg site.

Variable	Metric	Legacy SOLWEIG	SOLWEIG-LEB
K_{tot}	r	0.94	0.95
	RMSE [W m^{-2}]	231.74	203.66
	NRMSE	0.13	0.11
	MBE [W m^{-2}]	21.90	56.78
L_{tot}	r	0.89	0.89
	RMSE [W m^{-2}]	83.42	78.93
	NRMSE	0.25	0.23
	MBE [W m^{-2}]	28.78	25.25
MRT	r	0.92	0.94
	RMSE [$^{\circ}\text{C}$]	4.76	4.38
	NRMSE	0.13	0.12
	MBE [$^{\circ}\text{C}$]	1.36	1.90

575 Figure 8 compares observed and modelled radiation fluxes separately for each directional shortwave and longwave radiation component. For the shortwave components, the most pronounced improvements in SOLWEIG-LEB appeared in $K_{\downarrow}$ and $K_{\rightarrow, \text{south}}$. The RMSE of $K_{\downarrow}$ decreased from 84.6 W m^{-2} in Legacy SOLWEIG to 69.6 W m^{-2} in SOLWEIG-LEB, corresponding to an error reduction of approximately 15.0 W m^{-2} . The RMSE of $K_{\rightarrow, \text{south}}$ decreased from 66.0 to 56.0 W m^{-2} , representing an improvement of approximately 10.0 W m^{-2} . $K_{\rightarrow, \text{west}}$ also improved, with its RMSE decreasing from 73.0 to 580 66.1 W m^{-2} . In contrast, the differences between the two models were negligibly small for $K_{\uparrow}$ and $K_{\rightarrow, \text{north}}$. The largest shortwave RMSE reductions occurred in the downward, southward, and westward components, consistent with the vegetation concentrated to the south and west of OP2. Both observation points were affected by canopy edges and partial obstruction during parts of the day. For the directional longwave components, upward RMSE decreased from 22.2 to 20.3 W m^{-2} and downward RMSE from 33.6 to 31.4 W m^{-2} . Eastward, westward and northward RMSEs decreased by approximately 0.2 – 0.7 585 W m^{-2} , while southward RMSE increased from 10.8 to 11.1 W m^{-2} . Changes in directional longwave RMSE were limited to a few W m^{-2} and were smaller than the largest shortwave RMSE reductions. Section 4.3 separates the contributions of canopy attenuation and leaf energy balance to the radiation and MRT differences.

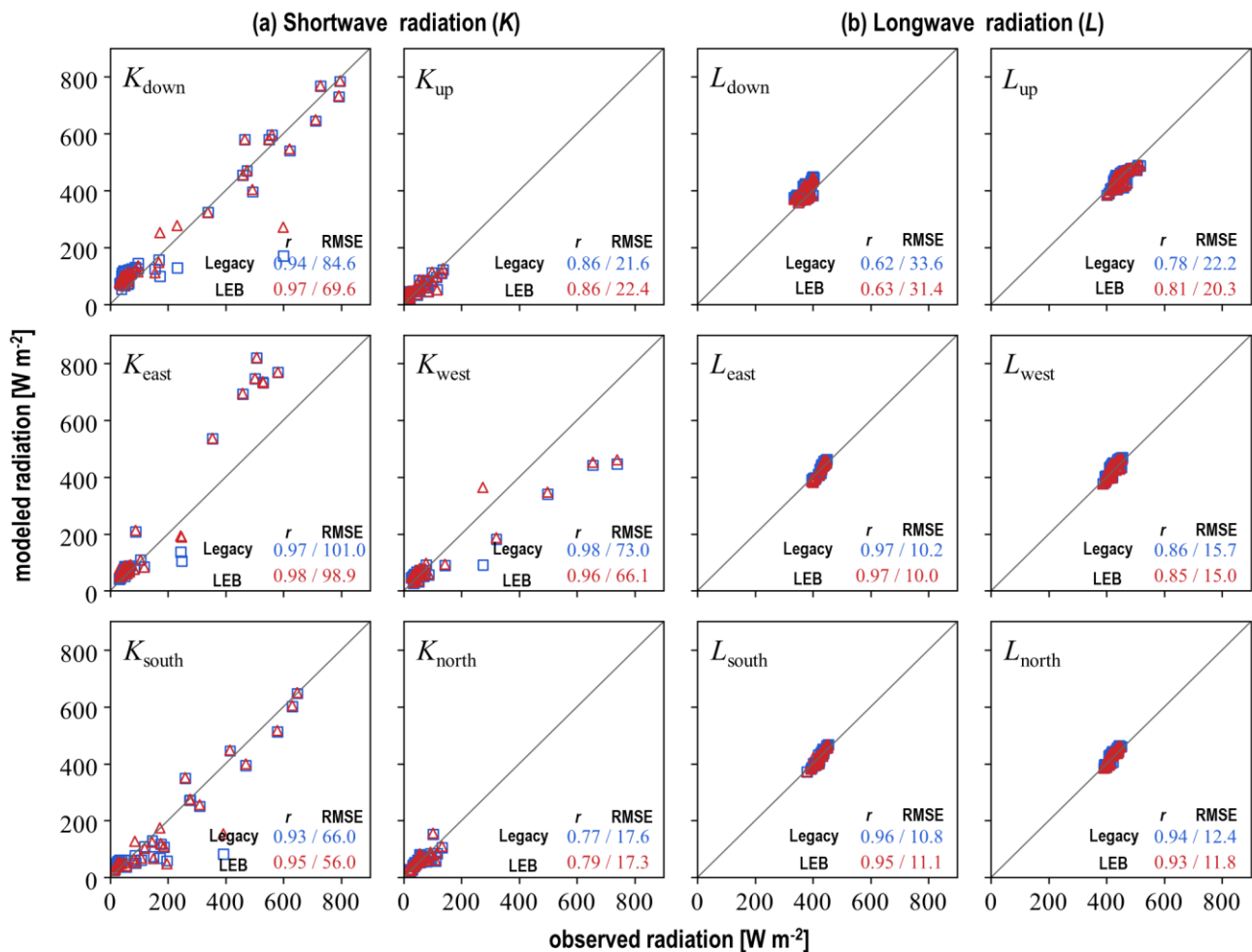


Figure 8. Comparison of observed and simulated six-directional (a) shortwave and (b) longwave radiation fluxes at the Göteborg site. Blue squares and red triangles denote Legacy SOLWEIG and SOLWEIG-LEB, respectively, and the diagonal line represents perfect agreement.

4.3. Contributions of LAD-based canopy attenuation and leaf energy balance

The comparison in Section 4.2 reflects the combined effects of modifications in canopy shortwave attenuation and vegetation surface temperature. To isolate and separate the individual contributions of these two processes, an additional LAD-only numerical experiment was performed in which the LAD-based canopy attenuation scheme was fully retained, but vegetation temperature was prescribed as $T_{veg} = T_{air}$, identical to the isothermal assumption in Legacy SOLWEIG. This sensitivity experiment is hereafter referred to as EXP1, whereas the full SOLWEIG-LEB experiment, incorporating both LAD-based attenuation and the voxel-scale leaf energy balance, is designated as EXP2. The same geometry, LAD distributions, meteorological forcing, and surface properties were applied across both EXP1 and EXP2. Consequently, the comparison between EXP1 and Legacy SOLWEIG isolates the structural and optical changes associated with the LAD-based canopy



representation, whereas the differential term $\text{EXP2} - \text{EXP1}$ isolates the additional effect of the leaf energy balance within an identical LAD-based radiation framework.

