

STICS intercrop: a work in progress for the ReMIX H2020 project

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Contents

Chapter 1

Prerequisites

Each chapter of the book match a specific objective. I first introduce the subject with a brief description, try to find some solutions for the specific issues and show the results.

The code is only visible on the `html` version of the book, so please refer to this format if you need any further information (open the `index.html` file).

This book is written using the R **bookdown** package, which can be installed from CRAN or Github:

To compile this example to PDF, you need XeLaTeX. You are recommended to install TinyTeX (which includes XeLaTeX): <https://yihui.name/tinytex/>.

Chapter 2

Light Interception

2.1 Introduction

In STICS, the light interception is either computed using a simple Beer law assuming a homogeneous, turbid canopy, or a radiation transfer model that consider the plants leaf area index, canopy shape, height and density. The Beer law option is very simple but generally fairly accurate for high density homogeneous crops, but may rapidly yield unsatisfying predictions for stands with higher structural complexity (e.g. perennial plantations or mixed crops). For mixed crops, the model uses the radiation transfer model in a particular manner that is described in further details below.

For the case of intercrops, the model first set the taller crop as “dominant”, and the shorter crop as “dominated”. The model then compute the radiation interception of each one according to the dominancy, the structure (height, width, light extinction coefficient...) and position (interrow distance, row orientation) of the species. Of course, the dominancy of each plant species can be inverted if the dominated plant become taller than the dominant plant, and the model checks every day for such a case.

To facilitate understanding, we will use a common intercrop example throughout the whole document. We take a mixed crop simulated for the day of the year 1 with a global radiation of 25 MJ m⁻² day⁻¹ (= 12 MJ m⁻² day⁻¹ of PAR), and a diffuse fraction of light of 0.4, an interrow spacing of 1 meter, a shape of 1 (1= rectangle, 2= upside triangle and 3= downside rectangle), a canopy width of 0.2 meter, a canopy thickness of 0.1 meter, a row orientation of 0 relative to the North-South axis at latitude 43.61 degrees north, an LAI of 2, a light extinction coefficient of 0.2. The canopy of the dominant plant is 1 meter above the dominated plant. All code used in this document can be viewed in each section by clicking on the **Code** button on the right.

2.2 Plant shape

Each plant radiation interception is computed using an approximation of its shape (**P_forme**= 1, rectangle, = 2 upside triangle, = 3 downside triangle), leaf area index (**lai** or **p(i)%lai(ens,n)**), height, width, density at emergence and leaf area density (**dfol**).

2.2.1 Plant width computation

First, the plant width is computed using the **formplante** function. This computation is possible thanks to the relationship between two ways for computing the plant leaf area, where one of them uses the plant width:

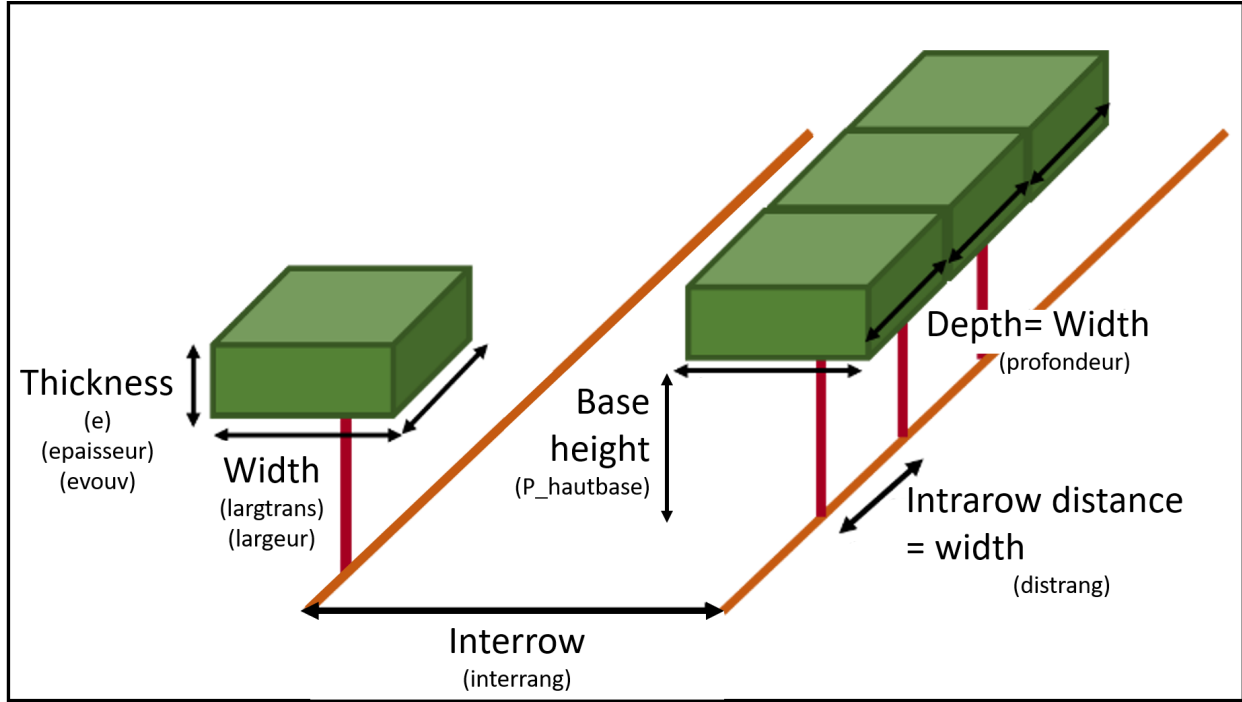


Figure 2.1: Diagram representing the different parameters used to compute plant width. The different names used in the model are shown between parenthesis

- First, assuming the plant has a square footprint (i.e. plant projection is square), we can find the plant leaf area using the leaf area index (**lai**) and the plant density:
 $LA = \frac{(lai + laisen + eai)}{densite}$ which is the equivalent to: $LA = (lai + laisen + eai) \cdot interrang \cdot distrang$
 where **lai** is the leaf area index, **laisen** is the senescent leaf area index, **eai** is the equivalent leaf area of the photosynthetic organs that are not leaves (e.g. flower buds), **interrang** is the inter-row spacing and **distrang** the intra-row distance.
- Second, using the leaf area density and the plant volume such as:
 $LA = dfol \cdot largeur \cdot epaisseur \cdot profondeur$ for a cuboid and $LA = dfol \cdot \frac{1}{2} \cdot (largeur \cdot epaisseur \cdot profondeur)$ for a triangular prism, where **dfol** is the leaf area density, **largeur** is the **plant width** (also called **largtrans**), **epaisseur** is the plant thickness and **profondeur** is the plant depth.

Knowing both equations, and assuming the two following hypothesis:

1. The plant depth is equal to the plant width
2. The intra-row distance between two plants is equal to the plant width

We can now compute the plant width as:

$$largeur = \sqrt{\frac{(lai + laisen + eai) \cdot interrang}{dfol \cdot varrapforme}}$$

where **varrapforme** (or **raptrans** further) is the ratio between the plant thickness and width and is computed as $varrapforme = \frac{(hauteur - P_{hautbase})}{largeur}$ where **hauteur** is the total plant height, **P_hautbase** is the plant (i.e. crown) base height and **largeur** is the plant width (see fig ?? for more details)

Table 2.1: Variable name modification in the formplante function

Original	Modified	Definition
hauteur	hauteur	Height
largeur	largtrans	Width
varrapforme	raptrans	Thickness/Width Ratio
enouv	enouv	Thickness

2.2.2 Plant width correction

If the dominated plant is higher than the base height of the dominant plant, the radiation interception of the dominant plant is partially reduced, by reducing the volume that can intercept light to the canopy volume above the dominated plant only. This correction is made to consider the competition for light between the two species, and is computed according to the shape of the plant.

Consequently, the model first compute the height of the dominated plant (`sc%originehaut`) by looking for the maximum height between the sunlit and shaded part of the dominated plant:

`sc%originehaut = max(p(i+1)%hauteur(sc%A0),p(i+1)%hauteur(sc%AS))`

`sc%originehaut` is fixed to 0 (= soil) while computing the dominated plant.

Hence, the new thickness (`enouv`) is computed as: $enouv = largeur \cdot |varrapforme| + hauteurzero$, and is used to re-compute the shape of the plant:

- The new thickness to width ratio (`raptrans`, formerly `varrapforme`): $raptrans = \frac{enouv}{largeur}$ for rectangle shaped plants,
- The new width (`largtrans`, formerly `largeur`): $largtrans = \frac{enouv}{varrapforme}$ for upsided triangle shaped plants,
- The new width (`largtrans`, formerly `largeur`): $raptrans = \frac{enouv}{largtrans}$ for downsided triangle shaped plants,

All variable names are changed, whether there is a correction or not. Here is a summary table:

Upside triangle is a triangle with its base at the bottom, while downside triangle is a triangle with the base at the top.

