SiriusQuality-BioMa-Irradiance-Component

A BioMA-SiriusQuality component of single and multi-layers big-leaf and sun/shade models of absorbed irradiance by crop canopies

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Summary

This document describes the procedure used in the SQ_Irradiance crop model component to calculate solar irradiance intercepted and absorbed by canopies. Absorbed irradiance rates are calculated either using the global incident solar irradiance or using direct and diffuse incident irradiance components. In the latter case, calculations can distinguish between sunlit and shaded leaf area fractions. Calculations are performed at an hourly time step when the direct and diffuse components are distinguished and at a daily time step when only the global irradiance is considered. Calculations can be performed considering the canopy as one leaf layer or considering the canopy as distinct vertical layers. In addition, the canopy can be considered having a spherical or ellipsoidal leaf angle distribution. The component is designed to calculate both photosynthetically active radiation (PAR) or near infrared radiation (NIR). The component is integrated in the wheat crop model *SiriusQuality* as an independent component developed in the public domain software framework BioMA (Biophysical Model Applications). Both *SiriusQuality* and BioMA are developed using Microsoft C# language in the .Net framework (version 4.5). The component was coded using the development environment Microsoft Visual Studio 2017.

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1. Theoretical background

The irradiance intercepted by canopies can be modeled with a one-dimensional turbid medium approach using the Beer-Lambert's law (equation (1)), assuming that the green area index of canopies is a continuous variable with depth (Monsi and Saeki, 2005):

$$I_{\mathrm{int,c,g}} = I_{\mathrm{inc,g}} \left(1 - \exp\left(-k_{\mathrm{g}} L_{\mathrm{t}}\right)\right) \tag{1}$$

where $I_{\mathrm{inc,g}}$ (MJ m^{-2} (ground)) is the incident global (direct beam and diffuse) photosynthetically active radiance (PAR) or near infrared radiation (NIR) at the top of the canopy, $I_{\mathrm{int,c,g}}$ (MJ m^{-2} (ground)) is the amount of PAR or NIR intercepted by the canopy, L_{t} (m^{-2} (leaf) m^{-2} (ground)) is the total green area index of the canopy, and k_{g} (m^{2} (ground) m^{-2} (leaf)) is the global irradiance extinction coefficient. The coefficient k_{g} accounts mainly for leaf angle distribution, leaf shape, internode length, canopy arrangement, solar elevation and composition of the incoming radiation, in addition to the optical characteristics of the canopy.

Equation (1) has long been used in crop models in order to model crop biomass production using the available solar energy, through the so-called *light (radiation) use efficiency* coefficient (Monteith, 1977; Sinclair and Muchow, 1999). This coefficient links the total biomass production to the total absorbed solar energy. However, when biomass production is modeled using a photosynthesis model, a distinction between absorption of direct and diffuse irradiance components is needed (Goudriaan and Van Laar, 1994). This is due to the fact that photosynthesis is a process that is nonlinear with the absorbed PAR: it increases sharply at low irradiance levels but saturates at high irradiance levels. Therefore, leaves that receive direct PAR (sunlit leaves) are often located in the "saturated" zone of the photosynthesis-light curve, while leaves that do not receive direct PAR (shaded leaves) are generally in the linear part of the photosynthesis-light curve. Consequently, when absorption by sunlit and shaded leaf fractions is not considered (as in equation (1)), photosynthesis is likely to be overestimated (De Pury and Farquhar, 1997; Goulas et al., 2004). Furthermore, accounting for solar beam penetration inside the canopy (i.e. sunflecks) by calculating sunlit absorption, allows a more accurate estimation of leaf photosynthetic capacity and nitrogen distribution vertical profiles (Hammer and Wright, 1994; De Pury and Farquhar, 1997).

In the *SQ-Irradiance* component, both big-leaf and sun/shade models for calculating absorbed irradiance by canopies are implemented. Net short-wave (solar) irradiance absorbed by canopies (or leaf layers) is also calculated. Absorbed irradiance in the PAR and NIR wavebands are calculated separately as the diffuse irradiance extinction, scattering, and reflectance coefficients are different for these two wavebands.

2. Overview of the calculation procedures

Absorbed solar irradiance by canopies is simulated using either the big-leaf approach b (Monsi and Saeki, 2005), or the sunlit/shade approach (Goudriaan and Van Laar, 1994; De Pury and Farquhar, 1997) (Figure 1). Calculations can be performed at an hourly time step when the direct and diffuse components are distinguished and at a daily time step when only the global irradiance is considered. The SQ_Irradiance component allows performing the calculations both at the leaf layer and the canopy scales, so that the impact of the spatial scale on the simulation of water and energy transfer in the soil-plant-atmosphere continuum and biomass production can be evaluated. Canopies with either spherical or ellipsoidal leaf angle distribution can be considered for the calculations. Finally, the component is designed to calculate the amount of PAR as well NIR intercepted and absorbed by canopies.

