## The crop dynamic simulation model CELSIUS (CEreal and Legume crops Simulator Under Sahelian Environment)

*Conceptual and mathematical description.*

## Part I. General description and credits to other models.

## CELSIUS (CEreal and Legume crops SImulator Under changing Sahelian environment) is a simulation model and as such it has a conceptual form (i.e. a schematic representation of the system simulated with the main variables and relationships between variables, a mathematical form i.e. the list of mathematical equations of the model, and a software form, the latter with the code expressed in a programming language as well as in a compiled, executable file. In the present document, we provide a simplified conceptual description and a commented, mathematical form of the model. The only exact description of the simulation model, however, is its un-compiled software form, which is available on request at [francois.affholder@cirad.fr](mailto:francois.affholder@cirad.fr), and was written using Microsoft Visual Basic for Application under Microsoft Access, using the principles of interfacing between models and databases in order to facilitate virtual experiments ([Affholder et al., 2012](#_ENREF_5)).

## CELSIUS consists on the previously published model PYE (Potential Yield Estimator - ([Affholder et al., 2013](#_ENREF_3))) plus a number of additions, with a system of simulation options allowing, among other possible combinations, to chose to simulate a crop exactly as PYE would do, or to use all the components forming CELSIUS.

## Thus CELSIUS allows to simulate crop development and growth, total above ground biomass at harvest (AGB) and grain yield (Y) under, depending on the simulation option chosen, the typical potential and limiting conditions corresponding to the concept of yield gap ([Van Ittersum and Rabbinge, 1997](#_ENREF_31); [van Ittersum *et al.*, 2013](#_ENREF_30)). More precisely, CELSIUS simulates AGB0 and Y0 which are respectively total above ground biomass and yield under potential conditions (no limitation other than temperature and radiation), AGBw and Yw corresponding to the same variables under water limiting conditions (rainfall limitation added to the potential conditions), AGBn and Yn under nitrogen limiting conditions (nitrogen limitation added to the potential conditions) and also AGBwn and Ywn under nitrogen and water limiting conditions (nitrogen and rainfall limitations added to the potential conditions).

CELSIUS runs on a daily time step and takes its whole crop development and growth module from STICS ([Brisson *et al.*, 1998](#_ENREF_10); [Brisson *et al.*, 2003](#_ENREF_9)). Seed germination and crop emergence are calculated as a single phase controlled by thermal time and water content of the topsoil. Crop phenology and potential leaf area index (LAI0) are simulated as determined by photo-thermal time.

Except the calculation of runoff, taken from Albergel *et al.* ([1991](#_ENREF_6)) and the effect on soil evaporation and runoff of a mulch of straw residues, taken from Scopel *et al.* ([2004](#_ENREF_27)). Its whole water balance module comes from Sarra ([Forest and Clopes, 1994](#_ENREF_19); [Affholder, 1997](#_ENREF_2)), also used in the more recent version of the model, Sarrah ([Dingkuhn et al., 2003](#_ENREF_18)). The water balance module of Sarra is based on the classical ‘tipping bucket’ approach ([van Keulen, 1975](#_ENREF_32)) and is very similar to the one used in STICS, hence the possibility to consistently couple the Sarra water balance module with the crop module of STICS while reusing many standard parameters of the latter. The water balance accounts for the interaction between root growth and the seasonal descent of the wetting front of the soil, a feature that proved to significantly affect crop growth in tropical environments with a relatively long dry season and where the soil profile is generally at or below wilting point at the onset of the cropping season ([Affholder, 1995](#_ENREF_1)). Runoff is computed following the approach of Sissoko ([2009](#_ENREF_28)). The latter combines the runoff model from Albergel et al. ([1991](#_ENREF_6)) based on the interaction between the time sequence of daily rainfall and soil crusting, according to a typology of soil crusting sensitivity, and a model of the impact on runoff of a straw mulch decaying over time as in Scopel et al. ([2004](#_ENREF_27)). Soil evaporation is reduced in case of the presence of a straw mulch following Scopel et al. ([2004](#_ENREF_27)) or of a plastic film following Luu Ngoc Quyen ([2012](#_ENREF_24)). A water stress coefficient is computed as a bilinear function of the fraction of transpirable soil water (FTSW) with a threshold parameter as in Allen et al. ([1998](#_ENREF_7)).