The correction of the shape of the plant can be summarised in the diagram Presented in Figure ??.

The correction of the shape of the plant is only used to compute the light transmitted to a plane at the dominated plant or soil height. The targeted plant interception is computed using its whole leaf area index and a light extinction coefficient.

2.2.3 Plant height

The plant height is simply computed using the plant base height, its width, and the thickness to width ratio:

$$hauteur = P_{hautbase} + largeur \cdot |varrapforme|$$

So indirectly, the plant height depends on its LAI, because the plant width is computed using it in the first place. This formalism maybe not optimal, because the plant `height` and LAI are not well related during advanced plant physiological stages.

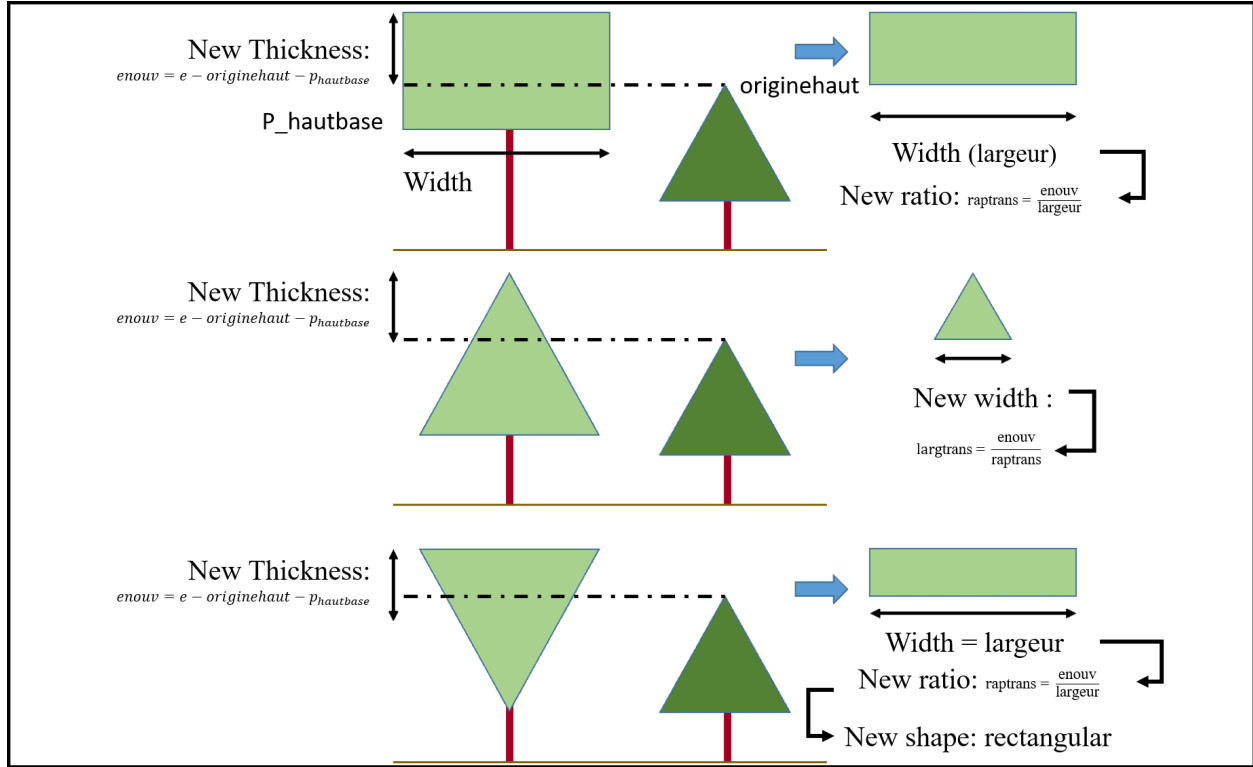


Figure 2.2: Competition for radiation interception of the dominant plant induced by a high dominated plant

2.3 Light interception

The light intercepted by a plant species is obtained by computing the light reaching a horizontal plane below its canopy, either at the height of the dominated plant (for the dominant plant) or the soil (for the dominated plant). Therefore, the light incident on this plane is either coming from:

- The incident light coming from the atmosphere, divided into two components, namely the diffuse and direct light. This light is called **rdroit** in the model,
- The light transmitted by the dominant crop, which is called **rtrans**, and that is generally of lower quality for photosynthesis. The effect of light quality is wrapped in the equivalent density formalism, see Chapter ?? for more details.

