Documentation for the SUNFLO crop model

January 21, 2015

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	mm
Rainfall	Rainfall	mm

Soil

label	description	value	unit	reference
RootingDepth	Potential rooting depth	1000.00	mm	(Lecoeur et al., 2011)
SoilWaterCapacity	Water content at field capacity (0-30 cm)	19.69	%	NA
SoilWaterCapacity	Water content at wilting point (0-30cm)	9.69	%	NA
SoilWaterCapacity	Water content at field capacity (30 cm-rooting depth)	19.69	%	NA
SoilWaterCapacity	Water content at wilting point (30 cm-rooting depth)	9.69	%	NA
SoilDensity	Soil bulk density (0-30cm)	1.30	$g.cm^{-3}$	NA
SoilDensity	Soil bulk density (30 cm-rooting depth)	1.30	$g.cm^{-3}$	NA
StoneContent	Stone content (0-rooting depth)	0.10	$[0,1]$	NA
MineralizationRate	Potential nitrogen mineralization rate	0.50	$kg.ha^{-1}.day^{-1}(normalized)$	(Valé et al., 2007)

Management

label	description	value	unit	reference
SowingDate	Sowing date	NA	$date(dd/mm)$	NA
HarvestDate	Harvest date	NA	$date(dd/mm)$	NA
SowingDensity	Plant density	7	$plant.m^{-2}$	NA
Fertilization	Fertilization (date 1)	NA	$date(dd/mm)$	NA
Fertilization	Fertilization (amount 1)	0	$kg.ha^{-1}$ eq. mineral nitrogen	NA
Fertilization	Fertilization (date 2)	NA	$date(dd/mm)$	NA
Fertilization	Fertilization (amount 2)	0	$kg.ha^{-1}$ eq. mineral nitrogen	NA
Irrigation	Irrigation (date 1)	NA	$date(dd/mm)$	NA
Irrigation	Irrigation (amount 1)	0	mm	NA
Irrigation	Irrigation (date 2)	NA	$date(dd/mm)$	NA
Irrigation	Irrigation (amount 2)	0	mm	NA
Irrigation	Irrigation (date 3)	NA	$date(dd/mm)$	NA

label	description	value	unit	reference
Irrigation	Irrigation (amount 3)	0	*mm*	NA

Species

Cultivar

label	description	value	unit	reference
ThermalTimeVegetative	Temperature sum to floral initiation	482.000	*C.d*	(Lecoeur et al., 2011)
ThermalTimeFlowering	Temperature sum from emergence to the beginning of flowering	836.000	*C.d*	(Lecoeur et al., 2011)
ThermalTimeSenescence	Temperature sum from emergence to the beginning of grain filling	1083.000	*C.d*	(Lecoeur et al., 2011)
ThermalTimeMaturity	Temperature sum from emergence to seed physiological maturity	1673.000	*C.d*	(Lecoeur et al., 2011)
PotentialLeafNumber	Potential number of leaves at flowering	29.000	*leaf*	(Lecoeur et al., 2011)
PotentialLeafProfile	Potential rank of the plant largest leaf at flowering	17.000	*leaf*	(Lecoeur et al., 2011)
PotentialLeafSize	Potential area of the plant largest leaf at flowering	448.000	cm^{-2}	(Lecoeur et al., 2011)
ExtinctionCoefficient	Light extinction coefficient during vegetative growth	0.880	-	(Lecoeur et al., 2011)
WaterResponseExpansion	Threshold for leaf expansion response to water stress	-4.420	-	(Casadebaig et al., 2008)
WaterResponseConductance	Threshold for stomatal conductance response to water stress	-9.300	-	(Casadebaig et al., 2008)
PotentialHarvestIndex	Potential harvest index	0.398	-	(Casadebaig et al., 2011)
PotentialOilContent	Potential seed oil content	55.400	$\%dry_matter$	(Casadebaig et al., 2011)

Phenology

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)
SowingDepth	Sowing depth	30.00	mm	NA
Germination	Temperature sum from sowing to germination	86.20	$C.d$	(Casadebaig et al., 2011)
ElongationRate	Reciprocal of hypocotyl elongation rate	1.19	$Cd.mm^{-1}$	(Villalobos et al., 1996)

Emergence

$Emergence = Germination + ElongationRate * SowingDepth$
with:

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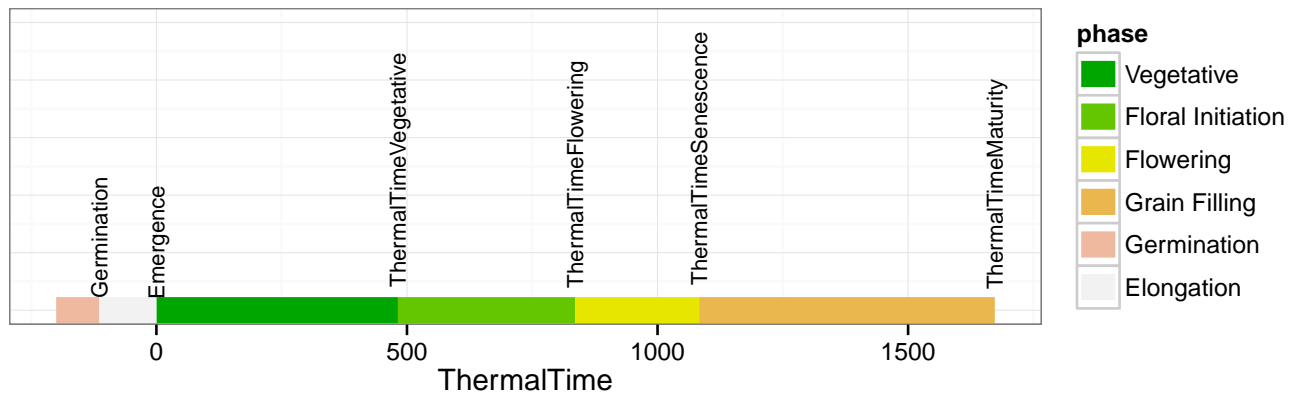- $SowingDepth = 30$, Sowing depth (mm).

ThermalTime

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

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	29.00	$leaf$	(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)
Phyllotherm_1	Phyllotherm (leaf <= 6)	71.43	$C.d$	(Rey, 2003)
Phyllotherm_7	Phyllotherm (leaf > 7)	16.34	$C.d$	(Rey, 2003)
PotentialLeafDuration	Thermal time between expansion and senescence	851.33	$C.d$	(Casadebaig, 2008)

LeafInitiationTime, LeafExpansionTime, LeafSenescenceTime

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

with:

- $Phyllotherm_1 = 76.43$ (°C.d)
- $Phyllotherm_7 = 16.34$ (°C.d)
- $a = 400$ (°C.d)

$$LeafExpansionTime_i = LeafInitiation_i + 1/a$$

with $a = 0.01379$.

LeafExpansionDuration

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

with:

- $PotentialLeafDuration = 851.3$ (°C.d)
- $a = 153$ (°C.d)
- $b = 0.78$

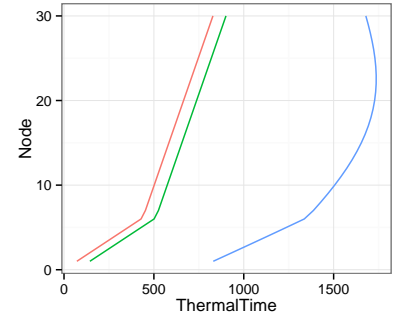$$LeafSenescenceTime_i = LeafExpansionTime_i + LeafExpansionDuration_i$$

PotentialLeafArea

$$PotentialLeafArea_i = PotentialLeafSize * exp^{a*(\frac{i-PotentialLeafProfile}{PotentialLeafProfile-1})^2+b*(\frac{i-PotentialLeafProfile}{PotentialLeafProfile-1})^3}$$
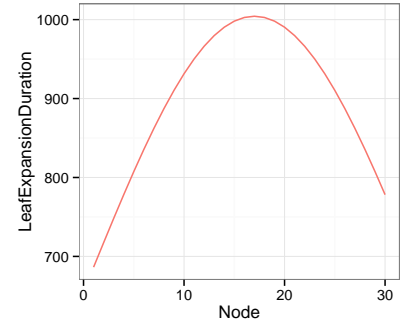
with: * $a = -2.05$ and $b = 0.049$, shape parameters * $PotentialLeafSize$ (cm2) and $PotentialLeafProfile$ (node), genotypic parameters.