A nitrogen stress coefficient is computed using a simple seasonal estimate of N available in soil from mineralization of soil organic matter, mineralization of a decaying biomass added to the soil, N inorganic fertilizers inputs, and symbiotic fixation of atmospheric N2, with a coefficient of N losses through N-leaching and volatilization. The nitrogen stress coefficient is a bilinear function of N available in soil, with a threshold parameter corresponding to the level of N available in soil above which N is not limiting crop growth. This approach of the relationship between N availability and yield reduction relatively to a potential yield is a simplification of the relationships used in the model Field ([Tittonell et al., 2010](#_ENREF_29)) or Quefts ([Janssen et al., 1990](#_ENREF_21)), especially by assuming that P and K limitations as well as interactions of soil pH with N availability are all constant across the set of situations to be simulated.

Under stress resulting from water-limiting or nitrogen limiting conditions, potential daily increase in leaf area index during vegetative growth is multiplied by a stress coefficient which is the lowest value of the water and nitrogen stress coefficients. During post flowering development phases, LAI decrease is accelerated by stresses.

Daily global solar radiation is intercepted by the resulting leaf area index following a beer law with an extinction coefficient, and converted into biomass following a net conversion efficiency approach, the potential efficiency being reduced by temperature below or above an optimum, and by water or nitrogen stress. CO2 concentration of the atmosphere increases conversion efficiency by a coefficient depending on the C3 or C4 type of the crop. A part of the accumulated dry matter is allocated to grain following an harvest index approach coupled with a sink limitation accounting for thermal or water stress during a fruit-forming sensitive stage ([Brisson et al., 1998](#_ENREF_10)).

Sowing date can be simulated as the first date at which the amount of daily rainfall exceeds a certain threshold, within a certain interval of dates. The crop can be killed by extreme stress and a new sowing can automatically be computed using the same decision rule.

**Part II. Detailed mathematical description**

**1. Modelling Options**

*See OptionModelClass in the software code.*

A number of Boolean Variables (having ‘True’ or ‘False’ as the only possible values) are used to set modelling options.

These are *Simlevee, CyberST, ActiveStressH, ActivestressN,* and *CorAlti*

If *Simlevee* is True then germination plus emergence are simulated, else they are forced to input values.

If *CyberST* is True then sowing, germination and emergence are simulated otherwise sowing is set to input value and germination plus emergence are accounted for according to the value of *SimLevee*

If *ActiveStressH* is True then water stress is used to reduce growth (Yw or Ywn calculated according to setting of *ActiveStressN*), else water stress is still calculated but has no impact on growth calculation (Y0 or Yn calculated according to setting of *ActiveStressN*). Whatever its setting *ActiveStressH* has no Impact on germination plus emergence or on crop survival due to extreme water stress.

If *ActiveStressN* is True then nitrogen stress is used to reduce growth (Yn or Ywn calculated according to setting of *ActiveStressH*), else nitrogen stress is still calculated but has no impact on growth calculation (Y0 or Yw calculated according to setting of *ActiveStressH*)

If *CorAlti* is True then Temperature is corrected according to difference of elevation between weather station and simulated plot else temperature from weather station is applied.

**2. Plant development and growth**

*2.1.- Crop emergence*

*See PlanteClass. GerminLevee in the software code.*

A day *n* after the starting day of the simulation is the day of crop emergence if the thermal time accumulated since the day of sowing *jsow*, discounting days with soil moisture below a certain threshold, exceeds a cultivar- dependent thermal time constant *CTger* as follows:

Equation CELSIUS.1

With:

*n*: current day of simulation,

*jsow*: day of sowing,

*Tm(j)* = mean temperature of day j,

*Tger*= cultivar dependent, min temperature for accumulation of thermal time during germination + emergence phase,

*Jlev*= day of emergence,

*WConstGer(j)*: water constraint applied to germination plus emergence, for day *j*. Integer, value 1 (soil water not constraining germination or emergence) or 0 (soil water constraining germination or emergence), Calculated I equation CELSIUS.21,