Consequently, numerous points (20, or 200 if the inter-row is lower than 1 m) are equally distributed every meter along the inter-row (*i.e.* one point every 5 cm, or every 0.5 cm with 200 points), at the height of the plane. These points are used to discretize the computation of the incident light at the surface of the plane. Hence, the total number of points to simulate is computed using the **interval** parameter, which is equal to 200 if the inter-row is lower than 1 meter or 20 if more. It is then used to compute the total number of points to simulate as: $N_{points} = \frac{ir}{2} \cdot interval$

In practice, the model really simulates only half of the inter-row, because it is considered that the other half have the same light conditions at daily time-scale. For example, if we take an interrow of 10 meters, the model simulates 100 points equally distributed from 0 to 5 meters.

Here is an example of the X position on the plane, starting from the left-hand side of the row, using an inter-row spacing of 1 meter and a plant width of 0.2 meter:

```

if(ir<1.0){
  interval = 200
}else{
  interval = 20.
}
i= 1:(ir / 2 * interval)
x= (i-1) / interval
cat(paste("x=", paste(x, collapse = ", ")))

```

x= 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45

The points are then divided into two groups :

- The sunlit points, which are located directly under the crown of the targeted crop.
- The shaded points, which are not directly under the crop crown, *i.e.* they have the sky above them.

Then the semi-hemisphere above each point is discretized onto 2 x 23 angles: 23 angles from top to right, and 23 angles from top to left. These angles are used to compute `kgdiffus`, the atmospheric diffuse radiation incident to the X point. However, if the X point is below the targeted crop canopy ($X < 1/2$), only the 23 angles from the top to the right are used to compute `kgdiffus` (considering that Xs are only computed from the left-hand plants row until the middle of the inter-row, see fig.?? for more details).

The model determines the two angles (θ_1 and θ_2) between which the point only receive incident light coming from the atmosphere (`rdroit`). Using these two angles (or their tangent, G), the model computes:

1. The daily direct radiation (i.e. cumulated hourly radiation) that is incoming only during the time period between two hours (`h1` and `h2`) when the sun angle is between θ_1 and θ_2 . Function `kgeom` called in `rtrans`.
2. The incident diffuse radiation for all angles between θ_1 and θ_2 . Function `kdifff` called in `rtrans`.
3. The light transmitted to the plane by the target crop for all angles below θ_1 or above θ_2 .

In practice, all points with an x position lower than $\frac{\text{largeur}}{2}$ are shaded, and all other are sunlit, so the model computes the diffuse radiation coming from the atmosphere only for one quarter of the hemisphere for shaded Xs ; the other quarter will receive transmitted light because all angles are superior to θ_2 .

Main functions used are `transrad`, `rtrans`, `kdifff` and `kgeom`.

The position of θ_1 and θ_2 (and their tangent) depends from three components: the crop shape, its inter-row spacing, and the sun azimuth (see fig. ??).

2.3.1 Incident direct radiation from the atmosphere

The incident direct radiation for each X point is computed for all angles of the hemisphere between θ_1 and θ_2 (see ??), and summed up to integrate the semi-hemisphere of each point.

Here is an example of the computation of the direct proportion received at each X point for a crop using the `kgeom()` function:

Where θ_1 and θ_2 are the angles visible in fig.3 and `kgdirect` the proportion of the semi-hemisphere that receive direct light, considering sun position throughout the day by using stand latitude, day of year and row orientation. In the model, θ_1 and θ_2 are computed in radian relative to the vertical plane above X. To provide a simpler representation, θ_1 and θ_2 are also given in degrees relative to the horizontal plane (i.e. soil or dominated plant species surface) in tab.??.