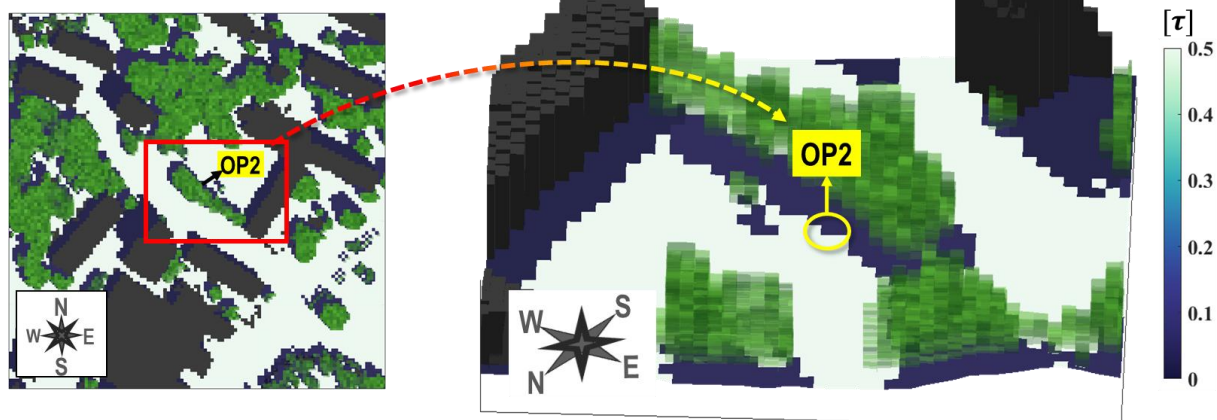
Figure 9 illustrates the spatial patterns of canopy attenuation at 11:00 LST on 12 July 2010 (① in Fig. 7) using ground-level direct shortwave transmissivity (τ). Higher values of τ indicate greater penetration of direct solar radiation; $\tau = 0$ when buildings completely block the radiative path, and $\tau = 1$ when the optical path is entirely unobstructed. Legacy SOLWEIG applies a fixed transmissivity of 0.03 to all pixels shaded by vegetation, regardless of the path length through the canopy (Fig. 9a). In contrast, SOLWEIG-LEB resolves transmissivity from the cumulative LAD accumulated along each radiative path, capturing pronounced attenuation contrasts between the dense canopy core and permeable crown edges (Fig. 9b). At OP2, direct radiation traversed a relatively short path near the northern crown edge, resulting in a local transmissivity of approximately 0.3, which was an order of magnitude higher than the fixed value of 0.03 in Legacy SOLWEIG. Figure 9c displays the resulting spatial discrepancies. The identical LAD-based transmissivity field was applied in both EXP1 and EXP2.

Figure 10 compares the spatial distributions of SVF, six-directional total shortwave radiation (K_{tot}), total longwave radiation (L_{tot}), and MRT at 11:00 LST on 12 July 2010. The first column illustrates the baseline absolute fields simulated by Legacy SOLWEIG, while the remaining columns display the difference fields for $\text{EXP1} - \text{Legacy SOLWEIG}$, $\text{EXP2} - \text{Legacy SOLWEIG}$, and $\text{EXP2} - \text{EXP1}$, respectively. Because EXP1 and EXP2 share the identical LAD-based attenuation scheme, they yield identical SVF and shortwave radiation distributions (Fig. 10a, b). At OP2, the observed K_{tot} was 810.30 W m^{-2} , whereas Legacy SOLWEIG substantially underestimated this radiative load at 450.70 W m^{-2} . This confirms that the conventional fixed-transmissivity scheme severely overestimates shortwave extinction along peripheral canopy trajectories. In contrast, both EXP1 and EXP2 simulated 826.41 W m^{-2} , achieving remarkable agreement with the in situ observation.

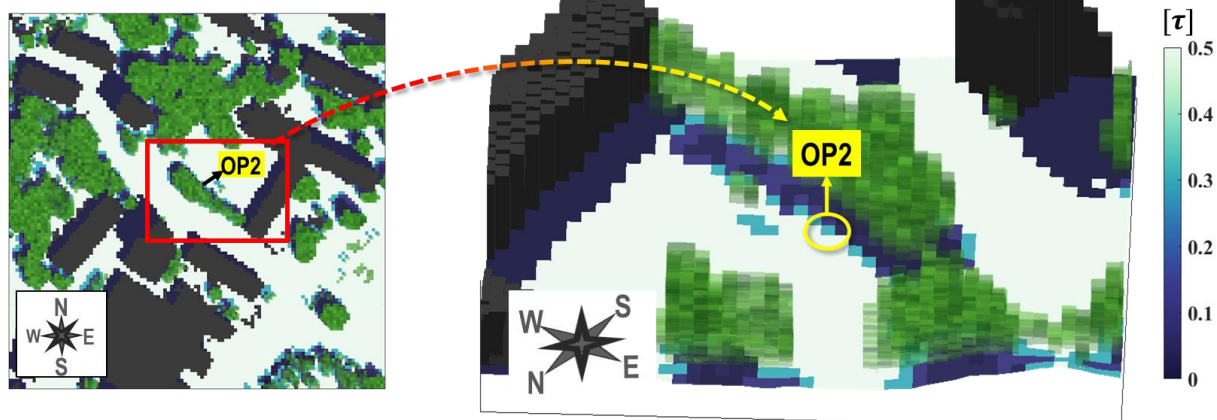
Spatial discrepancies associated with LAD-based attenuation were also pronounced across the broader domain outside OP2. Compared with Legacy SOLWEIG, SVF increased by more than 0.1 in boundary grid cells along crown perimeters, but decreased by approximately 0.01–0.02 within dense core canopies (Fig. 10a). At crown boundaries, K_{tot} increased locally by $300\text{--}400 \text{ W m}^{-2}$ or more, whereas it decreased by several tens of W m^{-2} beneath dense canopy interiors where cumulative optical depth exceeded that implied by the fixed legacy transmissivity (Fig. 10b). These spatial differences show that the voxel-resolved calculation represents path-length differences between crown interiors and edges that cannot be resolved by bulk transmissivity models.



(a) Legacy SOLWEIG



(b) SOLWEIG-LEB



(c) difference (LEB – Legacy)

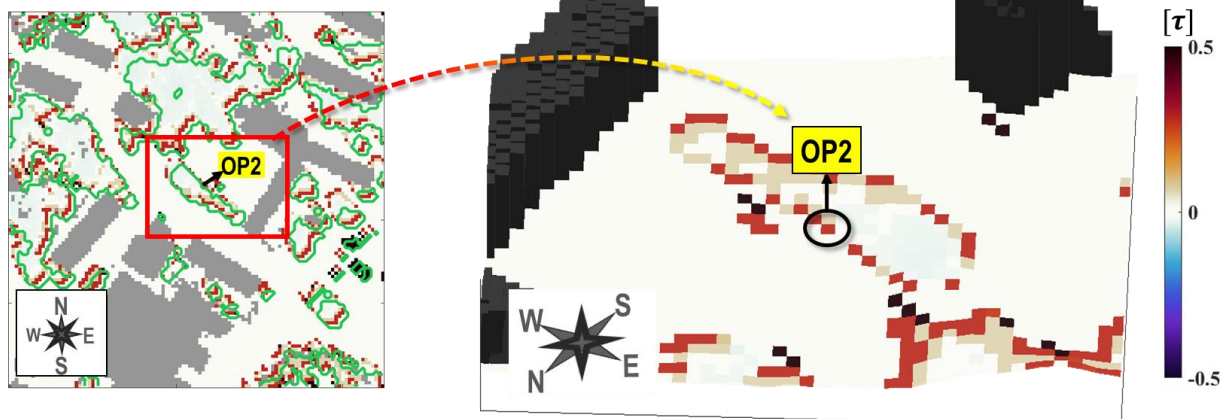


Figure 9. Ground-level direct-shortwave transmissivity at 11:00 LST on 12 July 2010. (a) Legacy SOLWEIG, (b) SOLWEIG-LEB, and (c) their difference. The right panels enlarge the area around OP2.

