# **Simulation of Crop Yield**

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The inputs to the model are:



* crop management (input manejo),
* soil description (input suelo),
* daily climate variables (input clima) and
* crop characteristics that describe its response to these variables (input cultivo).
* It’s a daily step model in which the main daily outputs is biomass.

# **Summary**

The main equation of the model (conceptual) is:

|  |  | (Eq. 1) |
| --- | --- | --- |

where *b* is the biomass at the end of the period, r = f(PAR,CT,EUR) (section 1) is the rate of daily growth dependent on PAR, EUR, and CT , CE is a weather stressor (section 2 and 3), δi indicates the occurrence of flood and δ = 0 (flood), and δi = 1 (no flood) (Section 4). The yield R is:

|  |  | (Eq. 2) |
| --- | --- | --- |

where IC is the "indice de cosecha".

# **Simulation of potential yield *r(t)***

Crop yield *R* is the product of the total amount of *b* produced per surface area and *IC* (total amount of biomass that is…) (Eq.2). The model estimates *b* at each day of simulation either until the crop reaches crop maturity, or the growth is affected by an environmental stressor (section 4). The total amount of biomass *b* obtained at the end of a period *i* (bT) is estimated by the following equation:

|  |  | (Eq. 3) |
| --- | --- | --- |

where the amount of biomass accumulated at day *i* (bi) is added to the amount accumulated the previous day (*bi-1*). The daily value of biomass (bi) is computed as:

|  |  | (Eq. 4) |
| --- | --- | --- |

Equation 4 (Figure 2) represents the relationship between the total amount of solar radiation that reaches the surface and is available to plants (PAR), the fraction of this solar radiation that it´s captured by the crop (%CT) and the efficiency in which this PAR it´s transformed into b (EURAct). PAR is a meteorological input (Input clima). Generally, this value corresponds to 0.45% of the daily solar radiation (MJ m-2).



## Crop phenology

In this version of the model it’ll not be developed.

## Capture of solar radiation

As crops grow new leaves are developed which gradually cover the area around plants, which in turn increases the interception of solar radiation (fPAR). The percentage of area covered by leaves is the % cobertura (CT, Figure 3). The maximum attainable value (Cmax) depends on the crop species and management variables like plant population. Those variables also affect the time in which this % is obtained (ds,max).

When the crop reaches its senescence status at ds,sen days after sowing, the %cobertura is reduced as leaves fall. Another parameter required it’s the initial cover Cin percentage (% of CT) - Cin is a function of crop type and management practices. The parameters 𝛼 and 𝛽 indicate the potential daily increment of the CT and are defined in equation 5. Those are obtained by dividing the difference between Cmax and Cin by the number of days until ds,max orthe end of the crop cycle for 𝛼 and 𝛽 respectively. In the Table 1 some parameters are described for maize. where CEH coeficiente de estrés hídrico para expansión foliar iis described in section 3.2 equation 15.



|  |  | (Eq. 2)  (Eq. 3) |
| --- | --- | --- |

Table 1: value of crop parameters under optimal growing conditions for Maize.

| Crop | Plant population (pl m-2) | Cin (%) | Cmax (%) | 𝛼(% d) | 𝛽 (% d) | din | dfin | dS,MAX | dS,SEN |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Maize | 6 | 0.39 | 89 | 1.39 | 1.3 | 7 | 120 | 55 | 82 |
| Maize | 8 | 0.52 | 99 | 1.37 | 1.3 | 7 | 120 | 49 | 79 |

## Radiation use efficiency

The efficiency in which PAR is transformed into b is called radiation use efficiency (EUR g MJ m2). This parameter depends on the crop specie and is affected by temperature and water.

EURAct expressed in g MJ m2 results from the following equation:

EURAct = EURPot \* T°EUR \* CEHR (Eq.5)

The potential radiation use efficiency (EURPot.) is an input Cultivo value, as it depends on the crop specie that is being simulated. This value, is also affected by the daily mean temperature (T°EUR) and the amount of water (CEHR). Under optimal conditions for crop growth only temperature effects are considered, assuming a value for CEHR of 1.