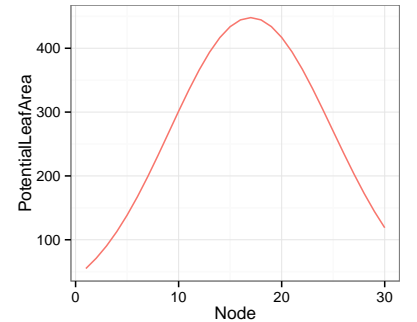## LeafGrowthRate, LeafSenescenceRate, LeafArea

$$LeafGrowthRate_i = (T_m - T_b) * PotentialLeafArea_i * a *$$

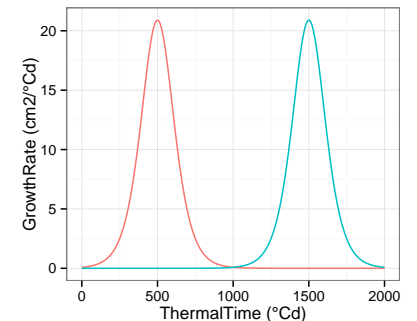$$\frac{exp^{-a(ThermalTime-LeafExpansionTime_i)}}{(1 + exp^{-a(ThermalTime-LeafExpansionTime_i)})^2}$$

$$LeafSenescenceRate_i = (T_m - T_b) * LeafArea_i * a *$$

$$\frac{exp^{-a(ThermalTime - LeafSenescenceTime_i)}}{(1 + exp^{-a(ThermalTime - LeafSenescenceTime_i)})^2}$$

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 $LeafSenescenceTime_i$

$$LeafArea_i = \int LeafGrowthRate_i - \int LeafSenescenceRate_i$$
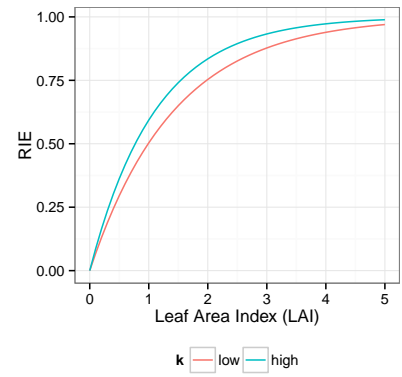
Light interception

LAI

$$LAI = SowingDensity * \sum_{i=1}^{LeafNumber} LeafArea_i$$

### RIE

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

Biomass production

RUE

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

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
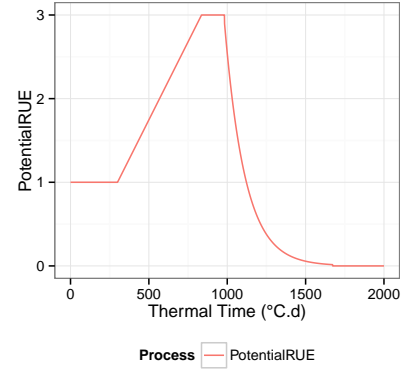
CropBiomass (Monteith, 1977)

$$dCropBiomass = Radiation * 0.48 * RIE * RUE * dt$$

CropPerformance

Thermal stress

ThermalStressRUE (Villalobos et al., 1996)

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

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)

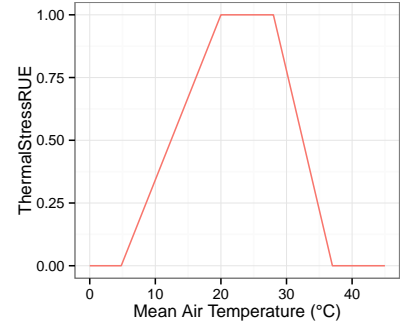### ThermalStressMineralization (Valé et al., 2007)

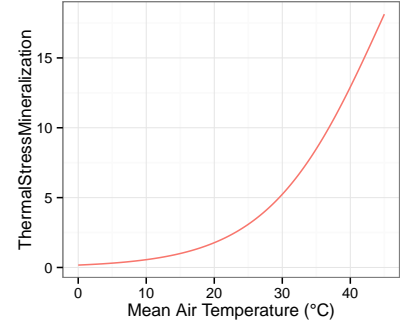$$ThermalStressMineralization = \frac{T_c}{1 + (T_c - 1) * exp^{(-0.119*(T_m-T_b))}}$$

with:

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

ThermalStressAllocation

Water stress

WaterDemand

$$WaterDemand = K_c * PET * RIE$$

with $K_c = 1.2$, crop coefficient

WaterSupply

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

$$Transpiration = WaterDemand * WaterStressConductance$$

$$Evaporation = (1 - RIE) * PET * SoilConductivity$$

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

with

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

WaterStress

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

$$WaterAvailable = WaterSupply$$

$$WaterTotal = SoilWaterCapacity * SoilDensity * (1 - StoneContent) * RootingDepth$$