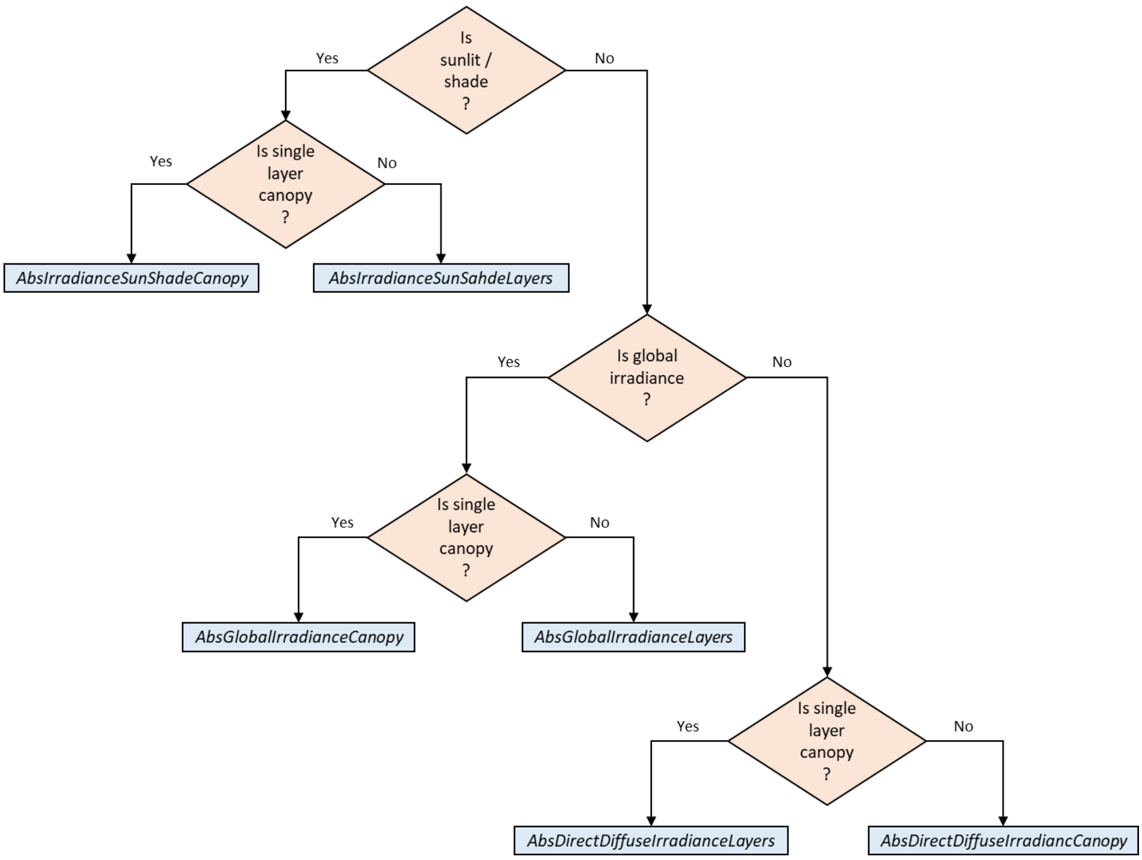

Figure 1. Flowchart of the strategies (rectangles) to calculate the absorbed irradiance using a sun/shade model or a big-leaf model with global or diffuse and direct irradiance. Each model can be applied either for single or multi-layer canopies. The control structure is coded in the composite contextual strategy Irradiance.

Extinction coefficients for direct irradiance are calculated in different strategies (atomic or unit model) for spherical and ellipsoidal distribution of leaf inclination angles for leaves considered as black objects (Figure 2). When an ellipsoidal leaf angle distribution is used, the extension coefficient for direct irradiance for black leaves uses the mean leaf inclination angle, which is calculated as a function of crop development. The extinction and reflectance coefficients for direct and diffuse irradiance are then calculated. These coefficients are used both for the big-leaf sunlit/shade approach.

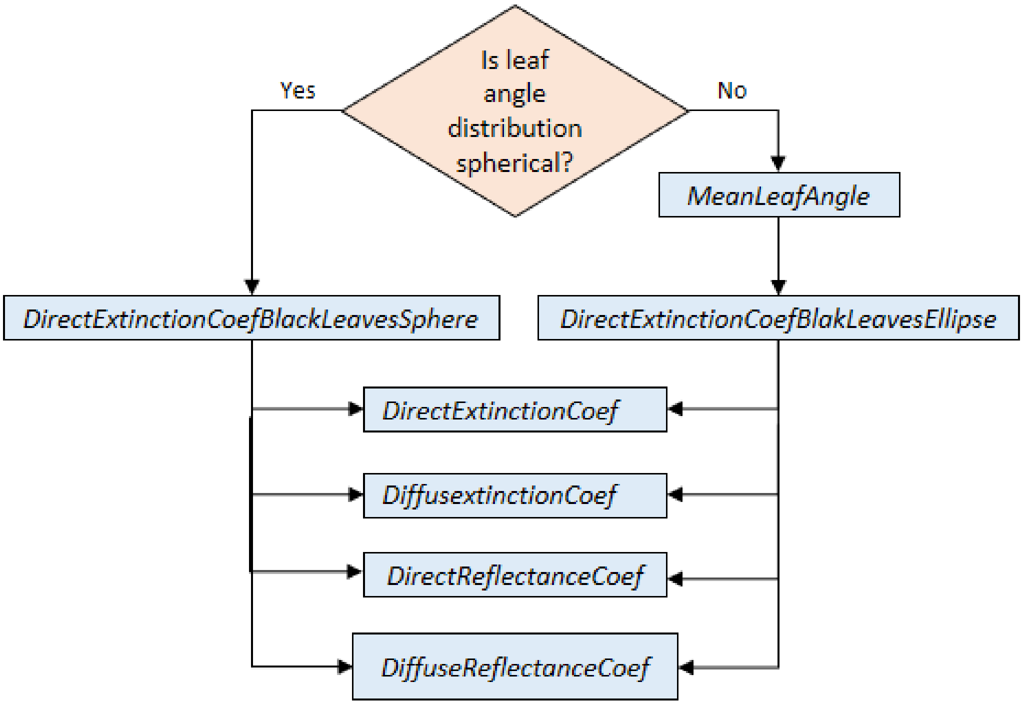

Figure 2. Flowchart of the strategies (rectangles) to calculate the reflectance and extinction coefficients for either ellipsoidal or spherical leaf angle. The control structure is coded in the composite contextual strategy Irradiance.

The organization of this document reflects the structure of the SQ_Irradiance component. The simple and composite contextual strategies are shown in Figure 3. This component is coupled with the BioMa SQ_Meteorology component which calculates the appropriate weather input from weather data. The composite strategy Irradiance computes outputs for both incident PAR and NIR.