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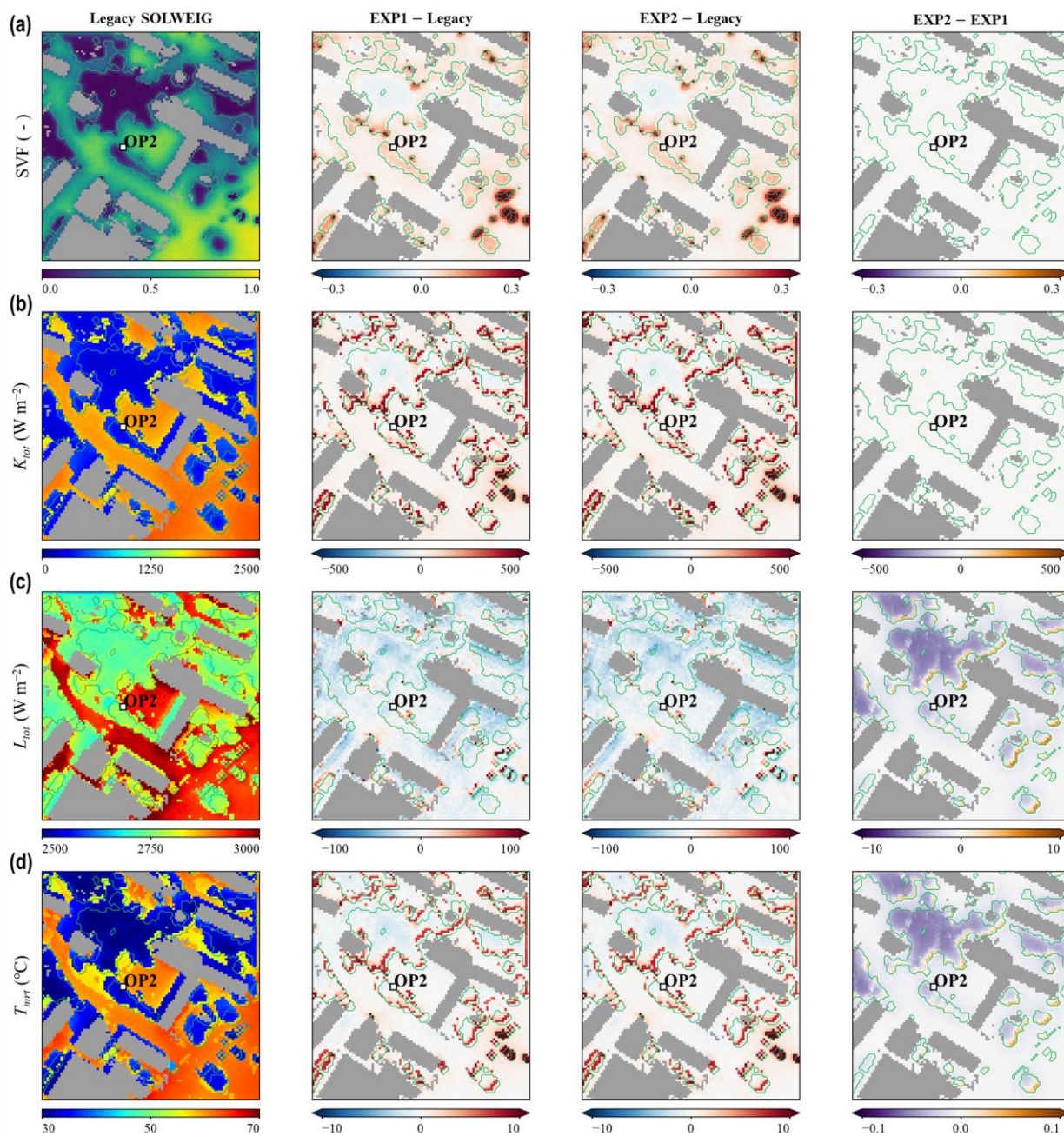


Figure 10. Spatial distributions of pedestrian-level (a) sky view factor (SVF), (b) six-directional shortwave radiation sum (K_{tot}), (c) six-directional longwave radiation sum (L_{tot}), and (d) mean radiant temperature (MRT) at 11:00 LST on 12 July 2010. EXP1 and EXP2 denote the LAD-only and full SOLWEIG-LEB configurations, respectively. The first column shows Legacy SOLWEIG, while the remaining columns show differences calculated as EXP1 – Legacy SOLWEIG, EXP2 – Legacy SOLWEIG, and EXP2 – EXP1, respectively.



L_{tot} in EXP1 was generally lower than in Legacy SOLWEIG, exhibiting local reductions of approximately 50–85 W m⁻² (Fig. 10c). SOLWEIG calculates downwelling sky longwave radiation using an effective sky emissivity parameterized from air temperature and humidity (Wallenberg et al., 2023). At this specific time step, the effective sky emissivity was approximately 0.82, lower than the vegetation emissivity of 0.90 applied in EXP1. Consequently, even under the isothermal assumption, an increase in vegetation transmissivity (and effective SVF) increases the relative view-factor weighting of radiatively colder open sky while reducing the downward emission contribution from the warmer tree crown. This directional re-weighting explains the systematic decrease in L_{tot} observed in EXP1.

The difference fields for EXP2 – EXP1 (the final column of Fig. 10) were zero for SVF and shortwave radiation, while localized deviations emerged beneath the canopy for longwave radiation and MRT. L_{tot} decreased by approximately 2–6 W m⁻² in areas beneath the canopy, with the reduction decaying toward the crown periphery. Conversely, it increased by up to 6.8 W m⁻² in some areas beneath the canopy. This divergence stems from the thermodynamic behavior of the leaf energy balance: leaves cooler than the air emitted less longwave radiation, whereas leaves warmer than the ambient air emitted greater longwave flux. Reflecting these longwave shifts, MRT decreased by approximately 0.02–0.06 °C in areas with reduced longwave radiation, and increased by up to 0.05 °C in areas with increased longwave radiation. These LEB-induced longwave and MRT modifications were minor in magnitude compared to the primary differences driven by LAD-based shortwave attenuation. Across the complete Göteborg validation dataset, the overall MRT RMSEs were 4.76 °C for Legacy SOLWEIG, 4.39 °C for EXP1, and 4.38 °C for EXP2.

Figure 11 compares the temporal variations in shortwave radiation, longwave radiation, and MRT using the differences for EXP1 – Legacy SOLWEIG, EXP2 – Legacy SOLWEIG, and EXP2 – EXP1. The domain in Fig. 10 was partitioned into three mutually exclusive spatial subregions: under-canopy, tree-adjacent, and open zones. Under-canopy zones were defined as grid cells falling within the vertical canopy footprint. Tree-adjacent zones comprised non-canopy grid cells with centres no more than 4 m horizontally from the canopy boundary, while open zones comprised cells farther than 4 m from the boundary. Buildings were excluded from the analysis. Solid lines denote spatial area-mean differences, while shaded bands represent the spatial 10th–90th percentile (P10–P90) range of paired cellwise model differences at each time step. Both LAD-enabled simulations (EXP1 and EXP2) exhibited nearly identical diurnal trajectories relative to Legacy SOLWEIG (Fig. 11a, b). Daytime area-mean shortwave radiation differences were positive and were substantially amplified in under-canopy and tree-adjacent zones relative to open zones. The area-mean shortwave increases in under-canopy and tree-adjacent zones reached approximately 170 and 150 W m⁻², respectively, while the spatial 90th percentile (P90) exceeded 600 W m⁻². Conversely, the area-mean longwave radiation differences relative to Legacy SOLWEIG were predominantly negative during daytime across all three zones, although the spatial P90 reached approximately 20 W m⁻² in tree-adjacent and open zones. Daytime MRT was also generally higher in EXP1 and EXP2 than in Legacy SOLWEIG. The area-mean MRT increases in EXP2 reached approximately 2.7, 2.5, and 1.1 °C in under-canopy, tree-adjacent, and open zones, respectively, with the spatial P90 exceeding 10 °C in under-canopy and tree-adjacent zones at some times. Overall, the spatial P10–P90 ranges of the



670 shortwave radiation and MRT differences were wider in under-canopy and tree-adjacent zones than in open zones, indicating greater spatial variability in the model differences associated with path-dependent canopy attenuation.

In contrast, the thermodynamic modifications introduced by the leaf energy balance solver (EXP2 – EXP1) remained minor (Fig. 11c). Because EXP2 and EXP1 shared identical shortwave ray-tracing, shortwave radiation differences were identically zero across all zones. The area-mean longwave radiation differences were positive or negative depending on the time and zone, generally confined within a few W m^{-2} . The resulting MRT differences were also small, with the P10–P90 range generally within approximately ± 0.06 °C, even in under-canopy zones where spatial variability was greatest. This demonstrates that while calculating leaf temperature modifies vegetation longwave radiation, its additional effect on pedestrian-level MRT is quantitatively modest under the evaluated conditions. Consequently, the improvement in pedestrian-level MRT relative to Legacy SOLWEIG was primarily associated with LAD-based path-dependent canopy attenuation under the evaluated conditions.