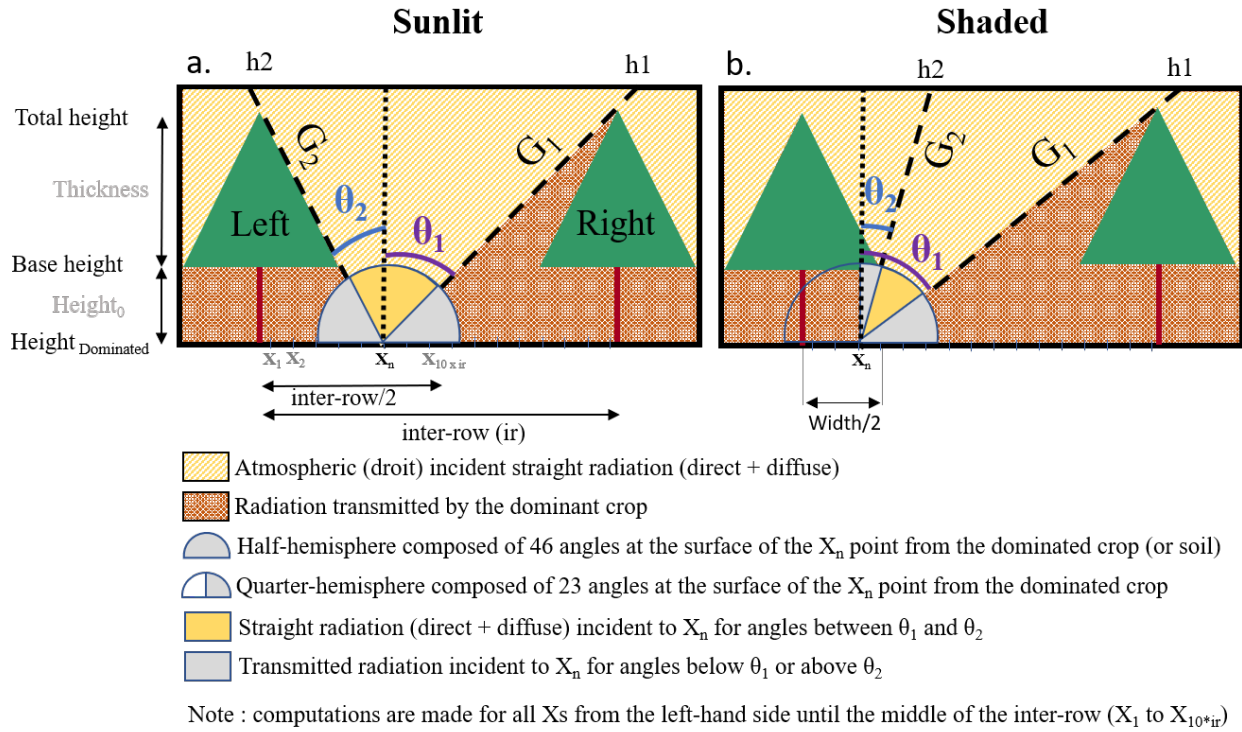


Figure 2.3: Diagram of the computation workflow of STICS for radiation interception for two X points placed above the dominated plant species. a. The X point is considered sunlit; b. The X point is considered shaded (right under the dominant plant canopy), so only the right-hand side of the semi-hemisphere is computed for atmospheric radiation

Table 2.2: Example of the computation of the incident direct radiation ratio kgdirect. See introduction section for further details on the crop.

X index	X value (m)	Theta 1 (rad)	Theta 2 (rad)	Theta 1 (deg)	Theta 2 (deg)	kgdirect
1	0.00	-0.7563093	0.1163553	46.66667	83.33333	0.2850744
2	0.05	-0.7563093	0.0581776	46.66667	86.66667	0.3140484
3	0.10	-0.6981317	0.0000000	50.00000	90.00000	0.3213938
4	0.15	-0.6981317	-0.0581776	50.00000	93.33333	0.3504662
5	0.20	-0.6399541	-0.1163553	53.33333	96.66667	0.3566258
6	0.25	-0.6399541	-0.1745329	53.33333	100.00000	0.3854034
7	0.30	-0.5817764	-0.2327106	56.66667	103.33333	0.3900624
8	0.35	-0.5235988	-0.2908882	60.00000	106.66667	0.3934016
9	0.40	-0.4654211	-0.2908882	63.33333	106.66667	0.3678012
10	0.45	-0.4654211	-0.3490659	63.33333	110.00000	0.3954097

Table 2.4: Example of the computation of the incident diffuse radiation ratio `kgdiffus`. See introduction section for further details on the crop.