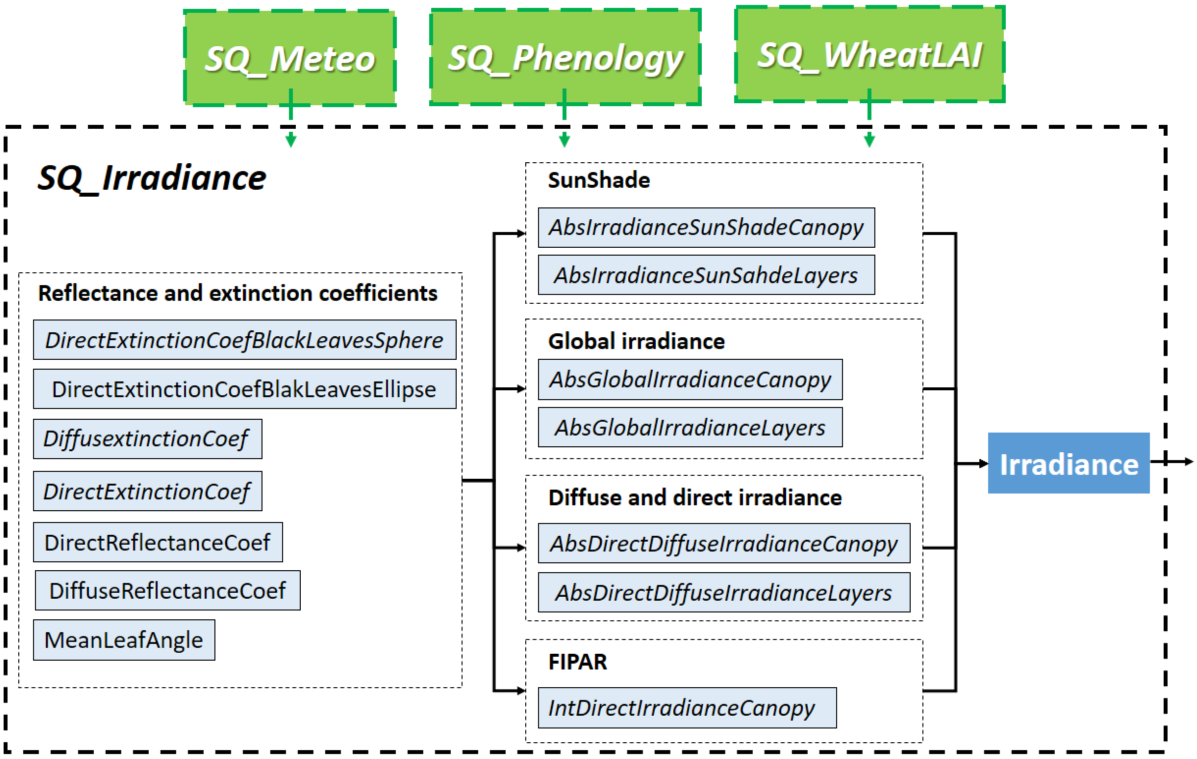

Figure 3. Package diagram of the BioMA-*SiriusQuality* SQ_Irradiance component. White boxes are simple strategies, the blue box is the composite contextual strategy and green boxes are external BioMa-*SiriusQuality* components on which the SQ-Irradiance component depends.

The calculation procedures for determining the extinction coefficients, reflectance coefficients and absorbed irradiance by sunlit and shaded leaves are given in the following Sections. For canopies with a spherical leaf angle distribution, the equations for calculating the extinction coefficient have been developed and described by Goudriaan (1977, 1988); Goudriaan and Van Laar (1994), and for canopies with ellipsoidal leaf angle distribution by Campbell (1986, 1990). The equation for calculating the absorbed irradiance for single and multi-layers canopies have been developed by De Pury and Farquhar (1997) and Leuning et al. (1995).The reader may refer to these studies for a full description of the theoretical assumptions lying behind development of the equations used here.

3. Extinction coefficients

Solar irradiance inside a canopy may be discretized into three distinct components: the *direct* (beam) irradiance, the *diffuse* irradiance (solar irradiance diffused by the sky) and the *scattered* irradiance ("second-hand" direct irradiance dispatched by canopy elements). The extinction of direct beam, combined direct beam and scattered, and diffuse irradiances inside the canopy are estimated using extinction coefficients that are specific to each irradiance component.

The absorption of direct-beam irradiance by a leaf surface depends on the angle between the solar beam and the leaf normal, in a way that absorption is maximum when this angle is null (leaf surface is perpendicular to the solar beam), while it minimal as this angle approaches 90° (leaf surface is parallel to solar beam).

Assuming leaves act as perfect black surfaces (i.e. they absorb all the intercepted irradiance), the direct-beam irradiance extinction coefficient (k'_{b}, m^2 (ground) m^{-2} (leaf)) is given by (Goudriaan and Van Laar, 1994):

$$k'_{\mathrm{b}} = C\frac{\bar{O}(\beta)}{\sin\beta} \tag{2}$$

where β (radian) is the incident solar zenithal angle and $\sin\beta$ accounts for the optical path, $\bar{O}$ is a projection function accounting for the actual effective cross section of the elements, which depends on the orientation of the green elements approximated as small flat surfaces and on the direction of the incident light (Campbell and Norman, 2012). In other words, $\bar{O}$ describes the projected area of a unit green area index onto a surface perpendicular to the incident radiation direction. C is a clumping factor (dimensionless) that describes the spatial dependency of the positions of the leaves in the canopy (Weiss et al., 2004). Clumped leaves with $C < 1$ tend to overlap in the Ω direction, while regularly distributed leaves with $C > 1$ tend to avoid themselves. Here we consider that C is constant and is defined as non-varietal parameter (Table A2).

If one assumes a spherical (uniform or isotropic) leaf angle distribution, that is the surface of all green elements of canopies are distributed as the facets at the surface of a sphere, then the projection $\bar{O}(\beta)$ is the same in all direction) and $\bar{O}$ equals 0.5, which the ratio between the area of the base of a hemisphere and that of the hemisphere itself. In that simple case, equation (2) simplifies to (De Wit, 1965; Goudriaan, 1977):

$$k'_{\mathrm{b}} = C\frac{0.5}{\sin\beta} \tag{3}$$

The distribution of leaf inclination angles can be generalized by considering the distribution of green elements in canopies as the facets at the surface of an ellipsoid of revolution with a vertical rotation axis (Campbell, 1986). The ellipsoid is characterized by its eccentricity (χ, dimensionless), that is the ratio between its vertical and horizontal diameters. By adjusting χ leaf angle distributions of any canopy from erectophile to planophile can be simulated. Wang et al. (2007) showed that the use of ellipsoidal function to characterize the leaf angle distribution is a good trade-off between feasibility and complexity as only one parameter, the average inclination angle green elements of the canopy ($\bar{\alpha}$,radian) is required. In such a case, the extinction coefficient of direct irradiance is calculated as follows (Campbell, 1986):

$$k'_{\mathrm{b}} = C\frac{\sqrt{\chi^2+cot^2\beta}}{\chi+1.774(\chi+1.182)^{-0.733}} \tag{4}$$

where χ is related to $\overline{\alpha}$ through an empirical equation (Campbell, 1990):

$$\chi = \left(\frac{\overline{\alpha}}{9.65}\right)^{-0.6061} - 3 \tag{5}$$

$\overline{\alpha}$ is a varietal parameter that describe the leaf angle distribution of green elements in canopies. Note that when $\chi = 1$ (that is, for $\overline{\alpha} = 56°$), the ellipsoidal distribution becomes the spherical distribution. $\bar{\alpha}$ increases during crop development and is calculated in a dedicated strategy (see section 3.3).

The extinction coefficient calculated by equations (3) and (4) applies only to the case where leaves are black (i.e. irradiance is neither transmitted through the leaves nor reflected by their surface). For leaves that have reflectance (ρ, dimensionless) and transmittance ratios that are not null, a part of direct irradiance is scattered. As a result, the attenuation of combined beam and scattered irradiance inside the canopy (i.e. total direct irradiance) is less steep than the direct beam irradiance, implying that the apparent extinction coefficient (k_{b}, m^2 (ground) m^{-2} (leaf)) is smaller than that of direct-beam irradiance. Goudriaan (1977) showed that the value of k_{b} is reasonably well approximated by:

$$k_{\mathrm{b}} = k_{\mathrm{b}}'\sqrt{1-\sigma} \tag{6}$$

where σ (dimensionless) is the leaf scattering coefficient (the sum of leaf reflectance and transmittance coefficients). σ typically equals 0.2 in the PAR (σ_{PAR}) waveband and 0.8 in the NIR waveband (σ_{PAR}) and is assumed to be constant and is defined as a non-varietal parameter (Table 2).

