*SQ\_Irradiance*: A BioMA-*SiriusQuality* component of big-leaf and sun/shade models of absorbed irradiance of 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 the canopy. Irradiance interception and absorption are calculated either using the global incident solar irradiance, or using direct and diffuse incident irradiance components. In the latter case, calculations are distinguished between sunlit and shaded leaves of the canopy and are performed on an hourly basis. Calculations can be performed considering the canopy as one leaf layer (the so-called big leaf approach) or considering the canopy as distinct vertical layers. The model is integrated in the wheat crop model [*SiriusQuality*2](http://www1.clermont.inra.fr/siriusquality/) as an independent component developed in the public domain software framework [BioMA](http://www.biomamodelling.org/) (Biophysical Model Applications). BioMA is developed using Microsoft C# language in .Net framework (version 4.5). The component was coded using the development environment Microsoft Visual Studio 2013.

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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 leaf area index (, m-2 (leaf) m-2 (ground)) of canopies is a continuous variable with depth (Monsi and Saeki, 1953):

(1)

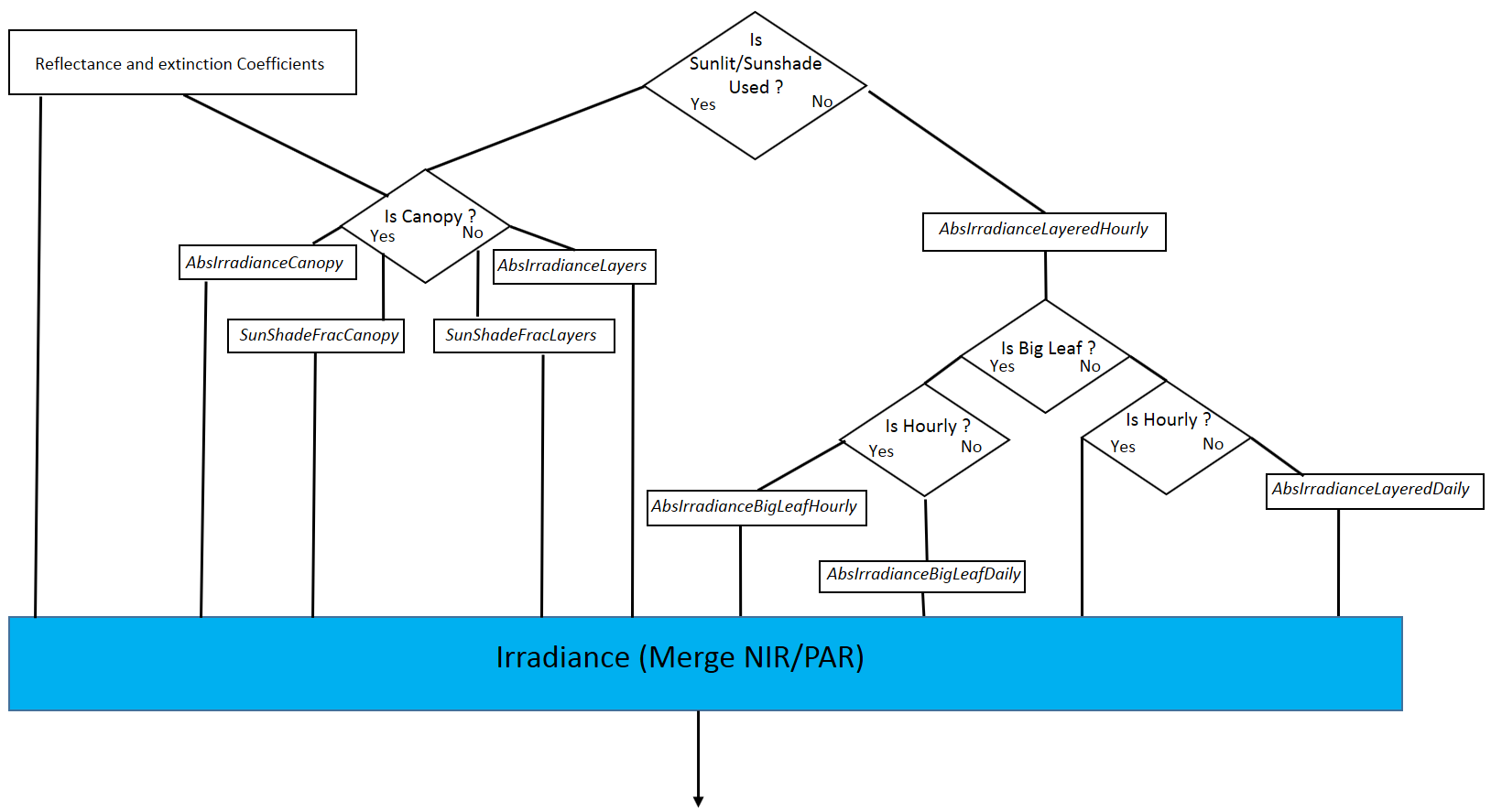
where (MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is the incident global (direct beam and diffuse) photosynthetically active irradiance (PAR) at the top of the canopy, (MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is the intercepted PAR at depth , and (m2 (ground) m-2 (leaf)) is the global irradiance extinction coefficient. The coefficient 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; Keating et al., 2003; Brisson et al., 2003). 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 increase zone 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; Goudriaan, 2016). 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 photosynthetically active (PAR) and near infrared (NIR) wavebands are calculated separately as the diffuse irradiance extinction, scattering, and reflectance coefficients are different for the PAR and NIR wavebands.