X index	kgdiffus
1	0.3489
2	0.3489
3	0.3489
4	0.4061
5	0.3864
6	0.3864
7	0.3864
8	0.4023
9	0.4023
10	0.3624

2.3.2 Incident diffuse radiation from the atmosphere

The incident diffuse radiation for all angles between θ_1 and θ_2 is computed using `G`, the apparent tangent to the considered θ . First the model computes it for θ_1 , and uses it as a threshold under which no diffuse radiation comes from the atmosphere because only transmitted radiation reaches this angle for the considered X point. Second, the model tests if the X point is below the target crop canopy, and if not it computes `G` for θ_2 , and applies the same methodology, with `G` being the upper threshold this time. This method avoids computing the left-hand quarter of the hemisphere since it receives only transmitted light necessarily if it is under the targeted crop.

Here is an example of the computation of the diffuse proportion received at each X point for the same crop as above (interrow= 1 meter, width= 0.2 meter, thickness= 0.1 meter, height= 1 meter) using the `kdif()` function:

Table 2.3: Computation of the diffuse light incident on each point x. Ten first rows only, for the full data, please refer to the html version of this book

X index	X value (m)	angle	G1 (tangent)	G2 (tangent)	hcrit	kgdiffus
1	0	1	1.222222	NA	14.51577	0.000
1	0	2	1.222222	NA	46.56057	0.000
1	0	3	1.222222	NA	50.56789	0.000
1	0	4	1.222222	NA	42.35117	0.000
1	0	5	1.222222	NA	26.22654	0.000
1	0	6	1.222222	NA	35.69363	0.000
1	0	7	1.222222	NA	49.29501	0.000
1	0	8	1.222222	NA	0.00000	0.014
1	0	9	1.222222	NA	49.29501	0.000
1	0	10	1.222222	NA	35.69363	0.000

The total diffuse radiation incident to each point X is simply the cumulative of each angle:

2.3.3 Total diffuse and direct radiation from the atmosphere incident to each X point

The total radiation from the atmosphere incident to each X point is computed by using the incident diffuse (`rdif`) and direct (`rdirect`) radiation coming from the atmosphere weighted respectively by the previously

Table 2.5: Example of the computation of the total incident radiation ratio. See introduction section for further details on the crop.

X index	X value (m)	Total incident ratio	Atmospheric ratio (rdroit)	Transmitted ratio (rtransmis)	Light environ
1	0.00	0.7727202	0.3106046	0.4621155	Shaded
2	0.05	0.7784515	0.3279890	0.4504624	Shaded
3	0.10	0.7799044	0.3323963	0.4475082	Sunlit
4	0.15	0.7931983	0.3727197	0.4204785	Sunlit
5	0.20	0.7918188	0.3685355	0.4232833	Sunlit
6	0.25	0.7975112	0.3858020	0.4117092	Sunlit
7	0.30	0.7984328	0.3885975	0.4098354	Sunlit
8	0.35	0.8011901	0.3969610	0.4042292	Sunlit
9	0.40	0.7961262	0.3816007	0.4145254	Sunlit
10	0.45	0.7963256	0.3822058	0.4141198	Sunlit

computed `kgdiffus` and `kgdirect` as follow: $rdroit = (kgdiffus \cdot rdif) + (kgdirect \cdot rdirect)$

2.3.4 Light transitted by the dominant crop to the X points

The light transmitted by the dominant crop to the dominated crop (`rtransmis`) is computed using the total radiation from the atmosphere incident to each X point (`rdroit`) and the effective targeted plant leaf area index as follow:

$$rtransmis = (1.0 - rdroit) \cdot e^{-P_{ktrou} \cdot (lai + eai)}$$

where P_{ktrou} is the targeted plant light extinction coefficient, `lai` the plant leaf area index, and `eai` the equivalent leaf area index, which represent the photosynthetic surface that is not from leaves (e.g. wheat ears, rapeseed pods, pea pods or grapes during their green stage).