The extinction coefficient of diffuse irradiance (k_{d}, m^2 (ground) m^{-2} (leaf)), is derived assuming that diffuse irradiance decreases exponentially along the canopy depth by integrating k_{b} over the hemisphere:

$$k_{\mathrm{d}} = -\frac{1}{L_{\mathrm{t}}}\ln\left(1 - 2\int_0^{\pi/2}\left(1-\exp(-k_{\mathrm{b}}L_{\mathrm{t}})\right)\times\cos\beta\times\sin\beta\times d\beta\right) \tag{7}$$

Equation (7) is integrated numerically with the Gauss Legendre Rule method using the C# library MathNet.Numerics.Integration.

The mean inclination angle of canopy green elements may change significantly during crop development. For instance, for wheat between terminal spikelet (growth stage [GS] 30) and flag leaf ligule (GS39), $\overline{\alpha}$ increases by 40% (for cultivars with erect leaf posture) to 80% (for cultivars with more horizontal leaf posture) (Liu et al., 2020). Her, we assume that $\overline{\alpha}$ is constant between crop emergence and GS30 and increases linearly during the stem extension period and $\overline{\alpha}$ is given by the following empirical relationship:

$$\overline{\alpha} = \begin{cases} \overline{\alpha}_{\mathrm{juv}}, & \mathrm{GS} \leq \mathrm{GS30} \\ \overline{\alpha}_{\mathrm{juv}} + TT_{30}\frac{(\overline{\alpha}_{\mathrm{mat}} - \overline{\alpha}_{\mathrm{juv}})}{P \times (\mathrm{FLN} - \mathrm{HS}_{30})}, & \mathrm{GS30} < \mathrm{GS} < \mathrm{GS39} \\ \overline{\alpha}_{\mathrm{mat}}, & \mathrm{GS} \geq \mathrm{GS39} \end{cases} \quad (8)$$

where, $\overline{\alpha}_{\mathrm{juv}}$ and $\overline{\alpha}_{\mathrm{mat}}$ (radian) are the average inclination angle of green elements of canopies during the vegetative phase (i.e. before GS31) and after GS39, respectively, TT_{30} (°Cd) is the thermal time accumulated after GS30, P (°Cd leaf^{-1}) is the phyllochron, FLN is the final leaf number, and HS_{30} is the decimal number of visible mainstem leaves (Haun stage) at GS30. TT_{30}, P, FLN, and HS_{30} are inputs of the SQ_Irradiance component. In *SiriusQuality*, the former is given by the SQ_ThermalTime component and the latter three by the SQ_Phenology component (Manceau and Martre, 2018) (Table A1 and A2).

4. Reflectance coefficients

Similarly to extinction coefficients, reflectance coefficients depend on leaves angle distribution and the inclination of solar beam and sky sectors, for direct-beam and diffuse irradiances, respectively. Canopy's reflectance of direct-beam irradiance (ρ_{b}, dimensionless) is lowest when the sun is closest to the zenith and highest as solar inclination approaches 0° (sun is grazing over horizontal leaves). Here, ρ_{b} is calculated following Goudriaan (1977) and is given by:

$$\rho_{\mathrm{b}} = 1 - exp\left(-\frac{2\rho_{\mathrm{h}}k'_{\mathrm{b}}}{1+k'_{\mathrm{b}}}\right) \quad (9)$$

where ρ_{h} (dimensionless) is the reflectance coefficient of a canopy having horizontal leaves, given by:

$$\rho_{\mathrm{h}} = \frac{1-\sqrt{1-\sigma}}{1+\sqrt{1-\sigma}} \quad (10)$$

The reflectance coefficient of diffuse irradiance (ρ_{d}, dimensionless) is calculated as the integral over the hemisphere of equation (9):

$$\rho_{\mathrm{d}} = 2\int_0^{\pi/2}\left(1 - exp\left(-\frac{2\rho_{\mathrm{h}}k'_{\mathrm{b}}}{1+k'_{\mathrm{b}}}\right)\right) \times \cos\beta \times \sin\beta \times d\beta \quad (11)$$

Equation (12) is integrated numerically with the Gauss Legendre Rule method using the C# library MathNet.Numerics.Integration.

5. Absorbed global irradiance

The simplest and most used model of absorbed irradiance in crop growth models, considers a constant extinction coefficient (k_{g}) that does not depend on the illumination conditions (Liu et al., 2020). Therefore, it is assumed that k_{g} is valid for any sun directions, that is k_{g} applies to both direct and diffuse incident PAR.

Thus, following the Beer-Lambert's law, the global (direct beam plus diffuse) irradiance absorbed per unit ground area of a leaf layer having a thickness ΔL (m^{-2} (leaf) m^{-2} (ground)), at depth L ($I_{\mathrm{abs},\Delta\mathrm{L}}$, MJ m^{-2} (ground) d^{-1} or MJ m^{-2} (ground) h^{-1}) is given as:

$$I_{\mathrm{abs},\Delta\mathrm{L,g}} = I_{\mathrm{inc,g}}\left(\exp(-k_{\mathrm{g}}L) - \exp\left(-k_{\mathrm{g}}(L+\Delta L)\right)\right) \tag{12}$$

At the canopy level, global irradiance absorbed per unit ground area ($I_{abs,C}$, MJ m^{-2} (ground) d^{-1} or MJ m^{-2} (ground) h^{-1}) is given by integrating equation (13) relative to L, which yields:

$$I_{\mathrm{abs,c,g}} = I_{\mathrm{inc,g}}(\,1 - \exp(-k_{\mathrm{g}}L_{\mathrm{t}})) \tag{13}$$

6. Absorbed direct and diffuse irradiance

In equations (13) and (14) k_{g} is assumed constant over time. However, the direct-beam irradiance extinction coefficient changes at an infra-daily scale. To include this change in the calculation of (average) global irradiance absorption in the big-leaf model, equation (13) is modified so that the absorbed global irradiance is the sum of absorbed direct-beam and diffuse irradiance. At the leaf-layer scale this model writes:

$$I_{\mathrm{abs},\Delta\mathrm{L,g}} = I_{\mathrm{abs},\Delta\mathrm{L,b}} + I_{\mathrm{abs},\Delta\mathrm{L,d}} \tag{14}$$

$$I_{\mathrm{abs},\Delta\mathrm{L,b}} = (1-\rho_{\mathrm{b}})I_{\mathrm{inc,b}}\left(\exp(-k_{\mathrm{b}}\,L) - \exp\left(-k_{\mathrm{b}}\,(L+\Delta L)\right)\right) \tag{15}$$

$$I_{\mathrm{abs},\Delta\mathrm{L,d}} = (1-\rho_{\mathrm{d}})I_{\mathrm{inc,d}}\left(\exp(-k_{\mathrm{d}}\,L) - \exp\left(-k_{\mathrm{d}}\,(L+\Delta L)\right)\right) \tag{16}$$

where, $I_{\mathrm{inc,b}}$ and $I_{\mathrm{inc,d}}$ (MJ m^{-2} (ground) h^{-1}) are the direct-beam and diffuse incident irradiance at the top of the canopy, respectively.

