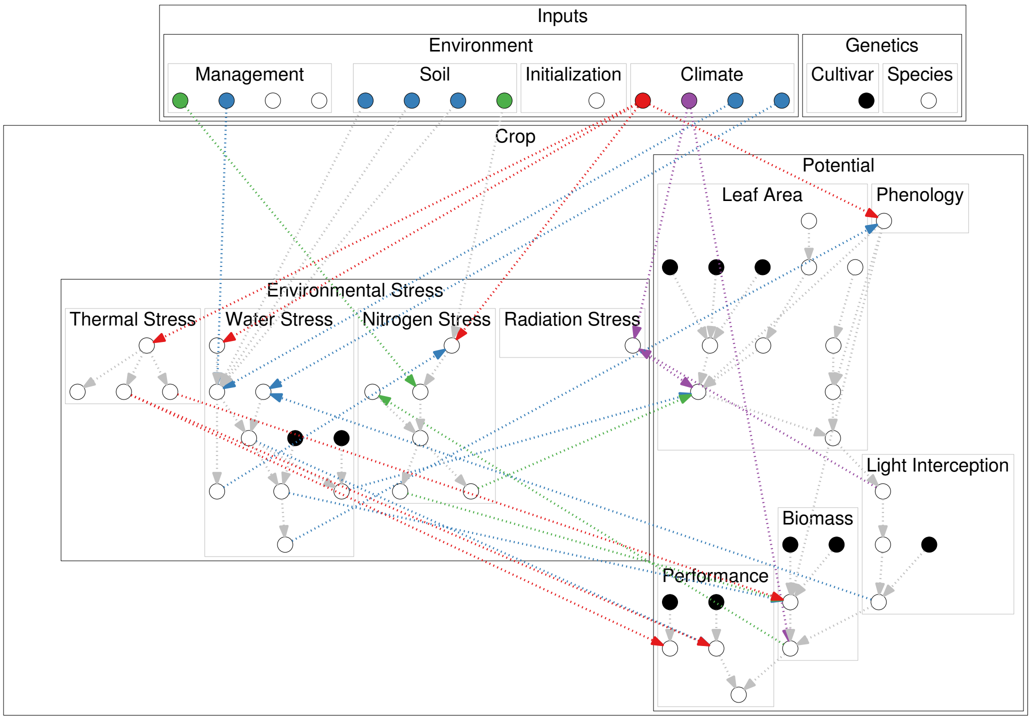
# *Documentation for the SUNFLO crop model*

*April 1, 2016*



## *Abstract*

SUNFLO is a process-based model for the sunflower crop which was developped to simulate the grain yield and oil concentration as a function of time, environment (soil and climate), management practice and genetic diversity (Casadebaig et al., 2011; Debaeke et al., 2010; Lecoeur et al., 2011).

This model is based on a conceptual framework initially proposed by Monteith (1977) and now shared by a large familly of crop models [REF]. In this framework, the crop dry biomass growth rate ($dDM/dt$) is calculated as an ordinary differential equation [EQ1] function of incident photosynthetically active radiation ($PAR$, $MJ.m^{-2}$), light interception efficiency ($1 - exp^{-k \cdot LAI}$) and radiation use efficiency ($RUE$, $g.MJ^{-1}$). The light interception efficiency is based on Beer-Lambert's law as a function of leaf area index ($LAI$) and light extinction coefficient ($k$). The radiation use efficiency concept (Monteith, 1994) is used to represent photosynthesis at the crop scale.

[EQ1]

$$dDM/dt = RUE \cdot (1 - exp^{-k \cdot LAI}) \cdot PAR$$

Broad scale processes of this framework, the dynamics of $LAI$, photosynthesis ($RUE$) and biomass allocation to grains were split into finer processes (e.g leaf expansion and senescence, response functions to environmental stresses) to reveal genotypic specificity and to allow the emergence of genotype x environment interactions. Globally, the SUNFLO crop model has about 50 equations and 64 parameters (43 plant-related traits and 21 environment-related).