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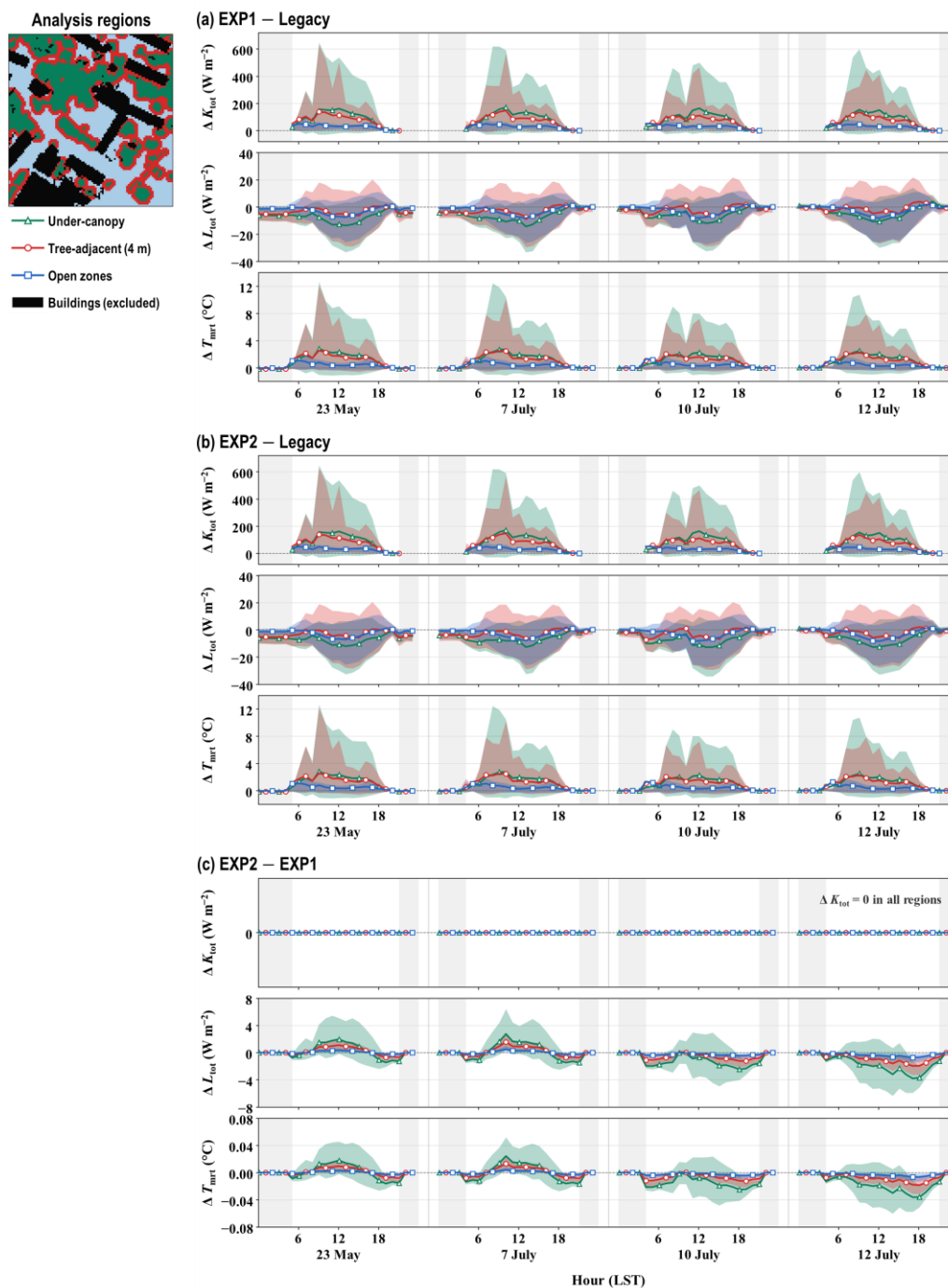


Figure 11. Differences in six-directional shortwave and longwave sums (ΔK_{tot} and ΔL_{tot}) and MRT (ΔT_{mrt}) for (a) EXP1 – Legacy SOLWEIG, (b) EXP2 – Legacy SOLWEIG, and (c) EXP2 – EXP1. EXP1 and EXP2 denote the LAD-only and full SOLWEIG-LEB configurations, respectively. Green, red, and blue indicate under-canopy, tree-adjacent (within 4 m), and open zones, respectively. Lines and shading show spatial means and 10th–90th percentile (P10–P90) ranges of paired cellwise differences at each time step. Black areas in the map indicate excluded buildings, and grey shading indicates nighttime.



4.4. Analysis of voxel-scale leaf energy balance processes

Pedestrian-level T_{mrt} describes human radiative exposure but does not resolve leaf thermal responses or canopy energy partitioning. This section examines the case at 11:00 LST on 12 July 2010 shown in Fig. 12. The spatial distributions of leaf net radiation (R_{net} in Eq. (14)), leaf temperature (T_{veg}), sensible heat flux (H), and latent heat flux (LE) in vegetation voxels are analysed to examine how energy within the canopy is partitioned between sensible heat exchange and transpiration. At this time, the background air temperature was 29.8 °C, relative humidity was 41.8 %, and global shortwave radiation input was 721.6 W m⁻². Background wind speed, air pressure, and CO₂ concentration were set to 3.0 m s⁻¹, 101.3 kPa, and 420 ppm, respectively. Under spatially uniform meteorological forcing, voxel-scale differences primarily reflected local radiative exposure associated with canopy geometry and the coupled responses of leaf temperature, leaf boundary-layer resistance, and stomatal resistance. As described in Section 2.5, SOLWEIG-LEB iteratively updates T_{veg} , vegetation longwave emission, H , and LE . Figure 12 shows the spatial distributions of R_{net} , T_{veg} , H , and LE . The left panel in each row shows the three-dimensional vegetation voxel distribution over the entire analysis domain, and the right panel shows an x–z cross-section at $y = 125$ m. The location of this cross-section is indicated by a red plane in the three-dimensional view. The three-dimensional distributions show overall differences among trees, whereas the cross-sections reveal horizontal and vertical heterogeneity within the canopy that is obscured by the outer voxels.

R_{net} ranged from 5.0 to 295.1 W m⁻² (Fig. 12a). Net radiation was higher on sun-facing canopy surfaces and in areas with greater radiative exposure and was lower on shaded canopy surfaces facing away from the sun. In the x–z cross-section, R_{net} was also non-uniform within individual canopies and varied substantially with canopy height and the depth of voxels within the canopy. These patterns reflect the effects of three-dimensional canopy structure and shading by surrounding objects on voxel-scale net radiation.

T_{veg} ranged from 28.5 to 31.8 °C (Fig. 12b). Relative to the background air temperature of 29.8 °C, the calculated T_{veg} ranged from approximately 1.3 °C lower to 2.0 °C higher. Higher leaf temperatures occurred mainly at sun-facing canopy edges and in areas with greater radiative exposure, whereas lower temperatures occurred on shaded canopy surfaces facing away from the sun and deep within the canopy. This distribution of T_{veg} reflects the balance between radiative heating, sensible heat exchange, and transpiration in each voxel.