For the whole canopy absorbed global irradiance ($I_{abs,C}$, MJ m^{-2} (ground) h^{-1}) is given by (De Pury and Farquhar, 1997):

$$I_{\mathrm{abs,c,g}} = I_{\mathrm{abs,c,b}} + I_{\mathrm{abs,c,d}} \tag{17}$$

with,

$$I_{\mathrm{abs,c,b}} = (1-\rho_{\mathrm{b}})I_{\mathrm{inc,b}}(\,1 - \exp(-k_{\mathrm{b}}\,L_{\mathrm{t}})) \tag{18}$$

$$I_{\mathrm{abs,c,d}} = (1-\rho_{\mathrm{d}})I_{\mathrm{inc,d}}(\,1 - \exp(-k_{\mathrm{d}}\,L_{\mathrm{t}})) \tag{19}$$

7. Absorbed irradiance by sunlit and shaded leaf fractions

Sunlit leaves receive irradiance that comes from solar beam ($I^{\mathrm{a}}_{\mathrm{abs,L,b}}$, MJ m^{-2} (leaf) h^{-1}) and from sky-diffusion ($I^{\mathrm{a}}_{\mathrm{abs,L,d}}$, MJ m^{-2} (leaf) h^{-1}), in addition to a "second-hand" direct irradiance scattered by other leaves ($I^{\mathrm{a}}_{\mathrm{abs,L,s}}$, MJ m^{-2} (leaf) h^{-1}). Shaded leaves receive only diffuse irradiance (that is, diffused irradiance from the sky in addition to the scattered direct-beam irradiance). Therefore, the total irradiance absorbed by sunlit ($I^{\mathrm{a}}_{\mathrm{abs,L,Sun}}$, MJ m^{-2}(leaf) h^{-1}) and shaded ($I^{\mathrm{a}}_{\mathrm{abs,L,Sh}}$, MJ m^{-2}(leaf) h^{-1}) leaves at depth L writes (Spitters, 1986):

$$I^{\mathrm{a}}_{\mathrm{abs,L,Sh}} = I^{\mathrm{a}}_{\mathrm{abs,L,d}} + I^{\mathrm{a}}_{\mathrm{abs,L,s}} \tag{20}$$

$$I^{\mathrm{a}}_{\mathrm{abs,L,Sun}} = I^{\mathrm{a}}_{\mathrm{abs,L,Sh}} + I^{\mathrm{a}}_{\mathrm{abs,L,b}} \tag{21}$$

Note all the terms in equations (21) and (22) are expressed per unit leaf area, while in the previous model, and in the sun/shade model in the SQ_Irradiance component described in the next section are expressed per unit ground area. This differences is indicated by the superscript a in the absorbed irradiance symbols.

$I_{\mathrm{abs,L,b}}$ does not change with depth inside the canopy (all sunflecks receive the same beam irradiance per a unit ground area) and is given as:

$$I^{\mathrm{a}}_{\mathrm{abs,L,b}} = I_{\mathrm{inc,b}}\,(1-\sigma)\,k'_{\mathrm{b}} \tag{22}$$

The diffuse irradiance is attenuated within the canopy following an exponential relationship and $I_{\mathrm{abs,L,d}}$ is given as:

$$I^{\mathrm{a}}_{\mathrm{abs,L,d}} = (1-\rho_{\mathrm{d}})\,I_{\mathrm{inc,d}}\,k_{\mathrm{d}}\exp(-k_{\mathrm{d}}L) \tag{23}$$

Finally, $I_{\mathrm{abs,L,s}}$ is calculated as the difference between total absorbed direct irradiance and (including scattering) and the absorbed direct irradiance alone:

$$I^{\mathrm{a}}_{\mathrm{abs,L,s}} = I_{\mathrm{inc,b}}\big((1-\rho_{\mathrm{b}})\,k_{\mathrm{b}}\exp(-k_{\mathrm{b}}L) - (1-\sigma)\,k'_{\mathrm{b}}\exp(-k'_{\mathrm{b}}L)\big) \tag{24}$$

Note the use of k'_{b} compared to k_{b} in the big-leaf model of absorbed direct-beam and diffuse irradiance in order to include irradiance scattering.

The fraction of leaf area in the sunlit ($f_{\mathrm{L,Sun}}$, dimensionless) is not explicitly used in the SQ_Irradiance component but is obtained by considering that all leaves are black (once a beam irradiance is intercepted by a layer, it is occulted from subsequent layers). In this case, $f_{\mathrm{L,Sun}}$ follows an exponential extinction curve that is adequately simulated using Beer's law with the direct-beam extinction coefficient k'_{b} (Goudriaan and Van Laar, 1994):

$$f_{\mathrm{L,Sun}} = \exp(-k'_{\mathrm{b}}\,L) \tag{25}$$

then, The fraction of leaf area in the sunlit ($f_{\mathrm{L,Sh}}$, dimensionless) is most simply calculated as the leaf area fraction that is not sunlit given by:

$$f_{\mathrm{L,Sh}} = 1 - f_{\mathrm{L,Sun}} \tag{26}$$

Equations (23) to (25) define the absorbed irradiance per unit leaf area at depth L. The irradiance absorbed per unit of ground area by the sunlit leaf area of a leaf layer of thickness ΔL at depth L ($I_{\mathrm{abs,\Delta L,Sun}}$, MJ m^{-2} (ground) h^{-1}) is calculated by integrating equations (23) to (25) between L and $L+\Delta$:

$$I_{\mathrm{abs,\Delta L,Sun}} = I_{\mathrm{abs,\Delta L,b,Sun}} + I_{\mathrm{abs,\Delta L,d,Sun}} + I_{\mathrm{abs,\Delta L,s,Sun}} \quad (27)$$

$$I_{\mathrm{abs,\Delta L,Sun}} = \int_{L}^{L+\Delta L} \left(I_{\mathrm{abs,L,b}} + I_{\mathrm{abs,L,d}} + I_{\mathrm{abs,L,s}}\right) f_{\mathrm{L,Sun}}\, dL \quad (28)$$

with,

$$I_{\mathrm{abs,\Delta L,b,Sun}} = I_{\mathrm{inc,b}}(1-\rho_{\mathrm{d}})\left(\exp(-\,k'_{\mathrm{b}}L) - \exp(-\,k'_{\mathrm{b}}(L+\Delta L))\right) \quad (29)$$

$$I_{\mathrm{abs,\Delta L,d,Sun}} = I_{\mathrm{inc,d}}\,(1-\rho_{\mathrm{d}})\frac{k_{\mathrm{d}}}{k_{\mathrm{d}}+k'_{\mathrm{b}}}\begin{bmatrix}\exp(-(k_{\mathrm{d}}+\,k'_{\mathrm{b}})L) \\ -\exp\left(-(k_{\mathrm{d}}+\,k'_{\mathrm{b}})(L+\Delta L)\right)\end{bmatrix} \quad (30)$$

