Supporting Information for: Quantifying water-use efficiency in plant canopies with varying leaf angle and density distribution

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This file contains the following: Supplemental Figures 1 to 2 and Supplemental Table 1.

1. Model verification

To verify the model set-up and chosen resolution, the 3D model was verified by comparing model outputs against fluxes of whole-canopy radiation interception and the sunlit leaf area fraction calculated from theory. To verify that shadows on leaves were accurately resolved, the fraction of sunlit leaf area was calculated in the 3D model Helios and compared against the theoretical value for a set of homogeneous canopies with LAI of 3 and azimuthally isotropic leaf angle distribution but with four different leaf inclination angle distributions: spherical (isotropic), uniform, planophile, and erectophile. For this case, leaves were considered to be black.

The Beer's law equation (Eq. 1), which calculates the radiation flux intercepted over the depth of the canopy (Monsi and Saeki, 1953),

$$Q_n = Q_0 \left[1 - \exp\left(-\frac{G\,LAI}{\cos\theta_s} \right) \right], \tag{1}$$

was integrated to calculate the fraction of sunlit leaf area f_{sun} as in (Goudriaan, 1977):

$$f_{sun} = \frac{\cos\theta_s}{G\,LAI} \left[1 - \exp\left(-\frac{G\,LAI}{\cos\theta_s} \right) \right], \tag{2}$$

where Q_0 is the direct-beam PAR radiation flux on a horizontal surface at the top of the canopy and θ_s is the solar zenith angle.

G was calculated mathematically based on the assumed leaf angle distribution as in (Bailey and Fu, 2022):

$$G = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\pi/2} g_L(\theta_L) |\sin\theta_s \sin\theta_L \cos\phi_L + \cos\theta_s \cos\theta_L| \, d\theta_L \, d\phi_L, \tag{3}$$

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Author's version.
Publisher's typeset version can be found at https://doi.org/10.1093/aob/mcae018

where θ_L is the leaf zenith angle and ϕ_L is the leaf azimuth angle, and $g_L(\theta_L)$ is the sine-weighted leaf angle distribution function assuming azimuthal isotropy.

f_{sun} was calculated from the 3D model output by summing the area of sunlit leaves and dividing by the total canopy leaf area. To determine whether the leaf element is sunlit or shaded, the fully sunlit flux (Q_{sun}) was calculated for each leaf based on its angle as:

$$Q_{sun} = Q_{source}|\vec{n_i} \cdot \vec{v}| \, , \tag{4}$$

where Q_{source} is the incoming direct solar radiation flux on a plane perpendicular to the sun, $\vec{n}_i$ is a unit vector normal to the surface of the i^{th} leaf element, and $\vec{v}$ is a unit vector pointing in the direction of the sun. If the actual absorbed flux for each leaf element was greater than 50% of Q_{sun}, the leaf was classified as sunlit.

It was previously verified in Bailey and Fu (2022) that the analytical probability leaf angle distribution can be replicated in Helios. Here, the theoretical G values were used to calculate the theoretical absorbed radiation and compared to the 3D model (Fig. S1). The instantaneous whole-canopy fluxes obtained from the 3D model were in agreement with the theoretical values for the four different homogeneous canopies (Table S1). It was thus concluded that the leaf sub-resolution of 10×10 was reasonable for the modeling study.

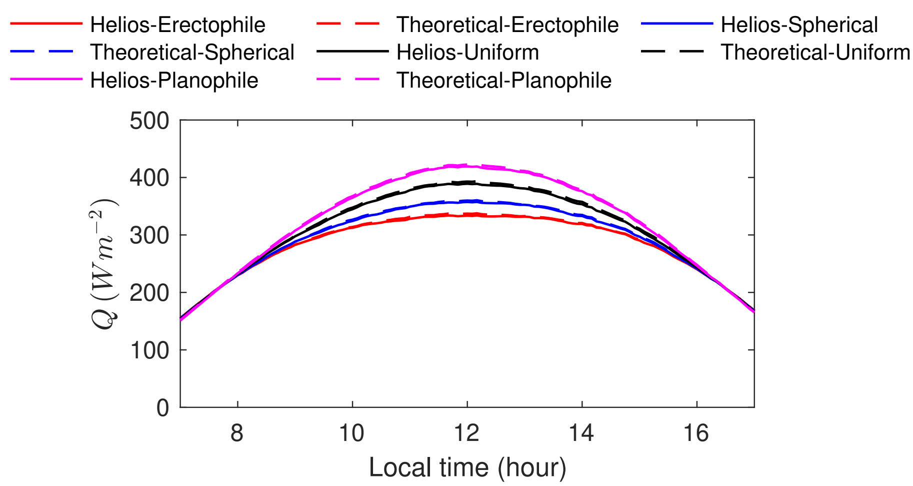

Figure S1: Theoretical and calculated (Helios) whole-canopy fluxes of PAR interception (Q) on Julian day 153 for a range of homogeneous canopies with LAI of 3 and different leaf inclination angle distributions: spherical, uniform, planophile, and erectophile.

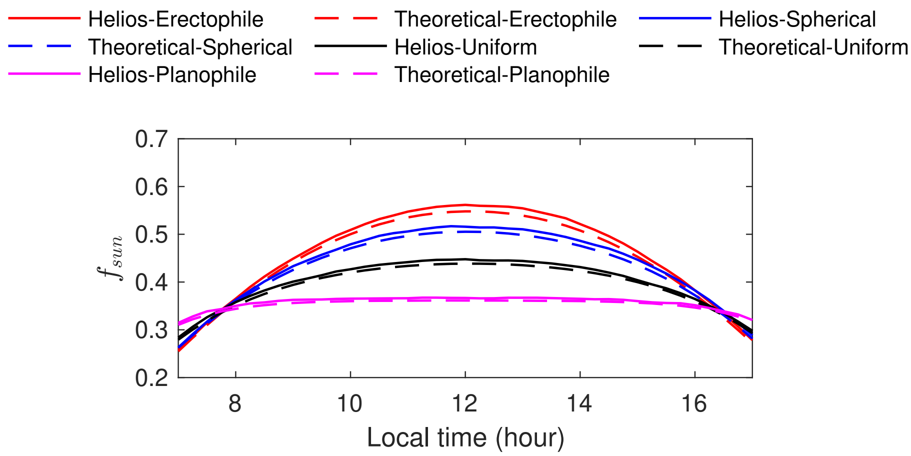

Figure S2: Theoretical and calculated (Helios) fraction of sunlit leaf area (f_{sun}) on Julian day 153 for a range of homogeneous canopies with LAI of 3 and different leaf inclination angle distributions: spherical, uniform, planophile, and erectophile.

Table S1: Model performance metrics for the four different leaf inclination distributions in a homogeneous canopy with isotropic leaf azimuth comparing the theoretical value of whole-canopy fluxes of PAR interception from Eq. 1 (Q) and the fraction of sunlit leaf area (f_{sun}) with Helios.

	Q		f_{sun}	
	R^2	NRMSE	R^2	NRMSE
Erectophile	0.9997	0.0049	0.9954	0.0185
Planophile	0.9996	0.0057	0.9915	0.0186
Uniform	0.9995	0.0064	0.9940	0.0188
Spherical	0.9998	0.0042	0.9953	0.0182

References

Bailey, B.N., Fu, K., 2022. The probability distribution of absorbed direct, diffuse, and scattered radiation in plant canopies with varying structure. Agricultural and Forest Meteorology 322, 109009.

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