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# *Inputs*

## *Climate*

| label | description | unit |
|---|---|---|
| TemperatureAirMin | Daily average of minimum air temperature | °C |
| TemperatureAirMax | Daily average of maximum air temperature | °C |
| Radiation | Daily sum of global incident radiation | MJ.m-2 |
| PET | Daily sum of reference evapotranspiration (Penman-Monteith) | mm |
| Rainfall | Daily sum of rainfall | mm |

## *Soil*

| label | description | value | unit | reference |
|---|---|---|---|---|
| RootingDepth | Potential rooting depth | 1000.0 | $mm$ | (Lecoeur et al., 2011) |
| SoilWaterCapacity | Gravimetric water content at field capacity (0-30 cm) | 19.7 | % | NA |
| SoilWaterCapacity | Gravimetric water content at wilting point (0-30cm) | 9.7 | % | NA |
| SoilWaterCapacity | Gravimetric water content at field capacity (30 cm-rooting depth) | 19.7 | % | NA |
| SoilWaterCapacity | Gravimetric water content at wilting point (30 cm-rooting depth) | 9.7 | % | NA |
| SoilDensity | Soil bulk density, sieved < 5mm, 0-30cm layer | 1.3 | $g.cm^{-3}$ | NA |
| SoilDensity | Soil bulk density, sieved < 5mm, 30 cm-rooting depth layer | 1.3 | $g.cm^{-3}$ | NA |
| StoneContent | Stone content (0-rooting depth) | 0.1 | $[0, 1]$ | NA |
| MineralizationRate | Potential nitrogen mineralization rate | 0.5 | $kg.ha^{-1}.day^{-1}$ | (Valé et al., 2007) |

## *Management*

| label | description | unit |
|---|---|---|
| SowingDate | Sowing date | $date(dd/mm)$ |
| HarvestDate | Harvest date | $date(dd/mm)$ |
| SowingDensity | Plant density | $plant.m^{-2}$ |
| Fertilization | Fertilization (date 1) | $date(dd/mm)$ |
| Fertilization | Fertilization (amount 1) | $kg.ha^{-1}$ eq. mineral nitrogen |
| Fertilization | Fertilization (date 2) | $date(dd/mm)$ |
| Fertilization | Fertilization (amount 2) | $kg.ha^{-1}$ eq. mineral nitrogen |
| Irrigation | Irrigation (date 1) | $date(dd/mm)$ |
| Irrigation | Irrigation (amount 1) | $mm$ |
| Irrigation | Irrigation (date 2) | $date(dd/mm)$ |
| Irrigation | Irrigation (amount 2) | $mm$ |
| Irrigation | Irrigation (date 3) | $date(dd/mm)$ |
| Irrigation | Irrigation (amount 3) | $mm$ |

*Species*

*Cultivar*

| label | description | value | unit | reference |
|---|---|---|---|---|
| ThermalTimeVegetative | Temperature sum to floral initiation | 482.00 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeFlowering | Temperature sum from emergence to the beginning of flowering | 836.00 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeSenescence | Temperature sum from emergence to the beginning of grain filling | 1083.00 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeMaturity | Temperature sum from emergence to seed physiological maturity | 1673.00 | $C.d$ | (Lecoeur et al., 2011) |
| PotentialLeafNumber | Potential number of leaves at flowering | 29.00 | $leaf$ | (Lecoeur et al., 2011) |
| PotentialLeafProfile | Potential rank of the plant largest leaf at flowering | 17.00 | $leaf$ | (Lecoeur et al., 2011) |
| PotentialLeafSize | Potential area of the plant largest leaf at flowering | 448.00 | $cm^{-2}$ | (Lecoeur et al., 2011) |
| ExtinctionCoefficient | Light extinction coefficient during vegetative growth | 0.88 | - | (Lecoeur et al., 2011) |
| WaterResponseExpansion | Threshold for leaf expansion response to water stress | -4.42 | - | (Casadebaig et al., 200 |
| WaterResponseConductance | Threshold for stomatal conductance response to water stress | -9.30 | - | (Casadebaig et al., 200 |
| PotentialHarvestIndex | Potential harvest index | 0.40 | - | (Casadebaig et al., 201 |
| PotentialOilContent | Potential seed oil content | 55.40 | $\%drymass$ | (Casadebaig et al., 201 |