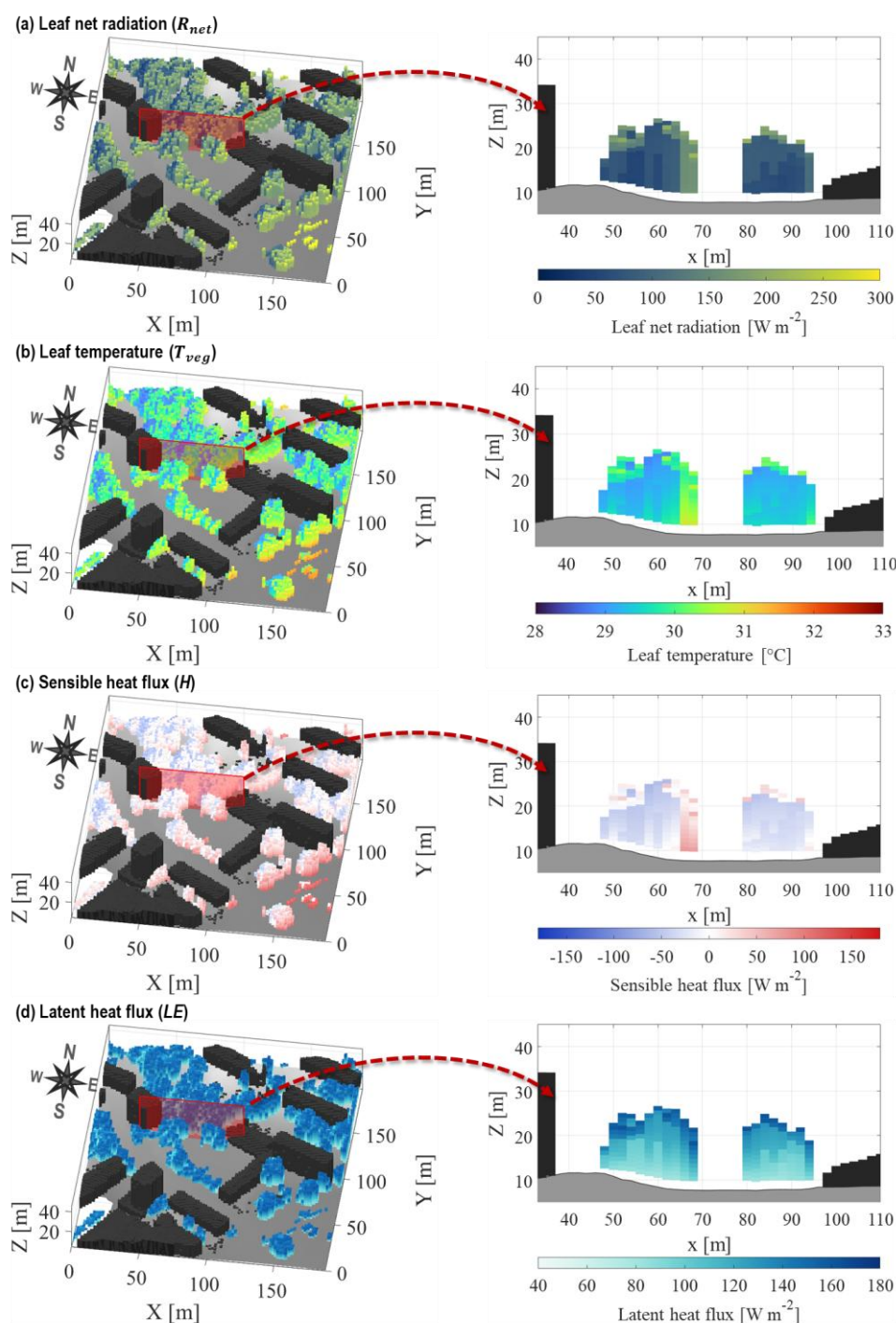


Figure 12. Voxel-scale distributions of (a) leaf net radiation, (b) leaf temperature, (c) sensible heat flux, and (d) latent heat flux calculated by SOLWEIG-LEB at 11:00 LST on 12 July 2010. Left panels show three-dimensional vegetation-voxel fields, and right panels show the corresponding x-z cross-sections at $y = 125$ m, indicated by the red planes in the three-dimensional views. Fluxes are per unit one-sided leaf area.



At the end of the calculation, R_{net} was approximately balanced by sensible heat exchange with the surrounding air, H , and latent heat flux associated with transpiration, LE (Fig. 12c, d). H per unit one-sided leaf area ranged from approximately -84.9 to 139.6 W m^{-2} (Fig. 12c) and was higher in canopy regions with higher leaf temperatures. LE varied over a narrower range of approximately 56.0 – 165.9 W m^{-2} (Fig. 12d). Positive H indicates heat transfer from the leaf to the atmosphere, whereas negative H indicates heat transfer from the atmosphere to the leaf. Thus, sensible heat exchange in both directions coexisted within the canopy. In voxels with negative H , sensible heat supplied by the atmosphere contributed, together with net radiation, to the energy required for transpiration. These voxel-scale fields distinguish the direction of leaf–air heat exchange and its contribution to transpiration, providing information beyond the pedestrian MRT response.

4.5. Computational performance and scalability

The benchmark evaluates preprocessing time, per-timestep runtime, and GPU memory demand for the configurations described in Section 3.3. This comparison quantifies the additional computational cost of LAD-based attenuation and leaf energy balance within the GPU framework. As the horizontal domain size increased from 50×50 to 600×600 grid cells, the numbers of active vegetation voxels and wall-surface voxels increased continuously (Fig. 13a). The largest 600×600 domain contained 360,000 horizontal grid cells, approximately 1.02 million active vegetation voxels, and 0.26 million wall-surface voxels. The increase in computational time with domain size was particularly pronounced during preprocessing in the CPU-based Legacy SOLWEIG (Fig. 13b). For the 600×600 domain, the SVF and wall-preprocessing time was 109.9 min for CPU-based Legacy SOLWEIG, whereas the corresponding GPU-based SOLWEIG-LEB preprocessing required 4.75 min. This corresponds to an approximately 23.1-fold speed-up, with the benefit of GPU parallelization becoming increasingly evident as the domain size increased.