$$I_{\mathrm{abs,\Delta L,s,Sun}} = I_{\mathrm{inc,b}}\begin{bmatrix}(1-\rho_{\mathrm{b}})\frac{k_{\mathrm{b}}}{k_{\mathrm{b}}+k'_{\mathrm{b}}}\left(\exp(-(k_{\mathrm{b}}+k'_{\mathrm{b}})L) - \exp\left(-(k_{\mathrm{b}}+k'_{\mathrm{b}})(L+\Delta L)\right)\right) \\ -(1-\sigma)\frac{1}{2}\left(\exp(-2\,k'_{\mathrm{b}}\,L) - \exp\left(-2\,k'_{\mathrm{b}}\,(L+\Delta L)\right)\right)\end{bmatrix} \quad (31)$$

where $I_{\mathrm{abs,\Delta L,b,Sun}}$, $I_{\mathrm{abs,\Delta L,d,Sun}}$ and $I_{\mathrm{abs,\Delta L,s,Sun}}$ (MJ m^{-2} (ground) h^{-1}) are the direct beam, diffuse, scattered direct irradiance absorbed by the sunlit leaf area of a canopy layer of thickness ΔL at depth L.

Irradiance absorbed by the shaded leaf area of a canopy layer is given by an integral of absorbed irradiance in the shade and the shaded leaf area fraction of that canopy layer. More simply, it is calculated as the difference between the total irradiance absorbed by a layer ($I_{\mathrm{abs,\Delta L,g}}$) given by equation (13), and the irradiance absorbed by the sunlit leaf area of that layer ($I_{\mathrm{abs,\Delta L,Sun}}$) given by equation (31):

$$I_{\mathrm{abs,\Delta L,Sh}} = I_{\mathrm{abs,\Delta L,g}} - I_{\mathrm{abs,\Delta L,Sun}} \quad (32)$$

Irradiance absorbed by the sunlit and shade leaf area of the canopy is given by integrating the irradiance absorbed by sunlit and shaded leaf area over the entire canopy (De Pury and Farquhar, 1997). Irradiance absorbed by the sunlit leaf area of the canopy per unit ground area ($I_{\mathrm{abs,C,Sun}}$, MJ m^{-2} (ground) h^{-1}) is the sum of direct-beam ($I_{\mathrm{abs,c,b}}$, MJ m^{-2} (ground) h^{-1}), diffuse ($I_{\mathrm{abs,c,d}}$, MJ m^{-2} (ground) h^{-1}), and scattered direct ($I_{\mathrm{abs,c,s}}$, MJ m^{-2} (ground) h^{-1}) irradiance absorbed by the sunlit leaf area of the canopy:

$$I_{\mathrm{abs,c,Sun}} = I_{\mathrm{abs,c,b,Sun}} + I_{\mathrm{abs,c,d,Sun}} + I_{\mathrm{abs,c,s,Sun}} \quad (33)$$

with,

$$I_{\mathrm{abs,c,b,Sun}} = \int_{0}^{L_t} I_{\mathrm{abs,L,b}} f_{\mathrm{L,Sun}} dL = I_{\mathrm{inc,b}}(1-\sigma)\left(1-\exp(-\,k'_{\mathrm{b}}L_{\mathrm{t}})\right) \quad (34)$$

$$I_{\mathrm{abs,c,d,Sun}} = \int_0^{L_t} I_{\mathrm{abs,L,d}} f_{\mathrm{L,Sun}} dL = I_{\mathrm{inc,d}}\,(1-\rho_{\mathrm{d}})\big(1-\exp(-(k_{\mathrm{d}}+\,k_{\mathrm{b}}')L_{\mathrm{t}})\big)\frac{k_{\mathrm{d}}}{k_{\mathrm{d}}+k_{\mathrm{b}}'} \quad (35)$$

$$I_{\mathrm{abs,c,s,Sun}} = \int_0^{L_t} I_{\mathrm{abs,L,s}} f_{\mathrm{L,Sun}} dL = I_{\mathrm{inc,b}} \begin{bmatrix} (1-\rho_{\mathrm{b}})\left(1-\exp(-(k_{\mathrm{b}}+k_{\mathrm{b}}')L_{\mathrm{t}})\right)\frac{k_{\mathrm{b}}}{k_{\mathrm{b}}+k_{\mathrm{b}}'} \\ -(1-\sigma)\,\left(1-\exp(-2\,k_{\mathrm{b}}'\,L_{\mathrm{t}})\right)/2 \end{bmatrix} \quad (36)$$

As for the multi-layer sun/shade model, irradiance absorbed by the shaded leaf area of the canopy is calculated as the difference between the total irradiance absorbed by the canopy ($I_{\mathrm{abs,c,g}}$) given by equation (18), and the irradiance absorbed by the sunlit leaf area ($I_{\mathrm{abs,c,Sun}}$) given by equation (40):

$$I_{\mathrm{abs,c,Sh}} = I_{\mathrm{abs,c,g}} - I_{\mathrm{abs,c,Sun}} \quad (37)$$

8. Intercepted direct-beam irradiance by canopies (Strategy: *IntDirectIrradianceCanopy*)

For comparison with observations of green fraction at different angles the fraction of direct irradiance intercepted by canopies ($\mathrm{FIPAR}^{\mathrm{dir}}$) at different elevation angles (θ, radian) is given by:

$$\mathrm{FIPAR}^{\mathrm{dir}} = 1 - \exp(-k_{\mathrm{b}}(\theta)L_{\mathrm{t}}) \quad (38)$$

$\mathrm{FIPAR}^{\mathrm{dir}}$ is calculated for 15°, 30°, 45°, 60°, 75°, 90° elevation angles.

9. Application

Figure 4 shows an example of the daily time course of hourly incident and absorbed irradiance. The absorbed irradiance was calculated for a single layer canopy either by Monsi and Saeki (2005) model of absorbed global irradiance (see Section 5.1.2) or by separating the canopy into sunlit and shade fractions following De Pury and Farquhar (1997; see Section 7.2). *SiriusQuality2* was run at Lincoln, New-Zeland with and without the option 'Use SunShade' in the interface. Irradiance absorption by the canopy was extracted on 27 September 1991 when the green area index was 5.17 m^{-2} (leaf) m^{-2} (ground).