2.3.5 Total light incident to X points

The total light incident to each X point is the sum of the three components: atmospheric diffuse light, atmospheric direct light and transmitted light by the dominant crop. Taking our previous example again, this computation leads to:

The Total incident ratio is computed as: `Total incident ratio= rdroit+rtransmis`. It is the proportion of the incident lighth from the atmosphere that reach the point on the plane below the plant canopy. This light either comes directly from the sky (`rdroit`) or passing through the plant canopy (`rtransmis`). Consequently, the first point X of our example that is right under the plant canopy receives in average `incident_light$Total[1]*100%` of the light coming from the atmosphere: `incident_light$rdroit[1]*100%` of the light directly from the sky (either direct or diffuse light) + `incident_light$rtransmis[1]*100%` of the light that is transmitted by the plant above.

2.3.6 Total radiation incident to the plane

After computing the total incident ratio for each point, the model averages the values between the so-called sunlit and shaded components. Each point positioned right under the plant canopy is considered shaded, and all other is considered sunlit (see fig. ??). using our previous example, this computation gives:

Finally, both ratios are used to compute the intercepted PAR `raint` (MJ m⁻² d⁻¹) of the target plant as:

$$raint = P_{parsurg} \cdot trg \cdot (1 - (rombre \cdot surfAO) - (rsoleil \cdot surfAS))$$

where $P_{parsurg}$ is a coefficient to compute PAR (Photosynthetically Active Radiation) from the global

Table 2.6: Example of the computation of the total incident radiation ratio for each light environment for a horizontal plane below the targeted plant canopy. See introduction section for further details on the crop.

STICS variable name	Light environment	Total incident light ratio
<code>rombre</code>	Shaded	0.7755858
<code>rsoleil</code>	Sunlit	0.7943134

radiation, `trg` is the active radiation (either global radiation or radiation transmitted below the dominant crop), `rombre` and `rsoleil` are the ratio of incident light for shaded and sunlit components of the plane, and `surfAO` and `surfAS` are the relative surfaces (0 to 1) of the shaded and sunlit components of the plane. The computation of `trg` is further described in Chapter ??.

For our example, the crop would have intercepted NA, NA MJ m-2 day-1 of radiation, with a PAR of 12.5 W m-2, an `rombre` of 0.7755858, NA, an `rsoleil` of NA, 0.7943134 and a relative surface of 0.2 and 0.8 for the shaded and sunlit component respectively.

The relative surfaces (0 to 1) of the shaded and sunlit components of the plane (`surfAO` and `surfAS`) that are computed during the dominant plant computation are then used as the shaded and sunlit surfaces for the dominated plant.

2.4 Summary

The interception of the targeted plant is obtained by:

1. Computing the light that is incident at a horizontal plane at the height of the dominated plant (or the soil) and,
2. Subtracting this incident light to the global PAR, which gives the PAR intercepted by the target plant.

This process is applied iteratively to the dominant and the dominated plant to compute both species PAR interception while taking account for their respective structure (shape, height, width...).

2.5 Discussion and proposed modifications

The dominated plant interception is computed in two separate computations, one for the sunlit component, and one for the shaded component, and interception is then weighted by their relative surface. The dominant plant is considered having 100% of its surface that is sunlit, so all this computation is made only for its sunlit part.

The radiation above the dominant plant (`trg`) is the global radiation, but the radiation above the dominated plant (also `trg`) is computed as: $trg = trg \cdot rsoleil$

where `rsoleil` is the average proportion of light intercepted by the sunlit area of the plane below the dominant plant.

This computation is only right for the sunlit component of the dominated plant. A modification is proposed, discussed and tested on Chapter ??.

Chapter 3

Light incident to the dominated crop (trg)

3.1 Computing the trg incident to the dominated plant

For the moment, STICS compute the radiation incident above the dominated (or associated) plant as:

Which means that `trg` for the dominated plant (`i > 1`) is computed as the global atmospheric radiation (`trg_bak` here), reduced by the average proportion of light transmitted by the sunlit area of the plane below the dominant plant (and above the dominated plant). This computation does not consider that the average proportion of light incident above the shaded part of the dominated plant (`rombre`) is different from `rsoleil`. See Chapter ?? for more details.

3.2 Proposed solution

We propose to change this computation to take the relevant incident light according to the light regime of the dominated plant under computation:

With this new computation, the radiation incident above the dominated plant depends from the component under consideration (shaded or sunlit), and is computed using the geometry of the dominant plant (for atmospheric+transmitted light computation).

3.3 Results

A comparison of the two was made using the `sticRs` package, from which a summary plot was extracted. The results are shown in Figure ??.

