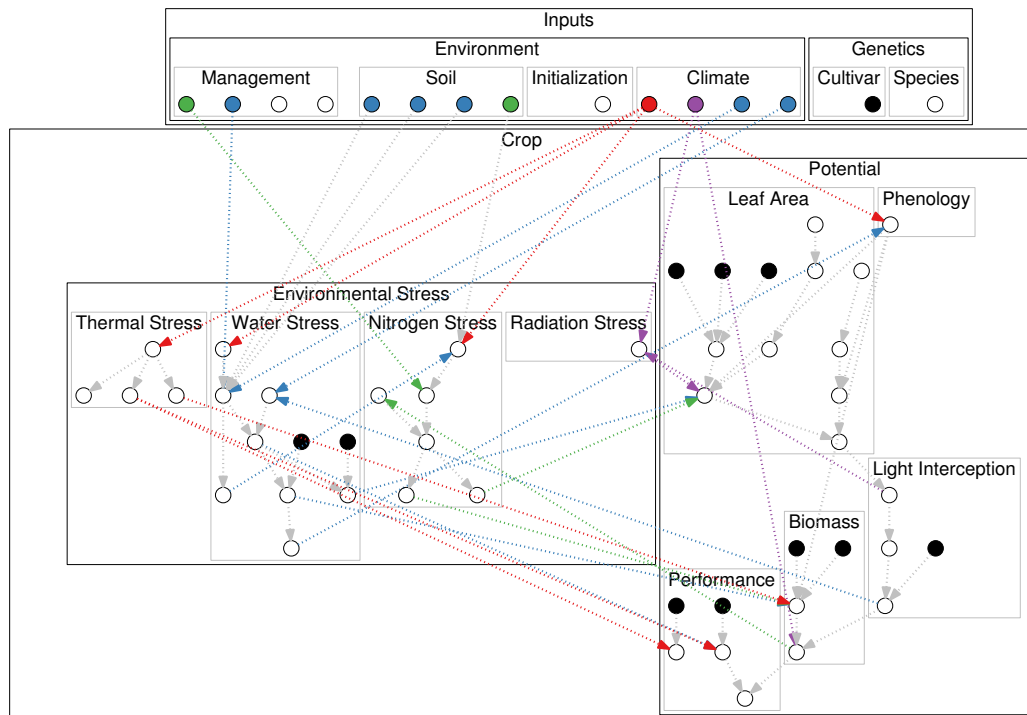# Documentation for the SUNFLO crop model

January 13, 2016

Abstract

SUNFLO is a process-based model for the sunflower crop which was developed 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).

Contents

Inputs

Climate

label	description	unit
TemperatureAirMin	Minimum air temperature	°C
TemperatureAirMax	Maximum air temperature	°C
Radiation	Global incident radiation	MJ.m-2
PET	Reference evapotranspiration (Penman-Monteith)	mm
Rainfall	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)
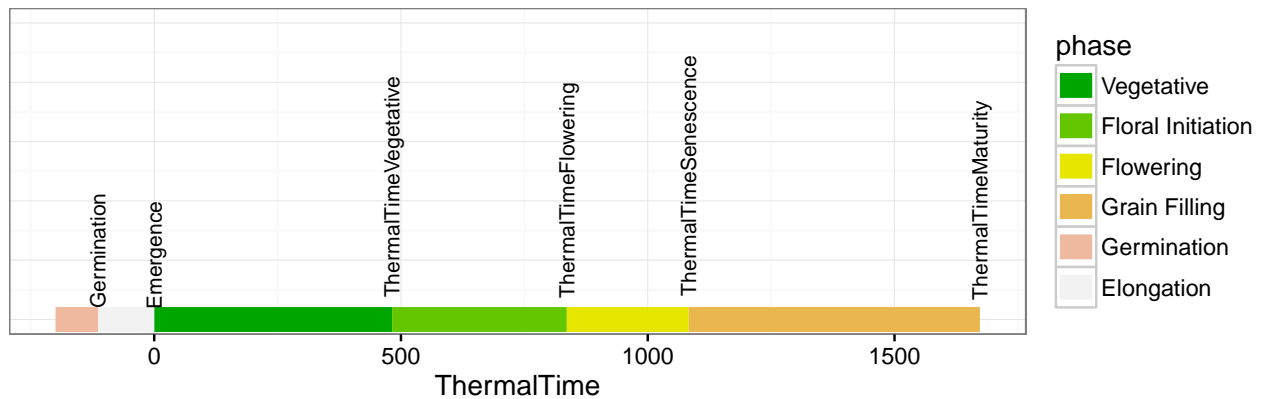- $SowingDepth = 30$, Sowing depth (mm).