## Phenology

| label | description | value | unit | reference |
|---|---|---|---|---|
| ThermalTimeVegetative | Temperature sum to floral initiation | 482.0 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeFlowering | Temperature sum from emergence to the beginning of flowering | 836.0 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeSenescence | Temperature sum from emergence to the beginning of grain filling | 1083.0 | $C.d$ | (Lecoeur et al., 2011) |
| ThermalTimeMaturity | Temperature sum from emergence to seed physiological maturity | 1673.0 | $C.d$ | (Lecoeur et al., 2011) |
| SowingDepth | Sowing depth | 30.0 | $mm$ | NA |
| Germination | Temperature sum from sowing to germination | 86.2 | $C.d$ | (Casadebaig et al., 2011) |
| ElongationRate | Reciprocal of hypocotyl elongation rate | 1.2 | $Cd.mm^{-1}$ | (Villalobos et al., 1996) |

### Emergence

$Emergence = Germination + ElongationRate \times SowingDepth$
with:

- $Germination = 86$, Thermal time for germination (°C.d);
- $ElongationRate = 1.19$, Hypocotyl elongation rate (°Cd/mm)
- $SowingDepth = 30$, Sowing depth (mm).

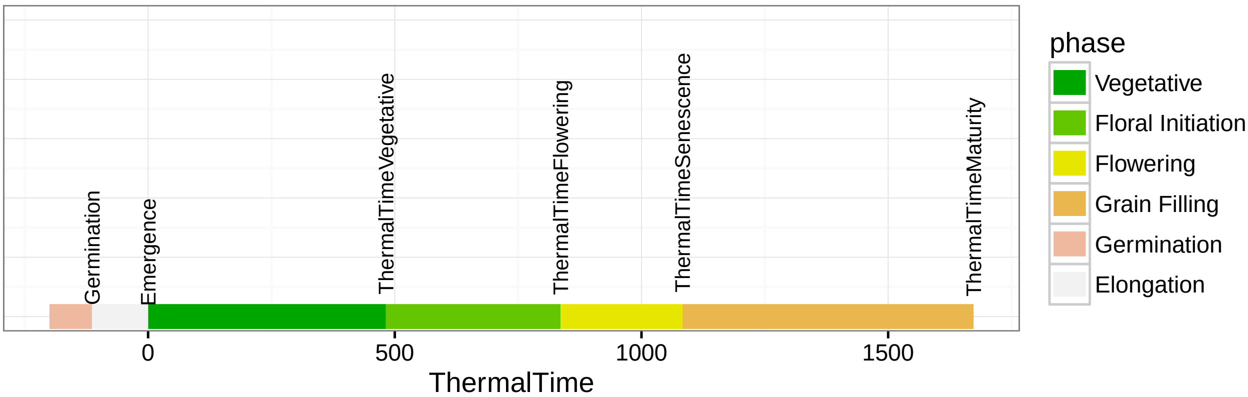
### ThermalTime

$$ThermalTime_d = \begin{cases} \int_0^d (T_m - T_b) \times (1 + WaterStressPhenology) & \text{if } T_m > T_b \\ 0 & \text{else} \end{cases}$$

with:

- $T_m$, Daily mean air temperature (°C);
- $T_b = 4.8$, Basal temperature (°C) (Granier and Tardieu, 1998);
- $ThermalStressPhenology$, Water stress effect on plant heating

### PhenoStages

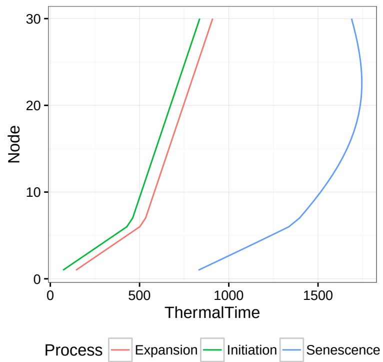



In the software model, phenostages are computed as integers $\in [0, 7]$ corresponding to duration between key stages:

- **0**, begining of simulation - sowing (bare soil)
- **1**, sowing (A0) - emergence (A2)
- **2**, emergence (A2) - floral initiation (E1)
- **3**, floral initiation (E1) - flowering (F1)
- **4**, flowering (F1) - onset of senescence (M0)
- **5**, onset of senescence (M0) - maturity (M3)
- **6**, maturity (M3) - harvest
- **7**, harvest - end of simulation (bare soil)

## *LeafArea*

| label | description | value | unit | reference |
|---|---|---|---|---|
| PotentialLeafNumber | Potential number of leaves at flowering | 29.0 | $leaf$ | (Lecoeur et al., 2011) |
| PotentialLeafProfile | Potential rank of the plant largest leaf at flowering | 17.0 | $leaf$ | (Lecoeur et al., 2011) |
| PotentialLeafSize | Potential area of the plant largest leaf at flowering | 448.0 | $cm^{-2}$ | (Lecoeur et al., 2011) |
| Phyllotherm_1 | Phyllotherm (leaf <= 6) | 71.4 | $C.d$ | (Rey, 2003) |
| Phyllotherm_7 | Phyllotherm (leaf > 6) | 16.3 | $C.d$ | (Rey, 2003) |
| NA | NA | 1.0 | - | (Casadebaig, 2008) |
| PotentialLeafDurationMin | Asymptote of leaf longevity funtion, base leaf duration | 153.0 | $C.d$ | (Casadebaig, 2008) |
| PotentialLeafDurationMax | Maximum thermal time between expansion and senescence | 851.3 | $C.d$ | (Casadebaig, 2008) |
| NA | NA | 0.0 | $leaf$ | (Casadebaig, 2008) |
| PotentialLeafDurationWidth | NA | 0.8 | $leaf$ | (Casadebaig, 2008) |
| PotentialGrowthSlope | NA | 0.0 | - | (Casadebaig, 2008) |




### *LeafInitiationTime, LeafExpansionTime, LeafSenescenceTime*

The rate of leaf appearance depends on air temperature and two phyllochrons as preformed lower leaves appear at a lower rate (Rey, 2003)

$$LeafInitiationTime_i = \begin{cases} i \times Phyllotherm_1 & \text{if } i \leq 6 \\ (i-5) \times Phyllotherm_7 + 6 \times Phyllotherm_1 & \text{if } i \leq LeafNumber \end{cases}$$

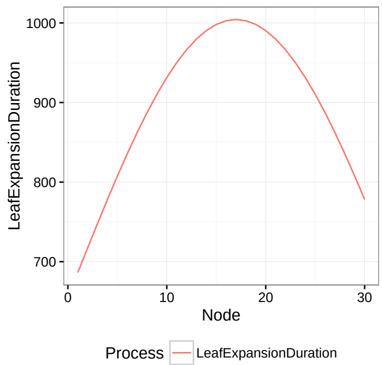
with:

- $Phyllotherm_1 = 76.43$ (°C.d)
- $Phyllotherm_7 = 16.34$ (°C.d)

Thermal time to 50% of final leaf area was defined as a function of the thermal time required for leaf appearance.

$$LeafExpansionTime_i = LeafInitiation_i + 1/a$$

with $a = 0.01379$.

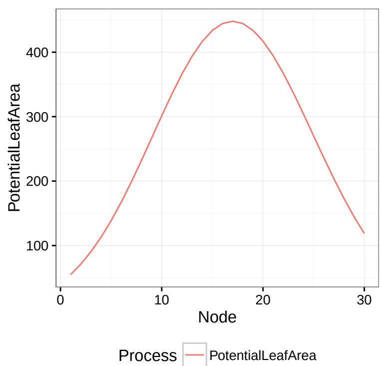



### *LeafExpansionDuration*

$$LeafExpansionDuration_i = a + b \times exp^{\frac{-(i-PotentialLeafProfile)^2}{(c \times PotentialLeafNumber)^2}}$$

with:

- $a = PotentialLeafDurationMin = 153$ (°C.d)
- $b = PotentialLeafDurationMax = 851.3$ (°C.d)
- $c = PotentialLeafDurationWidth = 0.78$




$$LeafSenescenceTime_i = LeafExpansionTime_i + LeafExpansionDuration_i$$

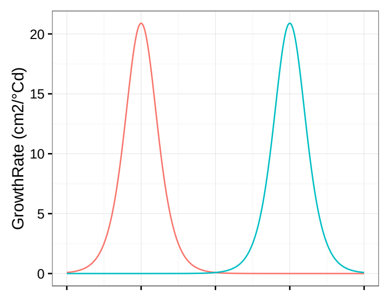
### *PotentialLeafArea*

$$PotentialLeafArea_i = PotentialLeafSize \times exp^{a \times (\frac{i-PotentialLeafProfile}{PotentialLeafProfile-1})^2 + b \times (\frac{i-PotentialLeafProfile}{PotentialLeafProfile-1})^3}$$

with: * $a = -2.05$ and $b = 0.049$, shape parameters * $PotentialLeafSize$ (cm2) and $PotentialLeafProfile$ (node), genotypic parameters.

### *LeafExpansionRate, LeafSenescenceRate*

$$LeafExpansionRate_i = (T_m - T_b) \times PotentialLeafArea_i \times a \times \frac{exp^{-a(ThermalTime - LeafExpansionTime_i)}}{(1 + exp^{-a(ThermalTime - LeafExpansionTime_i)})^2}$$



$$LeafSenescenceRate_i = (T_m - T_b) \times LeafArea_i \times a \times \frac{exp^{-a(ThermalTime - LeafSenescenceTime_i)}}{(1 + exp^{-a(ThermalTime - LeafSenescenceTime_i)})^2}$$

with:

- $T_m = 25$, mean air temperature (°C)
- $T_b = 4.8$, base temperature (°C)
- $a = 0.01379$

The illustration uses $i = 10$ as values for $PotentialLeafArea_i$, $LeafExpansionTime_i$ and $LeafSenescenceTime_i$

## *LeafArea, PlantLeafArea*

$$LeafArea_i = \int LeafExpansionRate_i - \int LeafSenescenceRate_i$$

$$PlantLeafArea = \sum_{i=1}^{LeafNumber} LeafArea_i$$

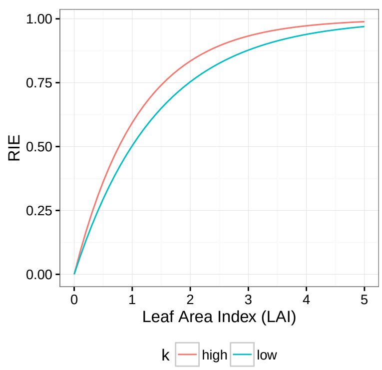
# Light interception

## LAI

$$LAI = SowingDensity \times PlantLeafArea$$

## RIE

$$RIE = 1 - exp^{(-ExtinctionCoefficient \times LAI)}$$



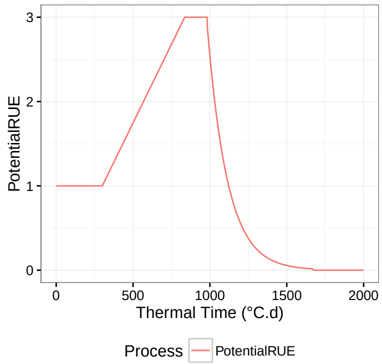
# *Biomass production*

## *RUE*

$$PotentialRUE = \begin{cases} r_0 & \text{if } ThermalTime < 300 \\ r_0 + 2 \times \frac{ThermalTime - 300}{ThermalTimeFlowering - 300} & \text{if } 300 < ThermalTime < ThermalTimeFlowering \\ r_{max} & \text{if } ThermalTimeFlowering < ThermalTime < ThermalTimeSenescence \\ a \times exp^{b \times (1 - \frac{ThermalTime - ThermalTimeMaturity}{ThermalTimeMaturity - ThermalTimeSenescence})} & \text{if } ThermalTimeSenescence < ThermalTime < ThermalTimeMaturity \\ 0 & \text{else} \end{cases}$$

with:

- $r_0 = 1$, vegetative RUE
- $r_{max} = 3$, maximum RUE
- $a = 0.015$, final RUE
- $b = 4.5$, slope of RUE decrease in grain filling stage



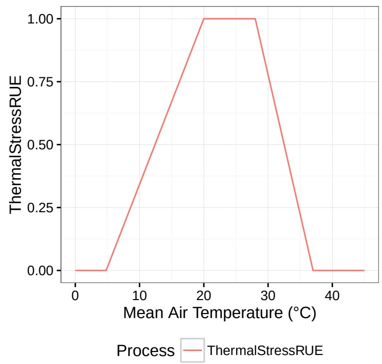

## *CropBiomass (Monteith, 1977)*

$$dCropBiomass = Radiation \times 0.48 \times RIE \times RUE \cdot dt$$

## *CropPerformance*

# *Thermal stress*

## *ThermalStressRUE (Villalobos et al., 1996)*

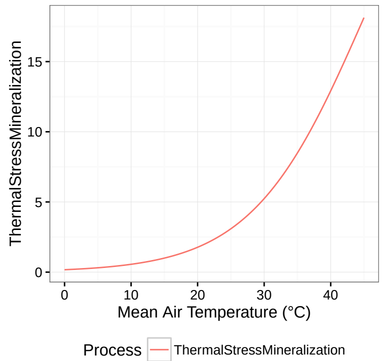



$$ThermalStressRUE = \begin{cases} T_m \times \frac{1}{T_{ol}-T_b} - \frac{T_b}{T_{ol}-T_b} & \text{if } T_b < T_m < T_{ol} \\ 1 & \text{if } T_{ol} < T_m < T_{ou} \\ T_m \times \frac{1}{T_{ou}-T_c} - \frac{T_c}{T_{ou}-T_c} & \text{if } T_{ou} < T_m < T_c \\ 0 & \text{else} \end{cases}$$

with:

- $T_b = 4.8$, base temperature (°C)
- $T_{ol} = 20$, optimal lower temperature (°C)
- $T_{ou} = 28$, optimal upper temperature (°C)
- $T_c = 37$, critical temperature (°C)

## *ThermalStressMineralization (Valé et al., 2007)*




$$ThermalStressMineralization = \frac{T_c}{1 + (T_c - 1) \times exp^{(-0.119 \times (T_m - T_b))}}$$

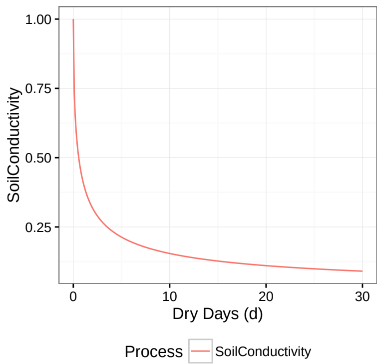
with:

- $T_b = 15$, base temperature (°C)
- $T_c = 36$, critical temperature (°C)

## *ThermalStressAllocation*

# Water stress

## WaterDemand




$$WaterDemand = K_c \times PET \times RIE$$

with $K_c = 1.2$, crop coefficient

## WaterSupply

$$WaterSupply = Rainfall + Irrigation - Transpiration - Evaporation - Drainage$$

$$Transpiration = WaterDemand \times WaterStressConductance$$

$$Evaporation = (1 - RIE) \times PET \times SoilConductivity$$

$$SoilConductivity = \sqrt{x+1} - \sqrt{x}$$

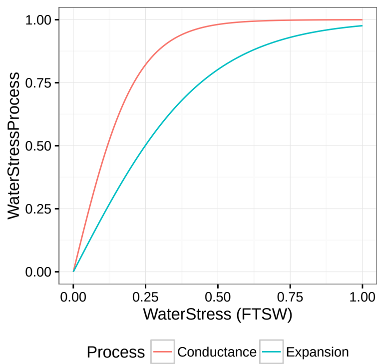
with

$$dx/dt = \begin{cases} 1 & \text{if } Rainfall + Irrigation <= 4 \\ 0 & \text{else} \end{cases}$$