1. Overview of the calculation procedures

Figure 1 shows the flowchart of the *SQ\_Irradiance* component. Solar irradiance interception is simulated using either the “average” approach, according to Beer’s law (Monsi and Saeki, 1953), or the sun/shade approach (Goudriaan and van Laar, 1994; de Pury and Farquhar, 1997). Average irradiance absorption (Section 4) can be calculated both at the hourly and daily time step. However, when the direct and diffuse irradiance components are considered separately, either using a big leaf (Section 5) or sun/shade (Sections 7 and 8) approach, calculations can only be performed on an hourly basis. Finally, 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 simulated biomass production may be evaluated.



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| Figure 1. Flowchart of the different strategies in the *SQ\_Irradiance* component.  Figure 3 shows the details of the calculation of reflectance and extinction coefficients. They can be calculated for a spherical or ellipsoidal leaf angle distribution in the canopy. |

Figure 2. Details of the Reflectance and Extinction Coefficient calculation in the *SQ\_Irradiance* component.

Figure 3 shows the flowchart of the calculation procedure of absorbed direct and diffuse irradiance.

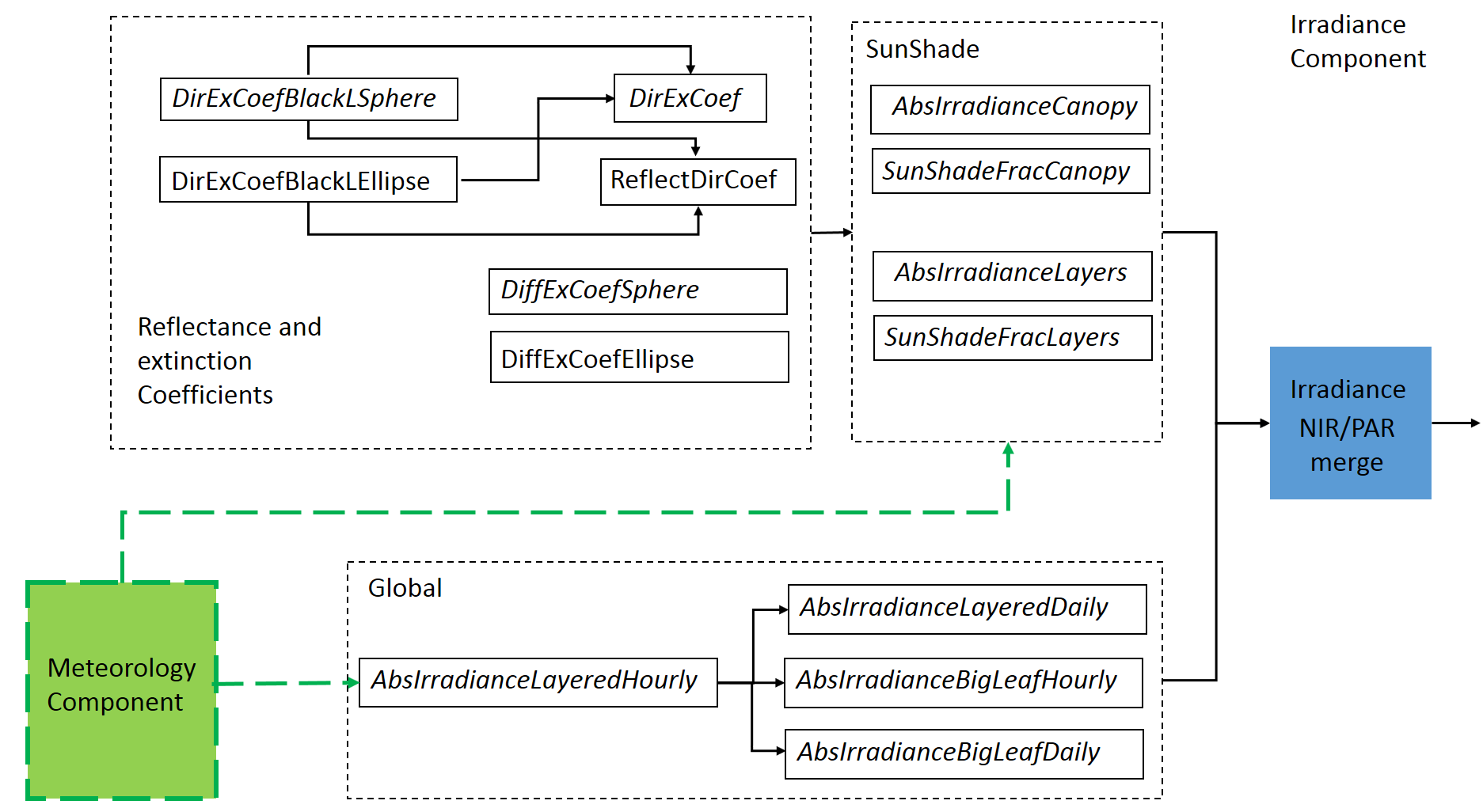
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| Coefficients of extinction of irradiance  Sunlit/shaded leaves fractions  absorbed irradiance per unit area of Sunlit/shaded leaves  Total absorbed irradiance of Sunlit/shaded leaves |
| Figure 3. Flowchart of the calculation procedure of direct and diffuse irradiance components. (dimensionless) is the leaf scattering coefficient, (dimensionless) is the solar elevation, (dimensionless) is the leaf inclination, , , and (m2 (ground) m-2 (leaf)) are the extinction coefficients of direct, combined direct and scattered, and diffuse irradiances, respectively, , and (dimensionless) are the canopy reflectance coefficients for direct and diffuse irradiance components, respectively, (m2 (leaf) m-2 (ground)) is the downward cumulative green area index, (m2 (leaf) m-2 (ground)) is layer thickness of leaf laminae, and (dimensionless) are the leaf fractions of sunlit and shaded leaves, respectively, and (MJ m-2 (ground) h-1) are the incident direct and diffuse PAR irradiance components, respectively, , , and (MJ m-2 (ground) h-1 for canopy calculations and MJ m-2 (leaf) h-1 for calculations per leaf layer) are the absorbed direct, combined direct and scattered, and diffuse irradiance components, respectively, and and (MJ m-2 (ground) h-1) are the total irradiance absorbed by sunlit and shaded leaves, respectively. The symboles , , , , , , and are further distinguished in the text with the suffixes and to indicate calculations at the leaf layer and the entire canopy scales, respectively. |

The calculation procedure of absorbed direct and diffuse irradiances by sunlit and shaded leaf fractions can be summarized as proposed by Hikosaka et al. (2016):

* For each time step the solar elevation is calculated based on the observer’s latitude and day of year (calculations are details in the *SQ\_Meteo* component);
* The solar elevation, together with the sky cover, determine the flux densities of direct and diffuse PAR irradiances that are incident at the top of the canopy (calculations are detailed in the *SQ\_Meteo* component);
* The solar elevation determines the penetration depth of direct-beam and scattered irradiances inside the canopy. The extinction coefficient of direct irradiance is calculated on an hourly basis. In contrast, it is assumed constant for diffuse irradiance since it is independent of solar elevation;
* Direct-beam irradiance reflectance by the canopy varies with solar elevation. It is therefore calculated on an hourly basis. In contrast, reflectance to diffuse irradiance is assumed constant since it is independent of solar elevation;
* Finally, absorbed irradiance by each of sunlit and shaded leaf fractions are calculated.

The calculation procedures for determining the extinction coefficients, reflectance coefficients and absorbed irradiance by sunlit and shaded leaves are given in the following Sections. The equations used therein have been developed and described by Goudriaan and van Laar (1994) for multi-layered canopies and by de Pury and Farquhar (1997) for big-leaf canopies. The reader may refer to these studies for a full description of the theoretical assumptions lying behind equation’s development.

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 Meteorology component which calculates the appropriate weather input from the meteorological files. The composite strategy “Irradiance” compute outputs from both incident Near Infra-Red Radiation and Photosynthetically Active Radiation.