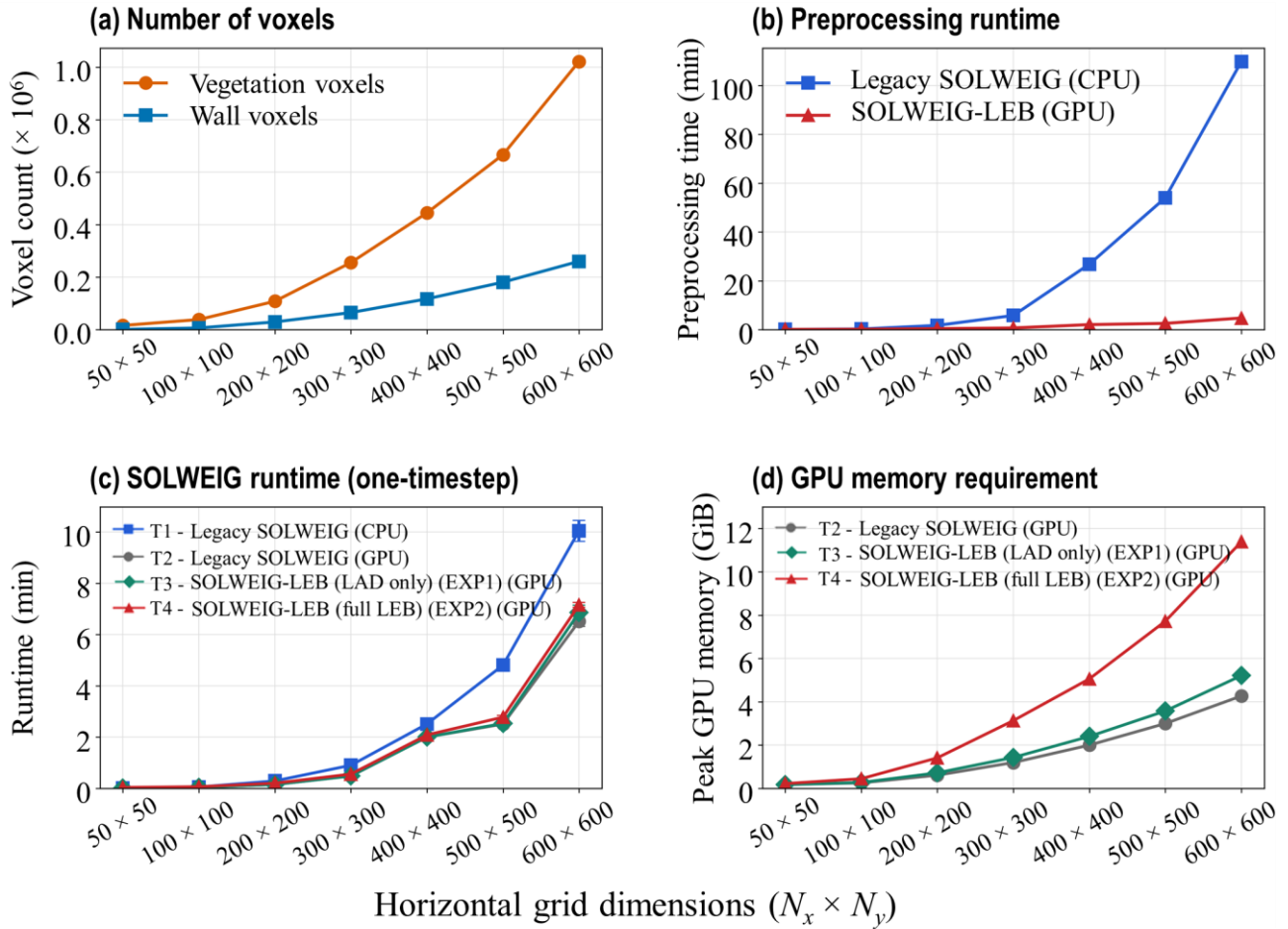


Figure 13. Computational workload and performance with increasing horizontal domain size. (a) Numbers of active vegetation and wall-surface voxels, (b) SVF and wall-preprocessing time for CPU-based Legacy SOLWEIG and GPU-based SOLWEIG-LEB, (c) single-timestep runtime for the four benchmark configurations, with error bars indicating the standard deviation of three repeated runs, and (d) peak device-memory usage for the GPU-based configurations.

The per-timestep runtime also increased systematically with domain size (Fig. 13c). For the same legacy-equivalent configuration at 600×600 , the mean runtime of the CPU-based T1 configuration was 10.05 min, whereas the GPU-based T2 configuration required 6.51 min, corresponding to a 35.2 % reduction in runtime. Within the same GPU framework, the additional computational overhead of the newly introduced vegetation schemes remained relatively limited. The runtime of T3, in which only LAD-based shortwave attenuation was activated, was 6.85 min, representing a 5.2 % increase relative to T2. The full-LEB configuration, T4, required 7.15 min, corresponding to a further 4.4 % increase relative to T3. Consequently, activating both LAD-based attenuation and the full LEB increased the runtime by only approximately 9.8 % relative to the legacy-equivalent GPU configuration. These results indicate that the three-dimensional canopy ray-tracing and iterative leaf energy balance introduce additional computational workload, but the actual increase in timestep runtime remains minor under



GPU execution. Under the tested hardware and implementation conditions, T4 required 28.9 % less runtime than the CPU-based T1 configuration, despite including both vegetation modules.

In contrast, GPU memory usage increased more prominently with domain size and the number of active vegetation voxels (Fig. 13d). For the 600×600 domain, peak GPU memory allocation was 4.27, 5.21, and 11.39 GiB for T2, T3, and T4, respectively. The memory footprint of T3 was approximately 22.0 % greater than that of T2, indicating that LAD-based attenuation alone imposed a relatively limited additional memory demand during the per-timestep calculation. In contrast, the full LEB configuration required approximately 2.2 times more GPU memory than T3 because multiple three-dimensional diagnostic arrays related to leaf temperature, radiation balance, sensible and latent heat fluxes, and iterative calculations were allocated and stored for each active vegetation voxel. At 600×600 grid cells, T4 used approximately 95.4 % of the available GPU memory, suggesting that memory capacity may constrain full-LEB applications at larger domain sizes. In the tested configurations, LAD-only T3 incurred smaller runtime and memory increases than T4, making it a less resource-demanding option when vegetation-voxel energy-balance diagnostics are not required.

765 5. Discussion

5.1. Evaluation performance and interpretation

In Mainz, SOLWEIG-LEB reproduced the daytime variation in leaf temperature under clear-sky and fully cloudy conditions, with lower RMSEs but larger absolute mean biases than the ENVI-met results reported by Simon et al. (2018). Differences in model formulation, meteorological forcing, and the estimated observation footprint should be considered when interpreting this comparison. In Göteborg, SOLWEIG-LEB reduced shortwave, longwave, and MRT RMSEs relative to Legacy SOLWEIG, although positive biases increased for total shortwave radiation and MRT. The largest shortwave improvements occurred in the downward and selected sideward components during periods affected by canopy edges and partial obstruction.

Previous studies have shown that prescribed canopy transmissivity strongly affects MRT estimates in tree shade. Lindberg and Grimmond (2011) demonstrated the sensitivity to fixed transmissivity, while Konarska et al. (2014) reported low mean direct transmissivity through dense, foliated crowns and greater variability near crown edges and gaps. Park et al. (2018) also showed that daytime MRT changes with LAD are primarily associated with shortwave attenuation.

The finding in Section 4.3 that EXP1 reproduced nearly all of the MRT RMSE reduction achieved by EXP2 (accounting for over 97 % of the total error reduction) demonstrates that, under the evaluated conditions, improvements in pedestrian-level MRT relative to Legacy SOLWEIG were overwhelmingly governed by LAD-based canopy radiative treatment. Furthermore, the pronounced spatial dispersion (evidenced by the broad spatial P10–P90 ranges) observed beneath and adjacent to the canopy underscores that local microclimatic extremes and fine-scale spatial heterogeneity must be considered alongside domain area-mean differences. The LAD-based scheme represents differences among paths through canopy cores, edges, and



gaps rather than applying a single bulk transmissivity to all vegetation-shaded locations. Its performance depends on the
prescribed LAD, leaf-angle distribution, canopy geometry, and observation location. These factors are particularly relevant
near canopy boundaries, where small geometric differences can alter direct solar exposure.

5.2. Added capabilities and intended scope of SOLWEIG-LEB

SOLWEIG-LEB integrates LAD-based canopy attenuation with a voxel-scale leaf energy balance, extending the
vegetation representation in SOLWEIG to include intra-canopy thermal states and energy partitioning. This development is
consistent with recent efforts to represent the thermal states of individual urban surfaces more explicitly within the SOLWEIG
framework. Wallenberg et al. (2026) introduced a method for calculating wall surface temperature based on local radiative
balance and material properties, and the present study advances this trajectory by establishing an explicit representation of
vegetation thermal states within SOLWEIG. SOLWEIG-LEB is a diagnostic model that calculates the canopy radiative
environment and leaf energy balance under prescribed meteorological forcing. Unlike prognostic microclimate models such
as ENVI-met or PALM-4U, which resolve atmospheric flow and turbulent transport of heat and moisture interactively through
time, SOLWEIG-LEB focuses on path-dependent radiative transfer associated with three-dimensional canopy structure and
steady-state thermal response of vegetation. This modular model structure allows the level of detail to be flexibly selected
according to the intended application and available computational resources. Under conditions similar to those evaluated here,
the LAD-only configuration (EXP1/T3) can be used when pedestrian radiative conditions and MRT are the primary variables
of interest, whereas the full LEB configuration (EXP2/T4) is appropriate when leaf temperature and intra-canopy sensible and
latent energy partitioning need to be explicitly resolved. In the benchmarks (Section 4.5), the full LEB required only a minor
increase in runtime (approximately 4.4 % relative to T3) but substantially more peak GPU memory than the LAD-only
configuration. Therefore, applications over large domains or at high spatial resolution should consider both the required
diagnostic variables and the available GPU memory. The voxel-scale leaf temperature and sensible and latent heat fluxes
calculated by the full LEB may also support future coupling with atmospheric models. When spatially aggregated using leaf-
area density information, these fluxes could provide volumetric source and sink terms representing vegetation heat and
moisture exchange in computational fluid dynamics (CFD) or multi-layer urban canopy models. In addition, the three-
dimensionally resolved intra-canopy light environment and leaf temperature can provide essential biophysical inputs for
modelling biogenic volatile organic compound (BVOC) emissions.