## WaterStress

$$WaterStress = \frac{WaterAvailable}{WaterTotal}$$

$$WaterAvailable = WaterSupply$$




$$WaterTotal = SoilWaterCapacity \times SoilDensity \times (1 - StoneContent) \times RootingDepth$$

## WaterStressExpansion, WaterStressConductance

$$WaterStressProcess = -1 + \frac{2}{1 + exp^{(a \times WaterStress)}}$$

with $a \in [-15.6; -2.3]$, genotype-dependant response parameter

## WaterStressPhenology

$$WaterStressPhenology = a \times (1 - WaterStressConductance)$$

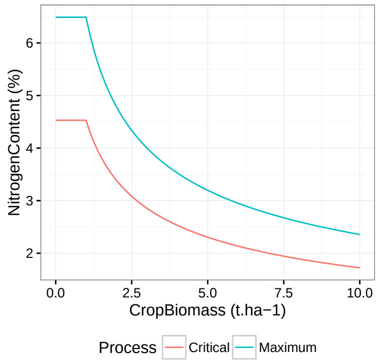
with $a = 0.1$, scaling parameter for water-stress plant heating

## WaterStressMineralization

$$WaterStressMineralization = 1 - (1 - y_0) \times (1 - RelativeWaterContent_{layer1})$$

# *Nitrogen stress*

## *NitrogenDemand*




$$NitrogenContent = min(a, a \times CropBiomass^{-b})$$

with:

- $CropBiomass$, Daily shoot biomass ($t.ha^{-1}$);
- $a = 4.53$ and $b = 0.42$ defining $NitrogenContentCritical$ (Debaeke et al., 2012);
- $a = 6.49$ and $b = 0.44$ defining $NitrogenContentMaximum$ (Debaeke et al., 2012);

$$NitrogenDemand = NitrogenCritical = NitrogenCriticalContent \times CropBiomass$$

## *NitrogenSupply*

$$NitrogenSupply = NitrogenAbsorbed = NitrogenAbsorbedMassFlow + NitrogenAbsorbedTransport$$

$$NitrogenAbsorbedMassFlow = TranspirationRate_l \times SoilNitrogen$$

## *NitrogenStress*

$$NitrogenStress = NitrogenSupply / NitrogenDemand = NNI$$

Vitesse d'extraction d'eau par les racine dans C1 (mm/j)

## *NitrogenStressExpansion*

## *NitrogenStressRUE*

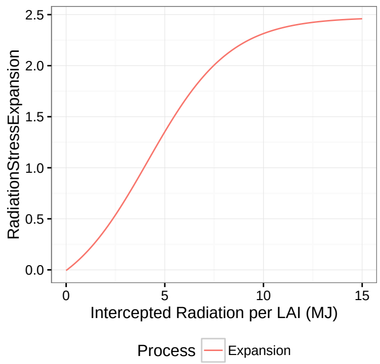
## Radiation stress

### RadiationStressExpansion (Rey, 2003)

$$RadiationStressExpansion = s \times a + \frac{b}{1 + exp^{(\frac{c - IPAR/LAI}{d})}}$$

with:

- $s = 2.5$, scaling parameter for density effect;
- $a = -0.14$; $b = 1.13$; $c = 4.13$; $d = 2.09$