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| **Figure 3.** Shema of the BioMA-*SiriusQuality* *SQ\_Irradiance* component. White boxes are simple strategies, and white boxes are composite or contextual strategies. |

1. Incident global irradiance in the photosynthetically active and near infrared wavebands

The energy of a photon varies with its wavelength but the ratio of energy in PAR to global solar (short-wave) irradiance is relatively constant and is about 0.48 (Varlet-Grancher *et al*., 1982), and we assume that the global NIR irradiance is the difference between the global solar (short-wave) irradiance and the global PAR irradiance. Therefore, the incident global irradiance in the PAR is given (, MJ m-2 (ground) s-1) by:

(2)

where (MJ m-2 (ground) d-1) is the incident global solar radiation

And the incident global NIR irradiance (, MJ m-2 (ground) d-1) is given by:

(3)

and are inputs of the *SQ\_Irradiance* component and are calculated in the *SQ\_Meteo* component.

All equations bellow apply both for the PAR and NIR wavebands and the subscripts PAR and NIR are omitted.

1. Big-leaf model of absorbed global irradiance of canopies

In the PAR domain, green elements of the canopy absorb the majority of the light intercepted. Then the intercepted canopy radiation is considered as a proxy of the absorption. Hence, following the Beer-Lambert’s law, global (direct beam plus diffuse) irradiance absorbed per unit ground area of a leaf layer having a thickness (m-2 (leaf) m-2 (ground)), at depth (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is given as:

(4)

At the canopy level, global irradiance absorbed per unit ground area (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is given by integrating equation (4) relative to , which yields:

(5)

1. Big-leaf model of absorbed direct-beam and diffuse irradiance of canopies

In equation (3) and (4) is assumed constant over time. However, the direct-beam irradiance extinction coefficient changes at an infra-daily scale (see Sections X and X). To include this change in the calculation of (average) global irradiance absorption in the big-leaf model, equations (4) and (5) are 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 (Goudriaan and van Laar, 1994):

(6)

where, and (dimensionless) are the direct-beam and diffuse irradiance reflectance coefficients, respectively; and (m-2 (ground) m-2 (leaf)) are the direct-beam and diffuse irradiance extinction coefficients, respectively; and and (MJ m-2 (ground) h-1) are the direct-beam and diffuse incident irradiance at the top of the canopy. (Note the use of compared to in the sun/shade model (Sections 8 and 9) in order to include irradiance scattering).

For the whole canopy absorbed global irradiance (, MJ m-2 (ground) h-1) is given by:

(7)

1. Direct-beam and diffuse irradiance 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 fraction of leaf area exposed to the sun receives irradiance from direct, diffuse and scattered components, while the fraction of shaded leaf area receives only the diffuse and scattered components. The extinction of direct beam, combined direct beam and scattered, and diffuse irradiances inside the canopy may be estimated using extinction coefficients that are specific to each irradiance type.

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 vanishes as this angle approaches 90° (leaf surface is parallel to solar beam).

* + 1. Spherical leaf angle distribution

Assuming leaves act as perfect black surfaces (i.e. they absorb all the intercepted irradiance), the direct-beam irradiance extinction coefficient (, m2 (ground) m-2 (leaf)) is given by (Goudriaan, 1977):

(8)

where , (rad) is the incident solar zenithal angle (m2 (ground) m-2 (leaf)) is the average projection of all the leaves in the direction of the solar beam given by:

(9)

Where (radians) is the distribution of leaf angles. describe the leaf angle distribution, so that:

(10)

The mean projection of the leaves is given by:

(11)

It one assumes a spherical (uniform or isotropic) leaf angle distribution (that is, the projection is the same in all direction), then equals 0.5, which the ratio between the area of the base of a hemisphere and that of the hemisphere itself, and equation (8) simplifies to (de Wit, 1965, Goudriaan, 1977):

(12)

The extinction coefficient calculated by equation (12) applies only to the case where all leaves are black (i.e. irradiance is neither transmitted through the leaves nor reflected by their surface). Nonetheless, for leaves that have reflectance (, dimensionless) and transmittance ratios that are not null, a part of direct irradiance is scattered. As a result, the extinction 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 (of combined direct and scattered irradiance; , m2 (ground) m-2 (leaf)) is smaller than that of direct-beam irradiance. Goudriaan (1977) showed that the value of is reasonably well approximated by:

(13)

where (dimensionless) is the leaf scattering coefficient, equal to the sum of and the leaf transmittance coefficient. typically equals 0.2 in the PAR () band and 0.8 in the NIR band () and is assumed constant.

The extinction coefficient of diffuse irradiance (, m2 (ground) m-2 (leaf)), is derived assuming that diffuse irradiance decreases exponentially along the canopy depth. So is given as:

(14)

where the coefficients 0.178, 0.514 and 0.308 represent the contributions from the three sky sectors of a standard overcast sky.