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

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

with:

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

$$LeafExpansionTime_i = LeafInitiation_i + 1/a$$

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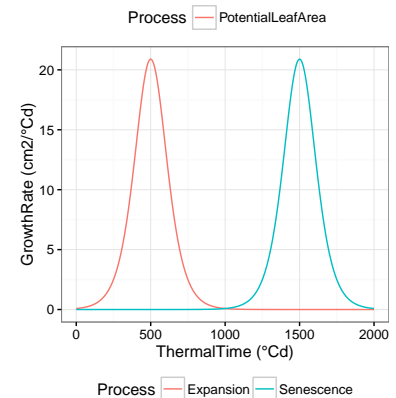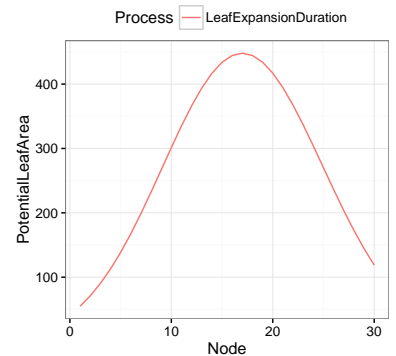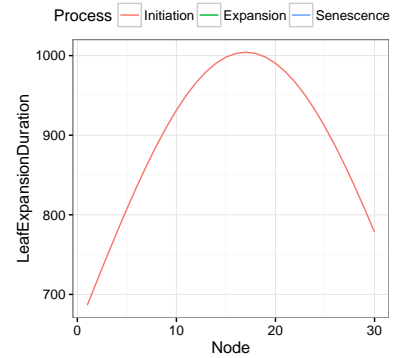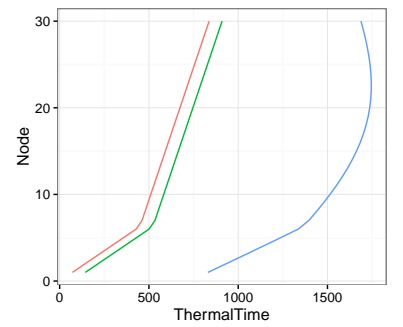
- $T_m = 25$, mean air temperature (°C)
- $T_b = 4.8$, base temperature (°C)
- $a = 0.01379$

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

LeafArea, PlantLeafArea

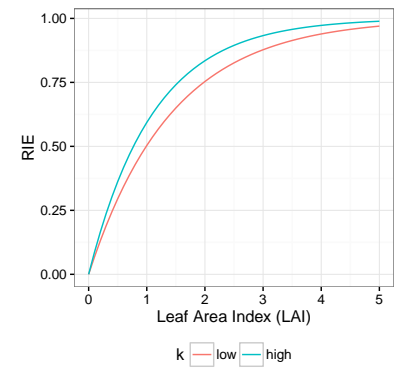$$LeafArea_i = \int LeafExpansionRate_i - \int LeafSenescenceRate_i$$

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

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
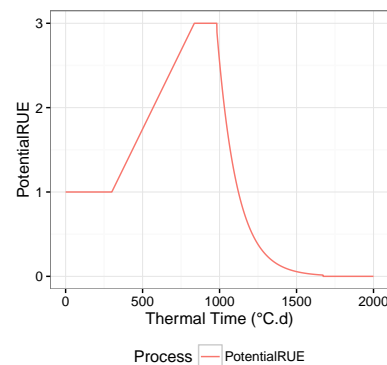
CropBiomass (Monteith, 1977)