5.3. Limitations and future development

The present evaluation has several limitations that should be addressed in future investigations. First, the Mainz
evaluation was restricted to a single tree species and two distinct radiative conditions. Because the exact three-dimensional
spatial coordinates and canopy extent of the observed foliage were unavailable, the observations had to be compared with the



estimated statistical range of the lower-canopy voxels. In addition, air temperature and relative humidity from a background station located approximately 3 km away were substituted as the meteorological forcing, which may have introduced representativeness errors. Second, the Göteborg evaluation covered only two distinct spatial locations across four days, restricted to summer foliated conditions. These initial results are therefore insufficient to comprehensively establish the model performance across different tree species, seasons, complex canopy geometries, and highly variable meteorological conditions. Further evaluation is warranted for leafless deciduous trees, evergreen trees, sparse canopies, and crown-edge conditions. Third, the numerical representation of the canopy structure is inevitably simplified. The current version assumes a spherical leaf angle distribution with a leaf projection function of $G_{proj} = 0.5$, and the leaf area is assumed to be uniformly distributed within the canopy envelope when high-resolution observed LAD profiles are unavailable. In reality, the actual LAD, leaf angle distribution, foliage clumping, and branch structure vary with species, season, and canopy height. Future developments should incorporate three-dimensional LAD and leaf-angle datasets derived from terrestrial laser scanning, hemispherical photography, or within-canopy radiation measurements. Fourth, the leaf energy balance module solves a steady-state balance and consequently neglects internal leaf heat storage and thermal inertia effects. Stomatal resistance is obtained by coupling the CANOAK C3 biochemical photosynthesis model with Ball–Berry stomatal conductance (Appendix A). The physiological parameters and their applicability to different tree species require further evaluation. Furthermore, sub-surface soil moisture and atmospheric CO₂ are prescribed, while hydrologic processes such as rainfall, canopy interception, soil evaporation, root-water uptake, and temporal soil-moisture changes are not represented. Soil-water stress can therefore be represented through the prescribed water-availability factor, but the model does not predict the evolution of soil water or plant hydraulic stress during prolonged drought or rainfall events. Fifth, the current version sets the leaf temperature equal to the ambient air temperature ($T_{veg} = T_{air}$) at night. It therefore cannot represent leaf temperatures below the ambient air temperature caused by nighttime radiative cooling, nor the resulting changes in vegetation longwave emissions and moisture exchanges. Future versions should solve the nighttime leaf energy balance by incorporating longwave radiation loss, convective heat exchange, and, where microclimatic parameters dictate, dew condensation processes. Another critical limitation is the absence of a two-way vegetation–atmosphere coupling framework. The calculated H and LE remain purely diagnostic outputs and do not actively update the prognostic air temperature or humidity fields. Likewise, a spatially uniform background wind speed is applied to all vegetation voxels, whereas actual within-canopy wind speed profiles and turbulence structures vary substantially depending on the canopy density and surrounding urban geometry. Thus, the current voxel-scale H and LE outputs must be interpreted as local equilibrium responses to a prescribed atmospheric condition. Further optimization of GPU memory allocation will be required for full-LEB applications to larger or higher-resolution domains.

Consequently, future developments will focus on coupling SOLWEIG-LEB with computational fluid dynamics (CFD) frameworks or multilayer urban canopy models. The high-resolution vegetation-voxel H and LE fields can be converted to atmospheric source terms using voxel leaf area, receiving air volume, and the latent heat of vaporization. Updated air temperature, humidity, and wind fields can then be returned to the leaf energy balance module. Further validation using



observations of leaf temperature, stomatal conductance, sap flow, and within-canopy meteorological parameters is also
850 required. Comprehensive sensitivity and uncertainty analyses should address the input sensitivities and uncertainties related to
LAD, G_{proj} , foliage clumping parameters, soil moisture, background wind speed, and stomatal parameters.

6. Conclusions

In this study, we developed SOLWEIG-LEB v1.0 as an advanced extension of the vegetation representation within
855 the SOLWEIG radiation model. The updated model replaces a single representative canopy transmissivity with path-dependent
shortwave attenuation based on leaf area density (LAD) and discrete radiative paths, and solves a voxel-scale leaf energy
balance for individual vegetation voxels to diagnose leaf temperature, vegetation longwave emission, and sensible and latent
heat fluxes. Evaluation against leaf-temperature observations in Mainz showed that SOLWEIG-LEB reproduced the daytime
variation and overall magnitude of leaf temperature under both clear-sky and fully cloudy conditions. In Göteborg, SOLWEIG-
860 LEB produced lower RMSEs for shortwave radiation, longwave radiation, and mean radiant temperature (MRT) than Legacy
SOLWEIG, although positive biases increased slightly for shortwave radiation and MRT.

Under the evaluated conditions, the main changes in pedestrian MRT relative to Legacy SOLWEIG were primarily
associated with LAD-based canopy attenuation, whereas the additional thermodynamic effect of the leaf-temperature
calculation was small. The maximum absolute area-mean MRT difference between the full LEB and LAD-only configurations
865 was approximately 0.04 °C under the canopy. Nevertheless, the full LEB successfully resolved spatial variations in leaf net
radiation, leaf temperature, and sensible–latent heat partitioning within the canopy, providing critical biophysical information
on vegetation thermal states and energy exchange beyond pedestrian MRT alone. The computational benchmarks showed
relatively modest increases in per-timestep runtime (approximately 9.8 % relative to the legacy-equivalent GPU configuration)
but substantially greater peak GPU memory demand when the full LEB configuration was activated. These results identify
870 memory demand as an important consideration for large-domain or high-resolution applications.

SOLWEIG-LEB therefore extends the existing SOLWEIG radiation framework from pedestrian radiative
assessment to the three-dimensional diagnosis of canopy thermal states and energy exchange while retaining its
computationally efficient, prescribed-meteorological-forcing approach. The resulting spatial information may support future
coupling with atmospheric or urban canopy models as volumetric source terms, as well as provide essential microclimatic
875 inputs for applications such as biogenic volatile organic compound (BVOC) emission modelling.



Appendix A. Photosynthesis and stomatal coupling for transpiration and leaf temperature

Stomata regulate CO₂ uptake for photosynthesis and water vapor loss through transpiration. SOLWEIG-LEB uses the CANOAK photosynthesis–stomatal coupling to calculate stomatal conductance and link it to transpirational latent heat loss and leaf temperature.

A1. Photosynthesis and net assimilation

Photosynthesis is calculated using the C₃ photosynthesis model of Farquhar et al. (1980) and the coupling approach of Baldocchi (1994). The Rubisco-limited and electron-transport-limited assimilation rates are calculated as follows:

$$W_c = \frac{V_{c\max}(C_i - \Gamma^*)}{C_i + K_c(1 + C_{O_2}/K_o)}, \quad (A1)$$

$$W_j = \frac{J(C_i - \Gamma^*)}{4(C_i + 2\Gamma^*)}, \quad (A2)$$

where W_c and W_j are the Rubisco-limited and electron-transport-limited assimilation rates, respectively. Both rates account for photorespiration but are expressed before subtracting mitochondrial respiratory CO₂ release. $V_{c\max}$ is the maximum carboxylation capacity, and J is the electron-transport rate. Assimilation, carboxylation capacity, and respiration rates are expressed in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ per unit one-sided leaf area. C_i is the intercellular CO₂ mole fraction, and Γ^* is the CO₂ compensation point at which uptake balances photorespiratory release in the absence of mitochondrial respiration. K_c and K_o are the Michaelis–Menten constants for CO₂ and O₂, respectively, and C_{O_2} is the O₂ mole fraction. Gas mole fractions, Γ^* , K_c , and K_o have units of $\mu\text{mol mol}^{-1}$. The electron-transport rate J increases with incident light and approaches $J_{\max}$ according to the following saturating light-response function.

$$J = \frac{\alpha_J I_{PAR}}{\sqrt{1 + (\alpha_J I_{PAR}/J_{\max})^2}}, \quad (A3)$$

where α_J is the effective light-response coefficient, I_{PAR} is the incident photosynthetically active radiation (PAR) photon flux ($\mu\text{mol photons m}^{-2} \text{ s}^{-1}$), and $J_{\max}$ is the maximum electron-transport rate. J and $J_{\max}$ have units of $\mu\text{mol electrons m}^{-2} \text{ s}^{-1}$ per unit one-sided leaf area. The implementation selects the process giving the lower assimilation rate at an initial $C_i = 0.7C_a$ and retains this process when solving the coupled assimilation–stomatal conductance equations. C_a is the ambient CO₂ mole fraction. Positive net assimilation is subject to an empirical cap based on the capacity for photosynthetic product utilization or export (Collatz et al., 1991):

$$A = \min[A_*, \frac{V_{c\max}}{2} - R_d], \quad (A4)$$

$$A_* = W_{lim}(C_{i,*}) - R_d, \quad (A5)$$



905 where A is net CO_2 assimilation after capping, and A_* and $C_{i,*}$ are the net assimilation and intercellular CO_2 mole fraction from the coupled solution before capping. W_{lim} is the selected W_c or W_j , and R_d is mitochondrial respiration. When the cap is active, leaf-surface and intercellular CO_2 mole fractions and stomatal conductance are recalculated using the capped A .