## *Outputs*

### *Timed variables*

| symbol | label | description | unit |
|---|---|---|---|
| TN | TemperatureAirMin | Minimum air temperature | $C$ |
| TX | TemperatureAirMax | Maximum air temperature | $C$ |
| TM | TemperatureAirMean | Mean air temperature | $C$ |
| GR | Radiation | Global incident radiation | $MJ.m^{-2}$ |
| ETP | PET | Reference evapotranspiration | $mm$ |
| RR | Rainfall | Rainfall | $mm$ |
| TTA2 | ThermalTime | Temperature sum from emergence | $C.d$ |
| PhenoStage | PhenoStage | Phenological stages index | - |
| FTSW | WaterStress | Water stress index | - |
| FHTR | WaterStressConductance | Transpiration response to water stress | - |
| FHRUE | WaterStressConductance | Photosynthesis response to water stress | - |
| ETRETM | WaterSupplyDemandRatio | Water supply:demand ratio | - |
| FTRUE | ThermalStressRUE | Photosynthesis response to thermal stress | - |
| NAB | NitrogenAbsorbed | Absorbed nitrogen | $kg.ha^{-1}.d^{-1}$ |
| NNI | NitrogenNutritionIndex | Nitrogen nutrition index | - |
| FNRUE | NitrogenStressRUE | Photosynthesis response to nitrogen stress | - |
| LAI | LAI | Leaf area index | - |
| RIE | RIE | Radiation interception efficiency | - |
| RUE | RUE | Radiation use efficiency | - |
| TDM | CropBiomass | Crop aerial dry biomass | $g.m^{-2}$ |
| GY | CropYield | Grain yield | $q.ha^{-1}$ |
| OC | OilContent | Grain oil content | $\%(drymatter)$ |

## *Indicators*

| level | factor | symbol | description | unit | formula |
|---|---|---|---|---|---|
| climate | light | SGR | Photosynthetically active radiation | $MJ.m^{-2}$ | $sum(GR * 0.48)$ |
| climate | water | SRR | Rain | $mm$ | $sum(RR)$ |
| climate | water | SETP | Potential evapotranspiration | $mm$ | $sum(PET)$ |
| climate | water | SCWD | Climatic water deficit | $mm$ | $sum(RR - PET)$ |
| species | temperature | TT | Thermal time (4.8 C basis) | $C.d$ | $sum(TM - 4.8)$ |
| species | temperature | D_SE | Duration of sowing - emergence phase | $d$ | - |
| genotype | temperature | D_EF | Duration of vegetative phase | $d$ | - |
| genotype | temperature | D_FM | Duration of flowering phase | $d$ | - |
| genotype | temperature | D_MH | Duration of grain filling phase | $d$ | - |
| species | temperature | NHT | Thermal stress, high temperature (discrete) | $d$ | $sum(TM > 28)$ |
| species | temperature | NLT | Thermal stress, low temperature (discrete) | $d$ | $sum(TM < 20)$ |
| species | temperature | SHT | Thermal stress, high temperature (continuous) | - | $sum(1 - HTRUE)$ |
| species | temperature | SLT | Thermal stress, low temperature (continuous) | - | $sum(1 - LTRUE)$ |
| species | temperature | SFTRUE | Thermal stress impact on photosynthesis | - | $sum(1 - FTRUE)$ |
| species | water | SFTSW | Edaphic water deficit (continuous) | - | $sum(1 - FTSW)$ |
| species | water | METR | Edaphic water deficit (continuous) | - | $mean(ET/PET)$ |
| species | water | NETR | Edaphic water deficit (discrete) | $d$ | $sum(ET/PET < 0.6)$ |
| genotype | water | SFHTR | Water stress impact on crop transpiration | - | $sum(1 - FHTR)$ |
| genotype | water | SFHRUE | Water stress impact on crop photosynthesis | - | $sum(1 - FHRUE)$ |
| species | nitrogen | SNAB | Absorbed nitrogen | $kg.ha^{-1}$ | $diff(range(NAB))$ |
| species | nitrogen | SNNI | Nitrogen deficit (continuous) | - | $sum(1 - NNI)$ |
| species | nitrogen | SFNRUE | Nitrogen stress impact on photosynthesis | - | $sum(1 - FNRUE)$ |
| genotype | - | LAI | Leaf area index | - | $max(LAI)$ |
| genotype | - | LAD | Leaf area duration | - | $sum(LAI)$ |
| genotype | light | SIR | Intercepted radiation | $MJ.m^{-2}$ | $sum(RIE * GR * 0.48)$ |
| genotype | - | MRUE | Photosynthesis | $g.MJ^{-1}.m^{-2}$ | $mean(RUE)$ |
| genotype | - | STDM | Aerial Biomass | $g.m^{-2}$ | $max(TDM)$ |
| genotype | - | GY | Grain yield | $q.ha^{-1}$ | $max(GY)$ |
| genotype | - | OC | Grain oil content | $\%(drymatter)$ | $max(OC)$ |

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