The relationship with temperature, as seen in Figure 4, responds to an optimum (2 to 3 in Fig.4) in which the EUR is maximum and beyond those limits it's being affected till it reaches the critical upper and lower points (T°base EUR 1 and 4 respectively) in which the coefficient becomes zero and the efficiency is null. Those values for some crops are included in Table 2. 



| Crop | T°br (°C) | T°or1 (°C) | T°or2 (°C) | T°cr (°C) | EURPot (g MJ m-2) |
| --- | --- | --- | --- | --- | --- |
| Maize | 8 | 29 | 39 | 45 | 3.65 |
| Soybean | 10 | 20 | 30 | 40 | 0.86 |
| Wheat | 2 | 15 | 25 | 35 | 1.25 |

## Yield estimation

Once daily biomass is defined and crop cycle ends, the final yield is estimated by equation 2. Some reference values of biomass, yield and IC are shown in table 3.

| Crop | Biomass (g m-2) | Yield (g m-2) | IC |
| --- | --- | --- | --- |
| Maize | 1996-2576 | 856-1245 | 0.43-0.50 |
| Soybean | 546-1088 | 317-479 | 0.40-0.50 |
| Wheat | 1331-1992 | 409-806 | 0.30-0.40 |

# Simulation of water balance

## Available soil water

The soil could be seen as a reservoir of water in which the maximum volume of water that can be stored (AUT;mm) corresponds to the total amount of water in the soil when it's saturated. The actual amount of water that is available for the crop (ADT) is obtained by balancing the inputs and outputs of water in the soil system. The amount of water that is available to the crop could be expressed as a percentage of the AUT (% AU).

The value of %AU is used by the model as a threshold for the estimation of stress that affects growth (see section 3). By threshold, they mean an upper bound?

## Estimation of the AUT

The total amount of water that could be stored in a soil depends on its characteristics referring to soil type and texture. The maximum water that a soil can hold it’s called CC (mm3 mm-3) and the minimum PMP (mm3 mm-3). The AUT result from multiplying CC by the soil depth. However not all the water contained in the soil could be extracted by crops, existing a lower limit in which the soil water retention don’t allow the plant to consume this water, this limit is the PMP. So AUT is defined as follows.

AUT = (CC \* soil depth) – (PMP \* soil depth) (Eq.5)

As the crop grows, root exploration become deeper and new soil layers are explored. This need to be considered in the estimation of the AUT because at early crop growth not all the water in the soil could be used by the crop. For this purpose, the soil could be divided in two layers C1 and C2 and AUT be estimated by the sum of each one (AU1 and AU2 respectively).

At early stages of crop development only C1 is considered. As the crop growths and new layers of soil are explored by the roots, AU2 starts being considered. The root exploration is considered by the Eq.6 where the root growth of the simulated day (Crec. Raíz díario – mm día-1) is added to the root depth of the day before (Prof. raíces i-1). The value of the root depth (Prof. raícesi is then used for the daily estimation of the AU2. Both parameters are input cultivo.

Prof. Raícesi (mm) = Prof raíces i-1 + Crec. Raíz diario (mm día-1) (Eq.6)

A general diagram of those relations is shown in figure 5, and in table 4, the daily root growth for different crops.



| Crop | Crec. Raíz diario (mm dia-1) |
| --- | --- |
| Maize | 30 |
| Soybean | 34 |
| Wheat | 21 |



## Estimation of ADT

Total available water is estimated daily by a balance between the inputs and the outputs of water. In the model the ADT is estimated for the two soil layers described above separately. For the first soil layer (A.disp1) ADT could be estimated by: i) Equation 7 ; ii) SMAP images (sm\_rootzone).

A.disp1 = A.disp 1 x-1 + precipitations – superficial drainage – run off – soil evaporation– crop transpiration (Eq.7)

For the second soil layer, A.disp 2 is estimated as follows.

A.disp2 = A.disp 2 x-1 + percolation – drainage – crop transpiration + available water for root extension (Eq.8)

The parameters of the above equations and their estimations are divided in inputs and outputs of water for their explanation.

### Inputs of water

For the first soil layer the only input of water are daily precipitations obtained by the input clima. For the second soil layer the inputs came from percolation of the upper soil layer and the new available water as a consequence of new soil exploration as root depth. Percolation is the same value of the drainage amount of water of the first layer of soil (see outputs for further explanation).

### Outputs of water

#### Superficial drainage

Drainage occurs in both soil layers. It starts to be considered when ADT of a layer is higher that AUT. The extra amount of water resulting by the difference between AUT-ADT will drain according to a drainage coefficient (Coef. Drenaje) that came from “input suelo” and depends on soil characteristics. That coefficient indicates the percentage of water that will drain per day after the soil is saturated (Table 3). In the figure 6 it’s exemplified how this coefficient works. 