*2.2 Crop development*

*See PlanteClass. phenoCTphot in the software code*

Five development stages are considered. A day *n* after starting day of the simulation is the day of completion of a certain stage *i* if the accumulated photo-thermal time since the preceding stage corresponds to the thermal constant of stage *i*, as in the following equation:

Equation CELSIUS.2

With:

And

Where:

*Dstge(i)*: day of completion of stage i; Positive integer, Dstge(0)= Jlev

*CT(i):* thermal time accumulated for completing stage i

*tdmin*: base temperature for thermal time accumulation

*tdmax:* maximal temperature for thermal time accumulation

*DL(j)*: photoperiod (astronomic diurnal duration) of day j

*MOPP*: threshold of photoperiod above which cultivar has its development rate reduced by photoperiod.

*SensPhot*: Coefficient of sensitivity of cultivar to photoperiod

*PhotFact*: reduction coefficient applied to development rate when when affected by photoperiod

*2.3 Leaf Area Index (LAI)*

*See PlanteClass. Calcule\_LAI\_SemiAride in the software code*

LAI on day *n* *(LAI(n)* is computed by adding *dlai(n)*, a daily increase (or decrease if negative), of LAI to the LAI of the previous day (*n-1*).

a) During development stages 1 and 2, daily increase of LAI (*dLAI(n))* for a day *n* is calculated using equations taken from STICS as follows:

Equation CELSIUS.3

)

With

And

Where

*f(Tm(n))* is the same function as in equation CELSIUS.2

*dLAImax*: maximum daily increase of LAI

*Vlaimax* is a general parameter defining the slope at inflexion point of dLAI as a function of thermal time.

*densplt*, stand density

*Ulai(n)* leaf development unit (equal to *Vlaimax* at inflexion point of *dlai(n)*, equal to 3 at end of stage 2)

*NTT(n):* normalized thermal time

*LAIcomp*: LAI threshold above which competition between plants for light occurs

*Δidens:* effect of stand density on LAI

*bdens*: cultivar dependant stand density threshold above which leaf area per plant is influenced by stand density

*adens*: cultivar dependant parameter defining the sensitivity to stand density of leaf area per plant when stand density is above *bdens*

*LAIStress(n):* stress coefficient applied to leaf area index (0 when stress is maximal, 1 when no stress occurs), calculated in equation CELSIUS.31

b) During development stage i among stages 3 to 5 (senescence of leaves accelerated by stress) LAI dynamics is simulated as follows:

Equation CELSIUS.4

With

And:

*SensSen*: cultivar dependent sensitivity coefficient for leaf senescence accelerated by stress

*LaiRec*: cultivar dependent potential value (in the absence of any stress) of LAI at maturity

*ΔLAIpot*: potential average decrease of LAI after stage 2, in the absence of stress

*2.4 Above Ground Biomass*

*See PlanteClass.biomassein the software code*

Intercepted solar radiation *raint(n)* for a day *n* is given by:

Equation CELSIUS.5 (taken from STICS)

Where:

*ParSurRg* is the ratio of photosynthetically active over total global solar radiation

*Rg(n)* is global solar radiation of day n

*kext*: a cultivar-dependent extinction coefficient.

Total aboveground biomass of day n (*Biom(n)*) is computed by adding *dBiom(n)*, the daily increase of biomass, to *Biom(n-1)*.

dBiom(n) is calculated using the following equation taken from STICS:

Equation CELSIUS.6

With:

Where:

*CO2c* is the atmospheric concentration of CO2 at the time of the simulation

*alphaCO2* is a cultivar dependant coefficient, mostly accounting for the C3 (*alphaCO2*=1.2) or C4 (*alphaCO2*=1.1) type of photosynthesis cycle of the species.