* + 1. Ellipsoidal leaf angle distribution

The distribution of leaf angle can be made more general than the spherical model by considering the distribution of area on prolate or oblate spheroids, rather than spheres. By adjusting the ratio of horizontal to vertical axis of the spheroid, leaf angle distributions of any canopy from erectophile to planophile can be simulated (Campbell, 1986). 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 parameter is required, i.e. average leaf angle. An analytical expression of the ellipsoidal distribution function () was derived by Campbell (1990) and is given by:

(15)

where, (dimensionless) is the ratio of vertical to horizontal projections of canopy elements; and is a normalized ellipse area, approximated by:

(16)

is related to through an empirical equation:

(17)

where, (rad) is the average leaf angle. is a genotypic parameter that describe the leaf angle distribution of canopies. Note that when = 1, the ellipsoidal distribution becomes the spherical distribution and then the extinction coefficient can be calculated using equation (12) (Campbell, 1986). changes along the growth cycle, which can be characterized as follows:

(18)

where, represents the cumulative thermal time with the base of zero degree starting from the emergence (). and refers to at stage of start of stem elongation (GS31) and flowering (GS59). and *alpha\_ala* are the minmum average leaf angle and the slope during the growth cycle (unit,rad).

for ellipsoidal leaf angle distribution is calculated following Verhoef (1984, 1998) and is given:

(19)

where (rad) is the half azimuth ranges for which the upper side of a leaf is illuminated Following Verhoef (1984), is given by:

(20)

and (dimensionless) is the probability of leaf angle varying between and :

(21)

Acoording to Verhoef (1984, 1998), it will be sufficient if the leaf angle is discretized into 13 classes (5, 15, 25, 35, 45, 55, 65, 75, 81, 83, 85, 87 and 89 degree).

Alternatively, could be approximately calculated as follows (Campbell 1986; Jones 2013):

(22)

where CI is the clumping index (default = 1). This formula can give good estimation of for average leaf angle and is implemented in *SQ\_Irradiance*. is given by equation (14).

The fraction of direct light intercepted could be calculated as follows:

(23)

* 1. Direct-beam and diffuse irradiance 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 reflection to direct-beam irradiance (, dimensionless) is lowest when the sun is closest to the zenith and highest as solar inclination approaches 0° (sun is grazing over horizontal leaves). is given by (Goudriaan, 1977):

(24)

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

(25)

The reflectance coefficient of diffuse irradiance (, dimensionless) may be deduced using equation (21) by aggregating reflectance coefficients relative to all sky rings (analogously to the method used to calculate from ). However, for simplicity is set to 0.057 in the PAR (), and 0.389 in the NIR () for a spherical leaf angle distribution and under a standard overcast sky (Goudriaan and van Laar, 1994). For the sake of simplicity, we consider the same reflectance coefficients for spherical and ellipsoidal distribution.

1. Sun/shade model of irradiance absorbed by multilayered canopy

Accurate simulation of canopy photosynthesis requires separating leaves into sunlit and shade fractions (Goudriaan and van Laar, 1994). Sunlit leaves are often PAR saturated while shaded leaves are not. As indicated above, sunlit leaves receive irradiance that comes from solar beam and from sky-diffusion, in addition to a “second-hand” direct irradiance scattered by other leaves (scattered-beam). 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 and shaded leaves at depth writes (Spitters, 1986):

(26)

(27)

where and (MJ m-2(leaf) h-1) are the absorbed irradiance by sunlit and shade leaf fractions at depth , respectively; , and (MJ m-2 (leaf) h-1) are the absorbed irradiance from solar beam, sky-diffused and scattered irradiance components, respectively; and and (dimensionless) are sunlit and shaded leaves fractions, respectively.

does not change with depth inside the canopy (all sunflecks receive the same beam irradiance per a unit ground area) and is given as:

(28)

The diffuse irradiance is distributed within the canopy following an exponential trend and is given as:

(29)

Finally, is given by:

(30)

translates the probability that incident direct-beam irradiance may not be intercepted over depths . This fraction 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 follows an exponential extinction curve that is adequately simulated using Beer’s law, by simply replacing the global extinction coefficient () by that of the direct-beam irradiance (Goudriaan and van Laar, 1994):

(31)

is most simply calculated as the leaf fraction that is not sunlit:

(32)

Equations (23) to (29) define the irradiance absorption per unit leaf area at depth . The irradiance absorbed per unit leaf area by a leaf layer of thickness may be calculated by integrating equations (23) to (29)between depths and (Hikosaka et al., 2016):

(33)

(34)

(35)

(36)

(37)

where , and are given in MJ m-2 (leaf) h-1. It follows that absorbed irradiances by sunlit (, MJ m-2 (ground) h-1) and shaded (, MJ m-2 (ground) h-1) leave per unit ground area is given as:

(38)

(39)

and global irradiance absorbed by layer is given by:

(40)

1. Sun/shade model of irradiance absorbed by canopies

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 (, MJ m-2 (ground) h-1) is:

(41)

where , , and are the direct-beam, diffuse, and scattered irradiance absorbed by the sunlit leaf area of the canopy. Note the last three terms are expressed per unit ground area while the terms , and in equation (23) and (19) are per unit leaf area. This is due to the multiplication by *L* directly inside the integrals in equation (39) to (41). Similarly, and are multiplied directly *L* inside the integrals.