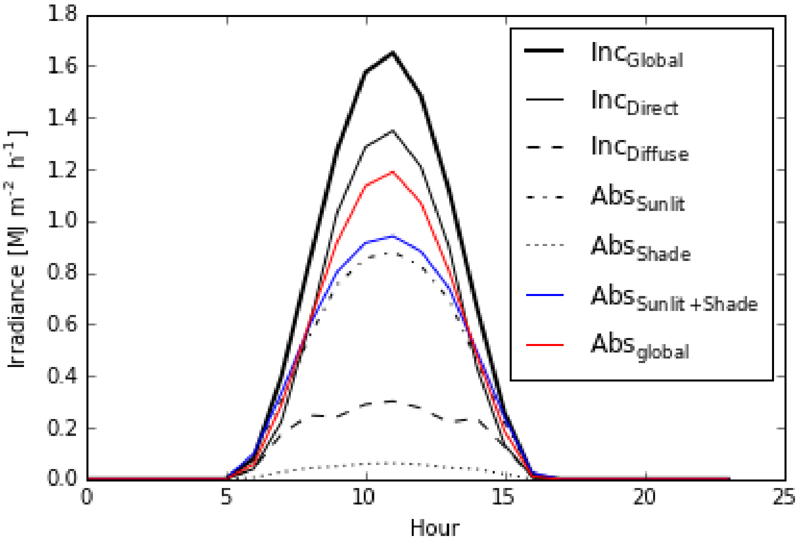

Figure 4. Comparison between the sunlit/shade and global methods for calculating the solar irradiance absorbed by a wheat crop grown in the field at Lincoln, New, Zeland. Absorbed irradiance by the sunlit/shade method was calculated according to de Pury and Farquhar (1997) while that of global irradiance was performed according to Monsi and Saeki (2005). Data are for 27 September 1991 when the green area index was 5.17 m^{-2} (leaf) m^{-2} (ground) (Jamieson et al., 1995). Simulations were done with *SiriusQuality* using the SQ_Irradiance component with the 'SunShadeCanopy' and "GlobalCanopy" options.

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12. Appendix

Table A1. List of variables used in the *SQ-Irradiance* component. In bold output variables of the *SQ-Irradiance* component. Inputs of the component ae in blue, outputs in green

Symbol in this document	**Name in the code**	**Unit**	**Description**	**Strategy or component on which Sq_Irradiance depends**
FLN	FLN	Leaf mainstem^{-1}	Final leaf number of mainstem	SQ-Phenology MeanLeafAngle
TT_{30}	tt30	°Cd	Thermal time accumulated after GS30	SQ-ThermelTime MeanLeafAngle
HS_{30}	hs30	Leaf mainstem^{-1}	Haun stage at growth stage 30	SQ-Phenology MeanLeafAngle
$I_{abs,c,b}$	I_cb_c	MJ m^{-2} (ground) h^{-1}	Absorbed direct irradiance by sunlit leaves of canopies	CalculateAbsDirectDiffuseIradianceCanopy AbsIrradainceSunShadeCanopy
$I_{abs,c,d}$	I_cd_dir	MJ m^{-2} (ground) h^{-1}	Absorbed diffuse irradiance by sunlit leaves of canopies	CalculateAbsDirectDiffuseIradianceCanopy AbsIrradainceSunShadeCanopy
$I_{abs,c,d,Sh}$	absorbedShadedIrradiance	MJ m^{-2} (ground) h^{-1}	Diffuse and scattered diffuse irradiance absorbed by shaded leaves of canopies	AbsIrradianceSunShadeCanopy
$I_{abs,c,g}$	absorbedGlobalIrradiance	MJ m^{-2} (ground) h^{-1}	Absorbed global irradiance by canopies	CalculateGlobalAbsorbedRadiationHourly AbsIrradianceSunShadeCanopy
$I_{abs,c,s}$	I_cs_dir	MJ m^{-2} (ground) h^{-1}	Absorbed scattered irradiance by sunlit leaves of canopies	AbsIrradianceSunShadeCanopy
$I_{abs,c,s,Sh}$	absorbedSunlitIrradiance	MJ m^{-2} (ground) h^{-1}	scattered direct irradiance absorbed by shaded leaves of canopy	AbsIrradianceSunShadeCanopy
$I_{abs,c,Sh}$	absorbedShadedIrradiance	MJ m^{-2} (ground) h^{-1}	Absorbed global irradiance by shaded leaves of canopies	AbsIrradainceSunShadeCanopy
$I_{abs,c,Sun}$	absorbedSunlitIrradiance	MJ m^{-2} (ground) h^{-1}	Absorbed global irradiance by sunlit leaves of canopies	AbsIrradainceSunShadeCanopy
$I_{abs,\Delta L,b}$	I_cb_l	MJ m^{-2} (leaf) h^{-1}	Absorbed beam irradiance by sunlit leaves of a layer of thickness ΔL at depth L	CalculateAbsDirectDiffuseIradianceLayers AbsIrradainceSunShadeLayers
$I_{abs,\Delta L,d}$	I_cd_l	MJ m^{-2} (leaf) h^{-1}	Absorbed diffuse irradiance by sunlit leaves of a layer of thickness ΔL at depth L	CalculateAbsDirectDiffuseIradianceLayers AbsIrradainceSunShadeLayers

Symbol in this document	**Name in the code**	**Unit**	**Description**	**Strategy or component on which Sq_Irradiance depends**
$I_{\mathrm{abs},\Delta\mathrm{L},\mathrm{g}}$	absorbedGlobalIrradianceLayeredHourly	MJ m^{-2} (ground) h^{-1}	Absorbed global irradiance by a layer of thickness ΔL at depth L	CalculateGlobalAbsorbedRadiationHourlyLayers AbsIrradianceSunShadeLayers
$I_{\mathrm{abs},\Delta\mathrm{L},\mathrm{s}}$	I_cs_l	MJ m^{-2} (leaf) h^{-1}	Absorbed scattered irradiance by sunlit leaves of a layer of thickness ΔL at depth L	AbsIrradianceSunShadeLayers
$I_{\mathrm{abs},\Delta\mathrm{L},\mathrm{Sh}}$	absorbedShadedIrradiance	MJ m^{-2} (ground) h^{-1}	Absorbed irradiance by shaded leaves of a layer having of ΔL at depth L	AbsIrradainceSunShadeLayers
$I_{\mathrm{abs},\Delta\mathrm{L},\mathrm{Sun}}$	absorbedSunlitIrradiance	MJ m^{-2} (ground) h^{-1}	Absorbed irradiance by sunlit leaves of a layer of thickness ΔL at depth L	AbsIrradainceSunShadeLayers
$I_{\mathrm{inc},\mathrm{b}}$	incidentDirectIrradiance	MJ m^{-2} (ground) h^{-1}	Incident direct irradiance at the top of the canopy	SQ-Meteo AbsDirectDiffuseIradianceCanopy AbsDirectDiffuseIradianceLayers GlobalAbsorbedRadiationHourlyLayers GlobalAbsorbedRadiationHourly AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers
$I_{\mathrm{inc},\mathrm{d}}$	incidentDiffuseIrradiance	MJ m^{-2} (ground) h^{-1}	Incident diffuse irradiance at the top of the canopy	SQ-Meteo AbsDirectDiffuseIradianceCanopy AbsDirectDiffuseIradianceLayers GlobalAbsorbedRadiationHourlyLayers GlobalAbsorbedRadiationHourly AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers
$I_{\mathrm{inc},\mathrm{g}}$	I_dir + I_dif	MJ m^{-2} (ground) h^{-1}	Incident global irradiance at the top of the canopy	SQ-Meteo
k'_b	k1_dir	m^{-2} (ground) m^{-2} (leaf)	Extinction coefficient of direct irradiance without scattering	DirectExtinctionCoefBlackLeavesSphere DirectExtinctionCoefBlackLeavesEllipse DirectReflectanceCoef DirectExtinctionCoef AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers

Symbol in this document	Name in the code	Unit	Description	Strategy or component on which Sq_Irradiance depends
k_b	k_dir	m^{-2} (ground) m^{-2} (leaf)	Extinction coefficient of direct irradiance with scattering	DirectExtinctionCoef AbsDirectDiffuseIradianceLayers AbsDirectDiffuseIradianceCanopy AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers FractionSunShadeCanopy FractionSunShadeLayers
k_d	k_dif	m^{-2} (ground) m^{-2} (leaf)	Extinction coefficient of diffuse irradiance	DiffuseExtinctionCoef AbsDirectDiffuseIradianceLayers AbsDirectDiffuseIradianceCanopy AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers
L	upperCumGAI	m^{-2} (leaf) m^{-2} (ground)	Cumulative green area index from the top of the canopy	SQ-WheatLAI FractionSunShadeLayers AbsDirectDiffuseIradianceLayes AbsIrradianceSunShadeLayers GlobalAbsorbedRadiationLayers GlobalAbsorbedRadiationHourlyLayers
ΔL	layerGAI	m^{-2} (leaf) m^{-2} (ground)	Green area index of a canopy layer	SQ-WheatLAI FractionSunShadeLayers AbsDirectDiffuseIradianceLayers AbsIrradianceSunShadeLayers GlobalAbsorbedRadiationLayers GlobalAbsorbedRadiationHourlyLayers
L_t	gaiTotal	m^{-2} (leaf) m^{-2} (ground)	Canopy green area index	SQ-WheatLAI DiffusionExtinctionCoef FractionSunShadeCanopy AbsDirectDiffuseIradianceCanopy AbsIrradianceSunShadeCanopy GlobalAbsorbedRadiationHourly IntDirectIrradianceCanopy
β	solarElevation	radian	Solar elevation angle	SQ-Meteo DirectExtinctionCoefBlakLeavesEllipse DirectExtinctionCoefBlakLeavesSphere

Symbol in this document	**Name in the code**	**Unit**	**Description**	**Strategy or component on which Sq_Irradiance depends**
ρ_b	rhoCanopyDir	dimensionless	Reflection coefficient for direct irradiance	DirectReflectanceCoef AbsDirectDiffuseIradianceLayers AbsDirectDiffuseIradianceCanopy AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers
ρ_d	rhoCanopyDif	dimensionless	Reflection coefficient for diffuse irradiance	DiffuseReflectanceCoef AbsDirectDiffuseIradianceLayers AbsDirectDiffuseIradianceCanopy AbsIrradianceSunShadeCanopy AbsIrradianceSunShadeLayers
ρ_h	rho_h	dimensionless	Reflection coefficient for direct irradiance of a canopy having horizontal leaves	DirectReflectanceCoef DiffReflectanceCoef
$\bar{\alpha}$	ala	radian	Mean leaf angle for ellipsoidal distribution	MeanLeafAngle IntDirectIrradianceCanopy DiffusionExtinctionCoef DiffReflectanceCoef DirectExtinctionCoefBlakLeavesEllipse
χ	Chi	dimensionless	Ratio of vertical to horizontal projections of canopy elements	DirectExtincationCoefBlackLeavesEllipse IntDirectIrradianceCanopy DiffusionExtinctionCoef DiffReflectanceCoef
$FIPAR^{dir}$	fiPARb	dimensionless	Fraction of direct intercepted irradiance	IntDirectIrradianceCanopy

Table A2: List of parameters and constants used in the SQ-Irradiance component**.**

Symbol in this document	Name in the code	Nominal value	Unit	Description	Strategy or component on which Sq_Irradiance depends	Type	Reference
C	CI	0.89	dimensionless	Clumping index	DirectExtinctionCoefBlackLeavesSphere DirectExtinctionCoefBlackLeavesEllipse DiffeflectanceCoef DiffusionExctionCoef IntDirectIrradianceCanopy	Non-varietal	(Baret et al., 2010)
k_g	Kl	0.46	m^2 (ground) m^{-2} (leaf)	Extinction coefficient of global irradiance	GlobalAbsorbedRadiationHourlyLayers GlobalAbsorbedRadiationHourly	Varietal	(Thorne et al., 1988)
P	Phyll	100	Leaf °Cd^{-1}	Phyllochrone	SQ-Phenology MeanLeafAngle	Varietal	(He et al., 2012)
τ_{PAR}	tauLeafPAR	0.143	Dimensionless	Leaf transmittance coefficient for PAR	DirectReflectanceCoef DirectExctinctionCoef DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)
τ_{NIR}	tauLeafNIR	0.411	Dimensionless	Leaf transmittance coefficient for NIR	DirectReflectanceCoef DirectExctinctionCoef DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)
ρ_{PAR}	rhoLeafPAR	0.057	Dimensionless	Leaf reflectance coefficient for PAR	DirectReflectanceCoef DirectExctinctionCoef DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)

Symbol in this document	Name in the code	Nominal value	Unit	Description	Strategy or component on which Sq_Irradiance depends	Type	Reference
ρ_{NIR}	rhoLeafNIR	0.389	Dimensionless	Leaf reflectance coefficient for NIR	DirectReflectanceCoef DirectExctinctionCoe DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)
$\sigma_{\mathrm{PAR}} = \tau_{\mathrm{PAR}} + \rho_{\mathrm{PAR}}$	sigma	0.2	Dimensionless	Leaf scattering coefficient for PAR	DirectReflectanceCoef DirectExctinctionCoef DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)
$\sigma_{\mathrm{NIR}} = \tau_{\mathrm{NIR}} + \rho_{\mathrm{NIR}}$	sigma	0.8	dimensionless	Leaf scattering coefficient for NIR	DirectReflectanceCoef DirectExctinctionCoef DiffReflectanceCoef AbsIrradianceSunShadeLayers AbsIrradianceSunShadeCanopy IntDirectIrradianceCanopy DiffusionExtinctionCoef	Non-varietal	(Goudriaan and Van Laar, 1994)
$\bar{\alpha}_{\mathrm{juv}}$	alaJuv	0.806	radian	Mean leaf angle for a ellipsoidal distribution during at terminal spikelet (GS30)	MeanLeafAngle	Varietal	(Liu et al., 2020)
$\bar{\alpha}_{\mathrm{mat}}$	alaMat	1.216	radian	Mean leaf angle for a ellipsoidal distribution at flag leaf ligule (GS39)	MeanLeafAngle	Varietal	(Liu et al., 2020)