*Ebmax* is the cultivar dependent maximum efficiency of net conversion of intercepted photosyntetically radiation into biomass

*BiomStress(n)* is the stress coefficient applied to Biomass (0 when stress is maximal, 1 when no stress occurs), calculated using equation CELSIUS.31

*2.5 Grain yield*

*See PlanteClass.Rendement in the software code*

Grain yield is calculated using equations taken from STICS

A non sink limited harvest index *HI(n)* on day *n* linearly increases with time at a cultivar dependent rate *Vitircarb*, starting at the first day of stage 4 and ending at maturity (*DayStge(5)*), and with a cultivar dependent ceiling value *HImax*, following the two equations below:

Equation CELSIUS.7:

When calculating final grain yield Y, sink limitation may occur due to a cultivar dependent ceiling value of the weight of 1 grain, *P1gmax*, and a grain number *Ngrains*, limited by possible stress impacting average growth rate *Vitmoy* during a Nbjgrain number of days preceding grain filling stage (starting a *DayStge(3))*, as follows:

Equation CELSIUS.8:

With

And

Where:

*Cgrain* and *Cgrainv0*: cultivar dependant parameters.

*2.6 Root growth*

*See PlantClass.Croirac in the model code*

Root biomass is not explicitly simulated, but the depth of the rooting zone, *Zrac(n)* is dynamically simulated from germination to *DayStge(3)* with a daily rate of root descent governed by thermal time, limited by the thickness of wet soil below root zone and by a maximal root depth *Zracmax*, as follows for a day *n*:

Equation CELSIUS.9

Where:

*WZuR*: Thickness of soil below the current root zone having moisture above wilting point (calculated using water balance equations.

*DeltaRMAx*: cultivar dependent maximal rate of root descent per unit thermal time.

**3. Mulch or soil - climate interface**

*3.1 Mulch biomass (Not used in the study)*

*See MulchClass.BiomasseMulch in the software code*

Equations taken from Scopel *et al.*, 2004.

The biomass of a straw mulch possibly present over the soil’s surface, *Qpaillis(n)*, is assumed to decrease with time except in case an amount *QpaillisApport(n)* is added that day:

Equation CELSIUS.10

Where:

: calibration parameter depending on the composition of mulch

An empirical relationship is used to convert *Qpaillis(n)* into the fraction of soil covered by the straw, *FracSoilCover(n)*:

Where

: calibration parameter depending on the composition of mulch

*3.2. Runoff*

*See MulchClass.Ruissellement in the software code*

The model combines a model from Albergel et al. (1991) for bare soils, with the model of mulch reducing runoff from Scopel et al. (2004), according to the following equation:

Equation CELSIUS.11:

Water supply *precip(n)* (consisting on Rainfall plus Irrigation of the day) is split into runoff *Ruis(n)* and water infiltrated into the soil and a straw mulch possibly present on the soil’s surface, accounting for LAI reducing runoff, a typology of crusting of soil’s surface, the biomass of straw mulch, and an indicator *IKJ(n)* characterizing the rainfall sequence of the previous days, increasing with the amounts of rainfall and decreasing when the number of days between rainfall events increases:

With:

And

Where:

*b\_ruis*: a parameter controlling the increase of runoff due to the presence of a straw mulch (generally a negative value, since straw mulch generally decreases runoff)

*Ap1…Ap4:* empirical coefficients controlling runoff on the part of the soil directly exposed to the impact of rain drops. When *Ap2…Ap4* are set to zero, *Ruis(n)* is a constant proportion *bruis* of the share of daily rainfall exceeding a threshold *Seuil\_Ruis*, equal to *Ap1* in this particular case. When *Seuil\_Ruis* is set to zero and *Ap1…Ap4* are non zero, these coefficients correspond to a typology of soil surface status as in Casenave and Valentin ([1989](#_ENREF_12); [Casenave and Valentin, 1992](#_ENREF_13)) as follows:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Soil surface type | Vesicular porosity | Ap1 | Ap2 | Ap3 | Ap4 |
| 1: no crust or predominant structural crust with remnant aggregates | <5% | 0.2 | 0.03 | 0.004 | 3 |
| 2: runoff crust covering less area than structural crust | 5 -30% | 0.35 | 0.04 | 0.004 | 3 |
| 3: runoff crust predominating | >30% | 0.900 | 0.05 | 0.002 | 10 |

Water a available for infiltration into soil and the porosity of the straw mulch is *W\_SM(n)*:

Equation CELSIUS.12

*3.3. Water stored into a porous straw mulch and evaporated (not used in the study)*

*See MulchClass.BilanMulch in the software code*

Equations taken from Scopel *et al.*, 2004.