The terms , , and are given by de Pury and Farquhar (1997) as:

(42)

(43)

(44)

Irradiance absorbed by the shaded leaf area of the canopy (, MJ m-2 (ground) h-1) is most simply given as the difference between the total irradiance absorbed by the canopy (, MJ m-2 (ground) h-1) and the irradiance absorbed by sunlit leaf area (equation 30):

(45)

Where,

Finally, the fractions of sunlit (, dimensionless) and shaded (, dimensionless) leaf area of the canopy, are needed for biomass and energy balance calculations in order to calculate irradiance absorbed per unit leaf area. These fractions are given as:

(46)

(47)

1. Global solar radiation Absorbed by canopies

Global solar (short-wave) irradiance absorbed by a leaf layer having a thickness ( , MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is given by the sum of the global irradiance absorbed in the PAR (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) and NIR (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) bands calculated separately:

(48)

Similarly, global solar (short-wave) irradiance absorbed by the canopy PAR (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) is given by the sum of the global irradiance absorbed in the PAR (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) and NIR (, MJ m-2 (ground) d-1 or MJ m-2 (ground) h-1) bands calculated separately:

(49)

1. Global irradiance intercepted and absorbed in the photosynthetically active and near infrared wavebands

The fraction of global solar radiation intercepted by a leaf layer (, dimensionless less) is calculated as:

(50)

The fraction of global solar radiation intercepted by the canopy (, dimensionless less) is calculated as:

(51)

The fraction of net longwave radiation absorbed by a leaf layer (, dimensionless) is given as:

(52)

The fraction of net longwave radiation absorbed by the canopy (, dimensionless) is given as:

(53)

1. Application example at the canopy scale for hourly calculations

Figure3 shows an example of the daily time course of irradiance calculated with the canopy-based absorbed irradiance simulated either by considering the “average” global irradiance absorption (see Section ‎3), or by separating the canopy into sunlit and shade fractions (see Section ‎0). *SiriusQuality2* was run at Lincoln, New-Zeland (treatment RS01; Jamieson et al., 1995) 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).

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| **Figure 4.** Comparison between the sunlit/shade (see Section ‎0) and global (see Section ‎3) methods for calculating the solar irradiance absorbed by the canopy. 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 (1953). |