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

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)
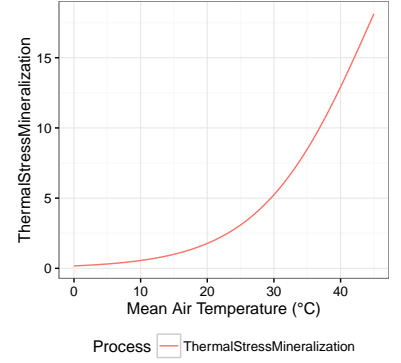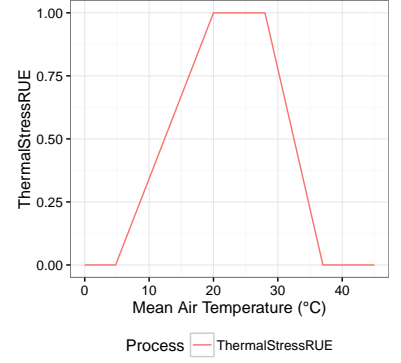- $T_c = 37$, critical temperature (°C)

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

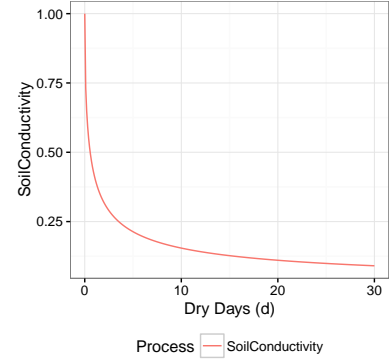$$WaterSupply = Rainfall + Irrigation - Transpiration - Evaporation - Drainage$$

$$Transpiration = WaterDemand \times WaterStressConductance$$

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

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

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
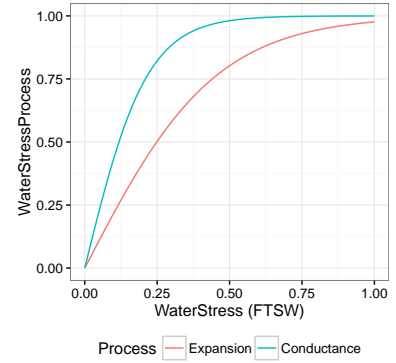
WaterStressPhenology

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

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);

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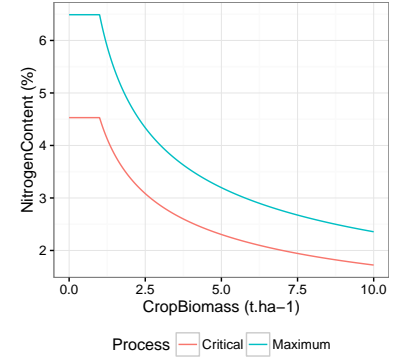
NitrogenSupply

$$NitrogenSupply = NitrogenAbsorbed = NitrogenAbsorbedMassFlow + NitrogenAbsorbedTransport$$

$$NitrogenAbsorbedMassFlow = TranspirationRate_l \times SoilNitrogen$$

NitrogenStress

$$NitrogenStress = NitrogenSupply / NitrogenDemand = NNI$$

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

NitrogenStressExpansion

NitrogenStressRUE

Radiation stress

RadiationStressExpansion (Rey, 2003)

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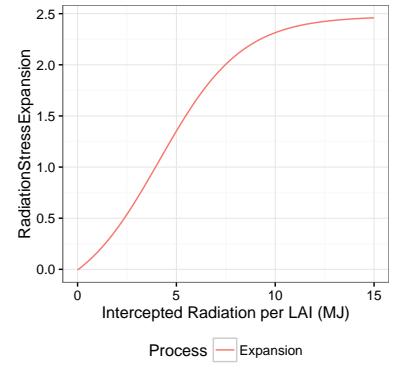
with:

- $s = 2.5$, 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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