WaterStressExpansion, WaterStressConductance

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

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

WaterStressPhenology

$$WaterStressPhenology = a * (1 - WaterStressConductance)$$

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

WaterStressMineralization

$$WaterStressMineralization = 1 - (1 - y_0) * (1 - RelativeWaterContent_{layer1})$$
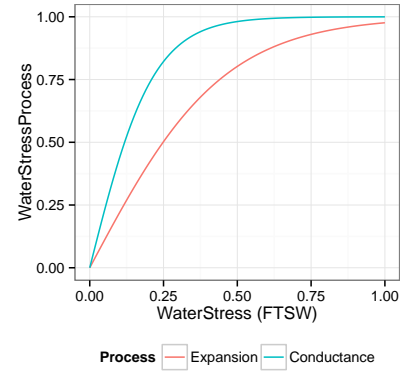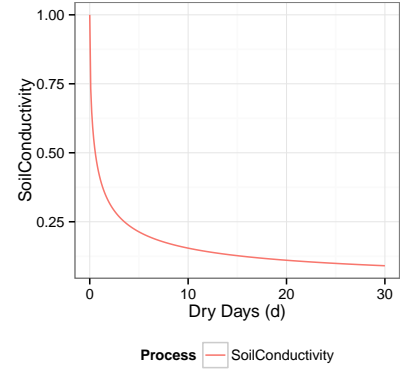
Nitrogen stress

Radiation stress

RadiationStressExpansion (Rey, 2003)

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

with:

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

Outputs

Timed variables

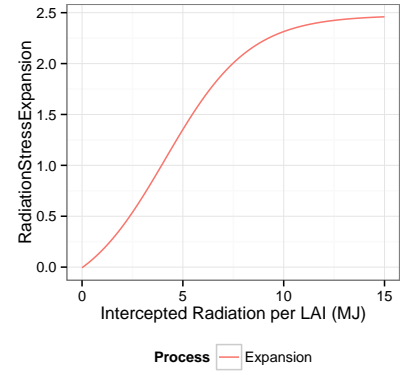| symbol	label	description	unit
TN	TemperatureAirMin	Minimum air temperature	C
TX	TemperatureAirMax	Maximum air temperature	C
TM	TemperatureAirMean	Mean air temperature	C
GR	Radiation	Global incident radiation	$MJ.m^{-2}$
ETP	PET	Reference evapotranspiration	mm
RR	Rainfall	Rainfall	mm
TTA2	ThermalTime	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	$sum(ETP)$
climate	water	SCWD	Climatic water deficit	mm	$sum(P-ETP)$
crop	water	SFTSW	Edaphic water deficit (continuous)	-	$sum(1-FTSW)$
crop	water	NETR	Edaphic water deficit (discrete)	-	$sum(ETR/ETM<0.6)$
crop	water	SFHTR	Water stress impact on crop transpiration	-	$sum(1-FHTR)$
crop	water	SFHRUE	Water stress impact on crop photosynthesis	-	$sum(1-FHRUE)$
crop	nitrogen	SNNI	Nitrogen deficit	-	$sum(1-NNI)$
crop	nitrogen	SNAB	Absorbed nitrogen	$kg.ha^{-1}$	$diff(range(NAB))$
crop	nitrogen	SFNRUE	Nitrogen stress impact on photosynthesis	-	$sum(1-FNRUE)$
crop	temperature	SFTRUE	Thermal stress impact on photosynthesis	-	$sum(1-FTRUE)$
crop	-	LAI	Leaf area index	-	$max(LAI)$
crop	-	DSF	Leaf area duration	-	$sum(LAI)$
crop	light	SIR	Intercepted radiation	$MJ.m^{-2}$	$sum(RIE*GR*0.48)$
crop	-	MRUE	Photosynthesis	$g.MJ^{-1}.m^{-2}$	$mean(RUE)$
crop	-	STDM	Aerial Biomass	$g.m^{-2}$	$max(TDM)$
crop	temperature	TT	Thermal time	$C.d$	$max(TTA2)$
crop	-	GY	Grain yield	$q.ha^{-1}$	$max(GY)$
crop	-	OC	Grain oil content	$\%(drymatter)$	$max(OC)$

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Rey, H., 2003. Utilisation de la modélisation 3D pour l'analyse et la simulation du développement et de la croissance végétative d'une plante de tournesol en conditions environnementales fluctuantes (température et rayonnement). (PhD thesis). Ecole Nationale Supérieure Agronomique de Montpellier, spécialité sciences agronomiques, CIRAD-AMAP / INRA - LEPSE.

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