1. Acknowledgements

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1. Appendix

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| **Table A1.** List of variables used in *SQ-Irradiance* component. A “-“ symbol in unit column means the variable is not used in the options proposed. | | | | | | | | | |
| **Symbol** | **Name in the code** | **Unit** | | | **Description** | | **Equation** | | **Strategy** |
|  |  | **Daily basis** | **Hourly basis** |  | |  | |  | |
|  | absorbedGlobalIrradiance |  |  | Absorbed irradiance by the entire canopy | | (5)(7)(45) | |  | |
|  | I\_cb\_c |  |  | Absorbed beam irradiance by sunlit leaves of the entire canopy | | (42) | |  | |
|  | I\_cd\_dir |  |  | Absorbed diffuse irradiance by sunlit leaves of the entire canopy | | (41)(43) | |  | |
|  | I\_cs\_dir |  |  | Absorbed scattered irradiance by sunlit leaves of the entire canopy | | (41)(44) | |  | |
|  | absorbedShadedIrradiance |  |  | Absorbed irradiance by shaded leaves of the entire canopy | | (45) | |  | |
|  | absorbedSunlitIrradiance |  |  | Absorbed irradiance by sunlit leaves of the entire canopy | | (41)(45) | |  | |
|  | I\_cb\_l |  |  | Absorbed beam irradiance by sunlit leaves at depth | | (26)(28)(35)(42) | |  | |
|  | - |  |  | Absorbed beam irradiance by sunlit leaves of a layer having a thickness , located just beneath a depth | | (35)(38) | |  | |
|  | I\_cd\_l |  |  | Absorbed diffuse irradiance by sunlit leaves at depth | | (26)(27)(29)(43) | |  | |
|  | - |  |  | Absorbed diffuse irradiance by sunlit leaves of a layer having a thickness , located just beneath a depth | | (36)(38)(39) | |  | |
|  | I\_cs\_l |  |  | Absorbed scattered irradiance by sunlit leaves at depth | | (26)(27)(30)(44) | |  | |
|  | - |  |  | Absorbed scattered irradiance by sunlit leaves of a layer having a thickness , located just beneath a depth | | (37)(38)(39) | |  | |
|  | absorbedShadedIrradiance |  |  | Absorbed irradiance by shaded leaves at depth | | (32) | |  | |
|  | - |  |  | Absorbed irradiance by shaded leaves of a layer having a thickness , located just beneath a depth | | (39)(40) | |  | |
|  | absorbedSunlitIrradiance |  |  | Absorbed irradiance by sunlit leaves at depth | | (26) | |  | |
|  | - |  |  | Absorbed irradiance by sunlit leaves of a layer having a thickness , located just beneath a depth | | (38)(40) | |  | |
|  | - |  |  | Absorbed global irradiance by a layer having a thickness located beneath a depth | | (4)(6)(40) | |  | |
|  | - |  |  | Absorbed net shortwave irradiance by the canopy | | (49)(51) | |  | |
|  | - |  |  | Absorbed net shortwave irradiance by a layer having a thickness located beneath a depth | | (48)(50) | |  | |
|  | absorbedGlobalIrradiancePAR |  |  | Absorbed PAR irradiance by the canopy | | (49)(51) | |  | |
|  | absorbedGlobalIrradiancePAR |  |  | Absorbed PAR irradiance by a layer having a thickness located beneath a depth | | (48)(50) | |  | |
|  | absorbedGlobalIrradianceNIR |  |  | Absorbed NIR irradiance by the canopy | | (49)(51) | |  | |
|  | absorbedGlobalIrradianceNIR |  |  | Absorbed NIR irradiance by a layer having a thickness located beneath a depth | | (48)(50) | |  | |
|  | incidentDirectIrradiance |  |  | Incident direct irradiance at the top of the canopy | | (6)(7)(30)(37) (42) | |  | |
|  | incidentDiffuseIrradiance |  |  | Incident diffuse irradiance at the top of the canopy | | (6)(7)(29)(36) (43) | |  | |