The comparison between both indicated that the dominated plant intercepted more PAR with the original computation (`raint`), due to its wrong light regime (`rsoleil` for both AS and AO). While the dry mass and height of the dominated plant did not change, its LAI was previously higher on the end of the rotation, which increased the `rsoleil` and `rombre` of the ground (visible as associated ones). These simulations also showed that the wheat (dominant) `eai` was highly overestimated, which will be fixed in the next simulations.

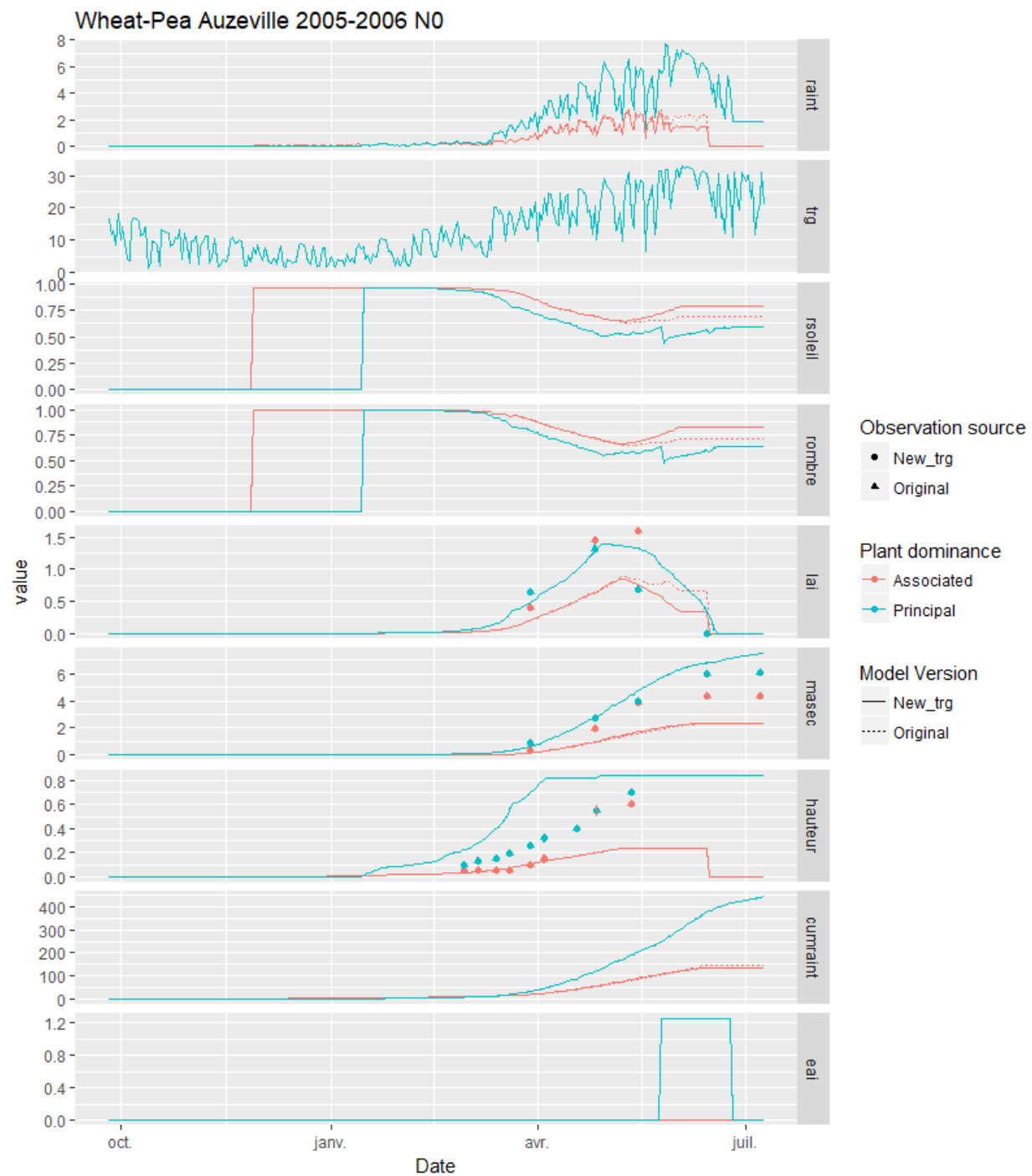


Figure 3.1: trg comparison