A2. CO_2 diffusion and stomatal conductance

910 Assimilation and stomatal conductance are linked through CO_2 diffusion between the ambient air, leaf surface, and leaf interior:

$$C_s = C_a - \frac{A}{g_{b,\text{CO}_2}}, \quad (\text{A6})$$

$$C_i = C_s - \frac{1.6 A}{g_{s,w}}, \quad (\text{A7})$$

915 where C_s is the leaf-surface CO_2 mole fraction. g_{b,CO_2} and $g_{s,w}$ are boundary-layer conductance for CO_2 and stomatal conductance for water vapor ($\text{mol m}^{-2} \text{s}^{-1}$), respectively, and the factor 1.6 represents the ratio of the molecular diffusivity of water vapor to that of CO_2 in air. Boundary-layer resistance for CO_2 is obtained by multiplying the water-vapor boundary-layer resistance $r_{b,vap}$ (s m^{-1}) by the water-vapor to CO_2 diffusivity ratio raised to the power of 2/3, then converted to molar conductance using the molar-volume conversion in Eq. (21). Stomatal conductance follows the Ball–Berry formulation in Eq. (22), with the water-stress adjustment in Eqs. (23) and (24). Residual stomatal conductance g_0 ($\text{mol m}^{-2} \text{s}^{-1}$) is used for non-positive net assimilation.

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A3. Temperature responses and physiological parameters

The coefficients governing photosynthesis and respiration are updated with leaf temperature. The following Arrhenius function is applied to K_c , K_o , CO_2/O_2 specificity $S_{c/o}$, and R_d :

$$q(T_{veg}) = q_{ref} \exp\left[\frac{E_a}{R_{gas}}\left(\frac{1}{T_{ref}} - \frac{1}{T_{veg}}\right)\right], \quad (\text{A8})$$

925 where q represents one of these coefficients, and q_{ref} is its value at the reference temperature $T_{ref} = 298.16 \text{ K}$. T_{veg} is leaf temperature (K), E_a is the temperature-response energy (J mol^{-1}), and R_{gas} is the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$). $S_{c/o}$ is a dimensionless coefficient describing the relative preference of Rubisco for CO_2 over O_2 and decreases with increasing temperature because its E_a is negative.

930 V_{cmax} and J_{max} follow a response that peaks at the optimum temperature and decreases at higher temperatures (Medlyn et al., 2002):

$$X(T_{veg}) = \frac{X_{opt} E_d \exp(E_d \beta)}{E_d - E_a + E_a \exp(E_d \beta)}, \quad (\text{A9})$$



$$\beta = \frac{1}{R_{\text{gas}}} \left(\frac{1}{T_{\text{opt}}} - \frac{1}{T_{\text{veg}}} \right), \quad (\text{A10})$$

where X represents V_{cmax} or J_{max} , and X_{opt} is its value at the optimum temperature $T_{\text{opt}} = 311$ K for the corresponding voxel. In Eq. (A9), E_a and E_d are activation and deactivation energies (J mol^{-1}), respectively, and β has units of mol J^{-1} .

935 The physiological parameters follow the CANOAK broadleaved-canopy representation and implementation (Harley and Baldocchi, 1995; Baldocchi and Wilson, 2001). The light-response coefficient is set to $\alpha_j = 0.22$ mol electrons mol^{-1} photons. The vertical variation in photosynthetic capacity is represented by $f_z = 0.35 + 0.65\zeta$, where ζ is voxel height above ground divided by canopy-top height in the same vertical column, constrained to 0–1. The voxel-specific capacities at the optimum temperature are set to $V_{\text{cmax,opt}} = 73f_z$ $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and $J_{\text{max,opt}} = 170f_z$ $\mu\text{mol electrons m}^{-2} \text{ s}^{-1}$. Reference respiration
 940 is calculated as $R_{\text{d,ref}} = 0.004657V_{\text{cmax,opt}}$ and multiplied by 0.4 when $I_{\text{PAR}} > 10$ $\mu\text{mol photons m}^{-2} \text{ s}^{-1}$. The seasonal factor was set to 1 during the evaluation periods. The CO_2 compensation point is calculated as $\Gamma^* = C_{\text{O}_2}/(2S_{\text{c/o}})$, with $C_{\text{O}_2} = 210000$ $\mu\text{mol mol}^{-1}$.

A4. Coupling to transpiration and the leaf energy balance

945 Calculated stomatal conductance is converted to stomatal resistance using Eq. (21). Together with leaf boundary-layer resistance and the leaf-to-air vapor pressure deficit, this resistance is used to calculate latent heat flux LE in Eq. (18). During daytime, leaf temperature determined by the balance among net absorbed radiation, sensible heat flux, and latent heat flux is fed back into the physiological coefficients and photosynthesis–stomatal calculations. This procedure is repeated to solve the leaf energy balance coupled to transpiration and leaf temperature.

950 Code and data availability

Software name: SOLWEIG-LEB v1.0

Developers: Geon Kang, Jae-Jin Kim, Fredrik Lindberg, Elliott Bridoux, and Nils Wallenberg

Contact: Geon Kang (kg85112@gmail.com)

Year first available: 2026

955 **Hardware required:** A 64-bit computer with a CUDA-compatible NVIDIA GPU. GPU-memory requirements depend on the model-domain size and vegetation-voxel configuration.

Software required: Python 3.12, CUDA 12.x, CuPy 13.3.0, GDAL 3.6 or later, and the dependencies specified in environment.yml. The archived release was tested on Windows 11.

Programming language: Python with GPU acceleration via CuPy/CUDA



960 **Program size:** Approximately 243 MB compressed and 246 MB uncompressed (code and data)

Availability and cost: Open source and free of charge

License: GNU General Public License v3.0 or later (GPL-3.0-or-later)

Repository: Zenodo (Kang et al., 2026), <https://doi.org/10.5281/zenodo.21904277>

965 **Data availability:** Model inputs, configurations, evaluation data, and postprocessing scripts are available in the Zenodo archive (Kang et al., 2026).

Author contributions

GK conceived the study, developed and implemented SOLWEIG-LEB, performed the simulations, model evaluation, data analysis, post-processing, and visualization, and prepared the original manuscript. FL and NW contributed to the model conceptualization and methodology, provided technical guidance on the SOLWEIG framework, and reviewed and edited the manuscript. EB provided the observational and spatial data for the Göteborg evaluation, provided information on the measurement setup and study site, and reviewed and edited the manuscript. JJK supervised the study, acquired funding, provided scientific guidance and project administration, and reviewed and edited the manuscript. All authors reviewed and approved the final manuscript.

Competing interests

975 The contact author has declared that none of the authors has any competing interests.

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During the preparation of this work, the authors used Google Gemini and OpenAI ChatGPT to improve language, readability, and textual organization. OpenAI Codex was used to assist with code review, debugging, and the implementation of GPU/CUDA parallelization. All AI-assisted text and code modifications were reviewed, edited, and validated by the authors.

980 The authors take full responsibility for the content, source code, results, and conclusions of the publication.

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