|  | - |  |  | Incident net shortwave irradiance at the top of the canopy | | (2)(3)(51) | |  | |
|  | - |  |  | Incident global irradiance at the top of the canopy | | (1)(4)(5) | |  | |
|  | - |  |  | Intercepted global irradiance beneath depth | | (1) | |  | |
|  | ShadeFraction |  |  | Shaded leaves fraction of the entire canopy | | (47) | |  | |
|  | SunlitFraction |  |  | Sunlit leaves fraction of the entire canopy | | (46)(47) | |  | |
|  | ShadeFraction |  |  | Shaded leaves fraction at depth | | (27)(32) | |  | |
|  | - |  |  | Shaded leaves fraction of a layer having a thickness , located just beneath a depth | | (34)(39) | |  | |
|  | SunlitFraction |  |  | Sunlit leaves fraction at depth | | (26)(31)(32)(42) (43)(44)(46) | |  | |
|  | - |  |  | Sunlit leaves fraction of a layer having a thickness , located just beneath a depth | | (33)(34)(38) | |  | |
|  | k1\_dir |  |  | Extinction coefficient of direct irradiance without scattering | | (8)(12)(13)(14) (22)(23)(24)(28) (30)(31)(33)(37) (42)(43)(44)(46) | |  | |
|  | k\_dir |  |  | Extinction coefficient of direct irradiance with scattering | | (6)(7)(13)(30) (37)(44) | |  | |
|  | k\_dif |  |  | Extinction coefficient of diffuse irradiance | | (6)(7)(29)(36) (43)(52)(53) | |  | |
|  | upperCumGAI, lowerCumGAI |  |  | Cumulative leaf area index | | (4)(6)(29)(30) (33)(36)(52) | |  | |
|  | gaiTotal |  |  | Total cumulative leaf area index | | (1)(5)(7)(14)(23) (42)(43)(46)(53) | |  | |
|  | - |  |  | Photosynthetically active irradiance | | (2)(3) | |  | |
|  | - |  |  | Near Infra-Red Radiation | | (3) | |  | |
|  | - |  |  | Leaf inclination angle | | (9)(10)(11)(15) (19)(20)(21) | |  | |
|  | solarElevation |  |  | Angle of solar declination | | (8)(9)(11)(12)(19)(20)(22) | |  | |
|  | layerGAI |  |  | Layer thickness (only leaf laminae, sheaths surface is not considered) | | (4)(6)(33)(36) (37)(38)(39) | |  | |
|  | rhoCanopyDir |  |  | Reflection coefficient for direct irradiance | | (24)(30)(37)(44) | |  | |
|  | rho\_h |  |  | Reflection coefficient for direct irradiance of a canopy having horizontal leaves | | (25) | |  | |
|  | - |  |  | The fraction of global solar radiation intercepted by the canopy | | (51) | |  | |
|  | - |  |  | The fraction of global solar radiation intercepted by a leaf layer | | (50) | |  | |
|  | - |  |  | The fraction of net longwave radiation absorbed by the canopy | | (53) | |  | |
|  | - |  |  | The fraction of net longwave radiation absorbed by a leaf layer | | (52) | |  | |
|  | ala |  | rad | Mean Leaf angle for ellipsoidal distribution | | (17)(18) | |  | |
|  | - |  |  | Probability of leaf angle varying between and for an ellipsoidal distribution | | (21) | |  | |
|  | - |  |  | Density probability of leaf angle ellipsoidal distribution | | (9)(10)(15)(21) | |  | |
|  | Chi |  |  | Ratio of vertical to horizontal projections of canopy elements | | (15)(16)(17)(22) | |  | |
|  | - |  |  | Normalized ellipse area | | (16) | |  | |
|  | - |  |  | Mean projection of the leaves | | (8)(9)(11) | |  | |
|  | - |  | rad | half azimuth ranges | | (19)(20) | |  | |
|  | fiPARb |  |  | Fraction of direct intercepted light | | (23) | |  | |
|  | TT |  | °Cd | Physiological thermal time | | (18) | |  | |
|  | TTGS31 |  | °Cd | Physiological thermal time at stem elongation | | (18) | |  | |
|  | TTGS59 |  | °Cd | Physiological thermal time at Anthesis | | (18) | |  | |