Straw mulch is assumed to have a certain capacity *CapacityMulch*, per unit o mulch biomass, for storing water, the corresponding reservoir *Stmulch* being updated on a day *n* as follows:

Equation CELSIUS.13

Where:

*Emulch(n)* is the amount of water lost by mulch on day *n* by evaporation

The water available for soil infiltration Win(n) is the part of W\_SM(n) not stored in Stmulch(n)

Potential evaporation *EoSM(n)* at the top of the straw mulch is calculated on a day *n* assuming that reference Penman-Monteith potential evaporation *ETP(n)* is reduced by LAI using an extinction law analogy as follows:

Equation CELSIUS.14

Potential evaporation applied to mulch, *EoMulch(n)* is calculated as follows:

Equation CELSIUS.15

Where:

*Gamma\_mulch* is a calibration coefficient depending on the species constituting the straw mulch.

Actual evaporation of mulch *Emulch(n)* is calculated as :

Equation CELSIUS.16

*Edecomp* is the amount of water contained in the quantity of mulch that decayed since the previous day:

**4 Soil water balance**

*4.1 Soil moisture*

*See SolClass.EauSol in the software code*

The soil moisture model is taken from SarraMillet (Affholder, 1997)

Four main water reservoirs are accounted for dynamically, all having a water storage capacity calculated as the product of the thickness of the reservoir and a total available water per unit thickness TAW, the latter being constant throughout the soil, and calculated as follows:

Equation CELSIUS.17

Where:

*hmin* and *hcc*: soil water content respectively at wilting point and at field capacity (in mass of water per mass of soil)

*da*: soil bulk density

The four mains water reservoirs are the following:

*Stger*, with a constant thickness *Zger* and starting at topsoil: contains the water impacting germination and seedlings growth until crop emergence.

*Stsurf* with a constant thickness *Zsurf* and starting at topsoil: contains the water impacting soil evaporation.

*Strac* with a dynamic thickness *Zrac* and starting at topsoil, calculated by equation CELSIUS.9, contains the water impacting crop transpiration, i.e. the transpirable soil water.

*Stdeep* with a dynamic thickness *Zsol-Zrac*, starting immediately below *Zrac* and ending at soil maximum depth *Zsol*.

More specifically three accessory reservoirs *Stnonrac* (thickness=*Zracmax-Zrac*), *Stmes* (*Zmes*), and *StTot* (*Zsol*) are calculated using the same principle, allowing calculation of drainage below the part of soil actually explored by roots at the end of root growth period, comparisons of simulated soil water with measurements performed down to a depth *Zmes* possibly differing from *Zsol*, and the calculation of the overall soil balance (*StTot* being the sum of *Strac* and *Stnonrac*).

For any of these reservoirs, noted generically *Stres(n)* or a reservoir of thickness *Zres*, the water balance accounting for soil evaporation *Esol(n)* and crop transpiration *Transpi(n)* is calculated as follows for a day *n*:

Equation CELSIUS.18

Where:

*CEres* and *TEres* are coefficients distributing Evaporation and transpiration among the reservoirs as follows:

*CEres=1* in *Stsurf, Zger/Zsurf* in *Stger, Zrac/zsurf* until *zrac* is greater than *Zsurf in Strac,* and *0* in *Stdeep*

*TEres= Zrac/Zsurf*, in *Stsurf* until *Zrac* overcomes *Zsurf, Zsurf/Zrac* afterwards*, Zrac/Zger* in *Stger* until *Zrac* overcomes *Zger, Zrac/Zger* afterwards*, 1* in *Strac,* and *0* in *Stdeep*

And:

*WIn(n)* is water input into the reservoir, corresponding to the drainage from the reservoir immediately above if applying or corresponding to water from irrigation or rainfall infiltrated into the soil.

Water *Dres(n)* drained out of a reservoir is calculated as the amount of water exceeding the storage capacity of the reservoir when calculating the balance, as follows:

Equation CELSIUS.19

Water constraint *WCSres(n)* is calculated for a reservoir *Stres(n)* as the ratio of actual water content of the reservoir over its storage capacity as follows:

Equation CELSIUS.20

This applies to *WCsurf(n), WCger(n)* and *WCrac(n*), the water constraint respectively in the surface reservoir (water constraint reducing evaporation relatively to potential evaporation), in the germination plus emergence reservoir and the root zone reservoir (limiting transpiration relatively to potential).

The factor in equation CELSIUS.1, delaying germination and emergence in the reservoir *Stger(n)* is calculated from *WCger(n)* as follows*:*

Equation CELSIUS.21

*4.2 Soil evaporation*

*See SolClass.Evaporation in software code*

Potential soil evaporation *Eos(n)* is calculated accounting from the reduction of energy reaching soil surface due to the presence of leaves and a straw mulch as follows:

Equation CELSIUS.22:

Soil evaporation *Esol(n)* on a day *n* is calculated as follows:

Equation CELSIUS.23:

Where:

*SeuiEvap*: soil dependent calibration parameter

*4.3 Crop transpiration*

*See CultureClass.CalcTranspiMC in the software code*

Potential evapotranspiration is calculated using a crop coefficient *KC(n)* approach taken from STICS, in which *Kc(n)* is calculated with an empirical relationship between *Kc(n)* and *LAI(n)*, and taken as follows:

Equation CELSIUS.24

Where:

*Kmax* : cultivar-dependent parameter

Potential crop transpiration *eo(n)* is calculated using the classical crop coefficient approach applied to Penman-Monteith reference potential evapotranspiration *Etp(n)*:

Equation CELSIUS.25

Potential crop transpiration *eop(n)* is calculated by subtracting potential evaporation to *eo(n)*, and accounting for an increase of up to 40% in the atmosphere’s water demand at the vicinity of the crop when soil (and mulch) evaporation is low:

Equation CELSIUS.26

Actual transpiration is reduced by the fraction of transpirable soil water following the approach of Allen *et al.* (1998) as follows:

Equation CELSIUS.27

**5 Stress calculations**

*5.1 Nitrogen constraint*

*See PlantClass. stressAzoteOld in the software code*

A nitrogen limiting coefficient is calculated as follows:

Equation CELSIUS.28

Where:

, , , and are the mineral nitrogen amounts available to crops from, respectively, soil organic matter mineralization, inorganic fertilization, mineralized N from organic fertilization, and symbiotic fixation of atmospheric N by leguminous crops

is the level of nitrogen supply above which growth is not limited,

a calibration coefficient (less than 1) accounting for losses of mineral N through volatilization and leaching.

*5.2 Temperature stress applied to biomass growth*

*See PlanteClass.Biomasse in the software code*

Equation taken from STICS

Equation CELSIUS.29

*Tcmin, tcopt, tcma*x: cultivar-dependent parameters, respectively the minimal, optimal and maximal air temperatures for light to biomass conversion efficiency

*5.3 Water stress*

*See PlanteClass. Calcule\_LAI\_SemiAride and PlanteClass.Biomass in the software code*

Water stress reducing biomass growth (*WSfactBio(n)*) and LAI growth (*WSFactLAI(n)* a day *n* are calculated using the respective thresholds *WSBioT* and *WSLaiT* of the reduction of the fraction of available soil water above which growth is reduced relatively to potential, as follows:

Equation CELSIUS.30:

*5.4 Interactions between water and nitrogen stresses.*

*See PlanteClass. Calcule\_LAI\_SemiAride and PlanteClass.Biomass in the software code*

The stress factors and reducing growth in LAI and aboveground biomass (equations 3 and 6) respectively are calculated as follows:

Equation CELSIUS.31

**Part III. Details about model calibration and test**

CELSIUS involves a number of empirical parameters, a majority of which are cultivar-dependent, that had to be estimated by calibrating the model against measurements of key variables controlled by these parameters.

The data set used for calibration and test was the data set of millet plots detailed in Affholder (1997), plus data of groundnut plots from the ESPACE-PRODCLIM database ([Forest and Cortier, 1989](#_ENREF_20)) and data of maize plots under the savannah environment of the Cerrado region of Brazil, as presented in Affholder *et al* ([2003](#_ENREF_4)) and Affholder *et al* ([2013](#_ENREF_3)). The soil water balance model as well as the sowing and emergence model, and their calibration parameters, were taken almost unchanged from Sarra-miilet that provided reliable predictions of soil moisture and date chosen by farmers for sowing as depending on the rainfall sequence (Affholder, 1997). Readers may therefore refer to this publication for details about calibration and test of these components.