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Table A2:** List of parameters and constants used in the *SQ-Irradiance* component**.** | | | | | |
| **Symbol** | **Name in the code** | **Nominal value** | **Unit** | **Description** | **Equation** | |
|  | Kl | 0.45 | m2 (ground) m-2 (leaf) | Global irradiance extinction coefficient | (1)(4)(5) | |
|  | - | 0.178 | m2 (ground) m-2 (leaf) | Extinction coefficient of diffuse irradiance that originates from a sky ring at 15°C declination angle. Diffuse irradiance in this case is treated as direct beam irradiance. | - | |
|  | - | 0.514 | m2 (ground) m-2 (leaf) | Extinction coefficient of diffuse irradiance that originates from a sky ring at 45°C declination angle. Diffuse irradiance in this case is treated as direct beam irradiance. | - | |
|  | - | 0.308 | m2 (ground) m-2 (leaf) | Extinction coefficient of diffuse irradiance that originates from a sky ring at 75°C declination angle. Diffuse irradiance in this case is treated as direct beam irradiance. | - | |
|  | - | 0.5 | m2 (ground) m-2 (leaf) | Average projection of leaves in the direction of beam irradiance assuming spherical leaf angle distribution | - | |
|  | rhoLeaf | 0.07 |  | Leaf reflectance coefficient in the PAR | (6)(7)(29)(43) | |
|  | rhoLeaf | 0.389 |  | Leaf reflectance coefficient in the NIR | (6)(7)(29)(43) | |
|  | rhoCanopyDiffPAR | 0.057 |  | Leaf Reflectance Coefficient for PAR in Canopy |  | |
|  | rhoCanopyDiffNIR | 0.389 |  | Leaf Reflectance Coefficient for NIR in Canopy |  | |
|  | tauLeafPAR | 0.143 |  | Leaf transmittance coefficient in the PAR | (14)(25)(28)(42)(44) | |
|  | tauLeafNIR | 0.389 |  | Leaf transmittance coefficient in the NIR | (14)(25)(28)(42)(44) | |
|  | alaMin | 0.46 | rad | Minimum mean leaf angle for a ellipsoidal distribution during the growth cycle | (18) | |
| alpha\_ala | alpha\_ala | 0.46 | Rad/°Cd | Slope of the mean leaf angle for a ellipsoidal distribution during the growth cycle | (18) | |
| CI | CI | 1.0 |  | Clumping Index | (22) | |

The value of the parameters is extracted from:

-Campbell, G. (1986). Extinction coefficients for radiation in plant canopies calculated using an ellipsoidal inclination angle distribution. *Agricultural and Forest Meteorology, 36*, 317-321

-Jones, H.G. (2013). *Plants and microclimate: a quantitative approach to environmental plant physiology*. Cambridge university press