Cultivar and species dependent parameters relative to growth and development under non nitrogen limited environment of millet cultivar ‘Souna3’, the cultivar most commonly grown in Senegal, were taken unchanged from Affholder *et al* (2013). This also applied to species dependent parameters relative to maize. Readers interested to specific values and the literature sources in which they were found may refer to that article.

Two groundnut cultivars had to be considered, each for one of the two subzones of the study, namely the cultivars 55-437 and 73-33, used respectively in the Sine and Saloum zones. Species dependent parameters were taken from the literature (table 1). Thermal time development constants of these cultivars were obtained by summing thermal time over the corresponding observed dates of beginning and end of the key phenological stages as recorded in plots of the ESPACE database. Cultivar-dependent parameters of groundnut were calibrated using the same principle as in Affholder *et al*, (2013), and notably parameters Cgrain and CgrainV0 were estimated for each cultivar by fitting the simulated number of grains to the boundary line of observed Ngrain plotted against simulated Vitmoy, for the whole set of groundnut plots in the database and setting the model for PYE calculation (*i.e.* with nitrogen stress not accounted for).

Except for thermal time constants, too few data were available in our database for calibrating with the same method as above the cultivar dependent parameters of maize for cultivar Noor96. We instead adapted the parameters of a cultivar used in family farms of Brazil, for which PYE had been previously calibrated ([Affholder et al., 2003](#_ENREF_4)), to obtain a potential yield Y0 of 3Mg.ha-1, matching with the potential yield claimed in the technical leaflet provided with seeds of that cultivar.

The parameters relative to nitrogen limitations (Nsymb, Ifertmax/ ) were set so that the maximum and median values of simulated AGBwn and Ywn, over the set of historical weather data of each of the two Sine and Saloum subzones, was equal to the maximum and median observed value in the database for the species and crop management considered, for each of the following crop management types: MilExt on bushfield, MilManu on bushfield, MilManu on homefield, GroundExt on bushfield, GroundManu on bushfield (see table 1 on main text for characteristics of the cropping systems).

Figure 1 shows a final comparison, after calibration of CELSIUS, between simulated and observed yield for Millet, using the same data set as in the validation of SarraMillet ([Affholder, 1997](#_ENREF_2)) with the exception of 12 plots (over 89) from a village in the north of the millet production area, for which rainfall data have been lost. With this plot sample for which Nitrogen amounts brought by organic and inorganic fertilization as well as organic N stocks in soils had been estimated in each plot, the model shows a relatively good capacity to predict the impact of nitrogen inputs and varying water stress on millet yield, as also denoted by the relatively satisfactory values of the Relative Root Mean Square of Error (RRMSE) and of model efficiency (ME), of respectively 27% and 0.68.

Table 1 : Species dependent parameters taken from the literature for simulation of groundnut. See Affholder *et al*, 2013 for parameters relative to Millet and Maize.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Value | Unit | References |
| tdmin | 10 | °C | ([Leong and Ong, 1983](#_ENREF_23); [Mohamed *et al.*, 1988](#_ENREF_25); [Bell and Wright, 1998](#_ENREF_8); [Caliskan *et al.*, 2008](#_ENREF_11)) |
| tdmax | 45 | °C |
| tcmin | 10 | °C |
| tcmax | 45 | °C |
| tcopt | 32 | °C |
| Ebmax | 2.6 |  | ([Sarr *et al.*, 2004](#_ENREF_26); [Clavel *et al.*, 2005](#_ENREF_14); [Kiniry *et al.*, 2005](#_ENREF_22)) |
| kext | 0.62 |  |
| HImax | 0.47 |  |
| LAImax | 6 |  |
| Zracmax | 170 | cm | ([Allen et al., 1998](#_ENREF_7); [Collino et al., 2000](#_ENREF_15); [Collino et al., 2001](#_ENREF_16); [Dardanelli et al., 2004](#_ENREF_17); [Sarr et al., 2004](#_ENREF_26)) |
| Kmax | 1.2 |  |

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| Figure 1. Model test after calibration |  |  |
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