In the figure above, “drenaje = 0 si agua disponible ≤ agua útil” es un poco confuso, yo podría los nombre completos “drenaje = 0 si agua disponible en el suelo ≤ máxima agua útil que el suelo puede contener” o las variables “Drenaje = 0 si AD\_T ≤ AU\_T”.

#### Run off

Run off is the amount of water that could not infiltrate into the soil after a rainfall. That depends on the soil texture and the amount of rainfall. As seen in figure 7, as the amount of precipitation increases more water is lost do to run off. Soil texture also modifies this relationship and it’s included in a calculation scheme called curve number (CN). This is an “input suelo”. The equation for it’s estimation is described next (Eq.9).

Escorrentia = (PP - (0.2) \* S)2 / (PP + S - (0.2) \* S) (Eq.9)

S = 254 \* (100/CN -1) (Eq.10)

PP corresponds to the total amount of precipitation that reaches the soil (Input clima) and in which S (mm) is the potential maximum storage (Eq.10). PP that falls on unsaturated soil infiltrates until the topsoil layer becomes saturated. Since then additional PP starts to run off. Soils with higher CN will have less S and may lose more water as run off. See table 3 for some reference values.



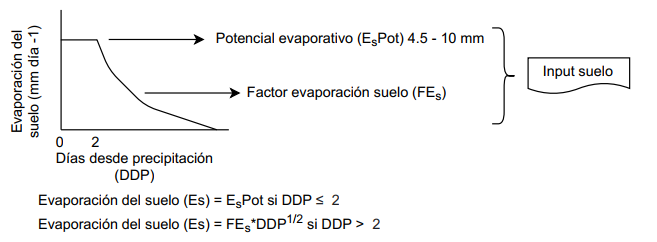
**Table 3**. Reference values of Coef. drenaje and CN for four different types of soils textures (Jones et al., 2003).

| **Soil type** | **Soil depth (layers)** | **Coef. drenaje** | **CN** |
| --- | --- | --- | --- |
| Silty clay | 0-60 | 0.1 | 89 |
| Silty clay | 60-210 | 0.25 | 86 |
| Silty loam | 0-60 | 0.2 | 81 |
| Silty loam | 60-210 | 0.35 | 78 |
| Sandy loam | 0-60 | 0.4 | 74 |
| Sandy loam | 60-210 | 0.5 | 69 |
| Sand | 0-60 | 0.4 | 75 |
| Sand | 60-210 | 0.55 | 67 |

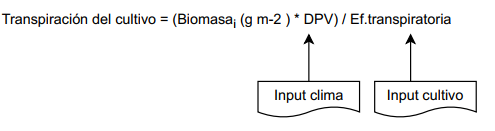
#### Soil evaporation

For the estimation of soil evaporation first a potential evapotranspiration of the soil from a wet surface needs to be set as “input soil” variable (EsPot) this value usually goes through 4.5 to 10 mm and depends on the soil texture. At first, the evaporation is at its maximum, and the soil dries at its potential evaporation (figure 8). Two days after its saturation soil evaporation starts to decline as described in equation 11 in which FEs is a constant that depends on soil characteristics. The value that it takes goes from 1.7 to 8.2. This it’s obtained by the “input suelo”.

Evaporación del suelo = FEs \* DDP1/2  (Eq.11)



#### Crop transpiration

Crop transpiration and growth are linked because each process depends on air diffusion thought stomata. So, crop transpiration is estimated from daily bi, vapor pressure deficit (DPV; “input clima”), and a coefficient of transpiration efficiency (“input cultivo”). Figure 9 express those relationships between the three components.

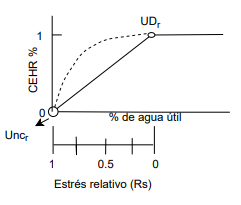


| Crop | Ef. Transpiratoria (Pa) |
| --- | --- |
| Maize | 9.0 |
| Soybean | 4.5 |
| Wheat | 5.8 |

# Water stress coefficients CE

Crops respond to soil water content limiting the growth. The %AU could be used as an estimator of stress of the crop. This affects the EURPot and the CT. Those effects are summarized below.

## 3.1. Water stress effects on EURPot

The EURPot is not only affected by temperature (see section 1.3) but also by water. The relation is described in the figure 10 in which exists a threshold value (UDr) since the value of CHER (%) became smaller affecting to a greater extent the EURPot (see Eq.5 in section 1.3). Both UD and Uncr are input cultivo parameters. The shape of the response curve solid or dotted line will depend on the crop characteristics in their response to water deficit (Dotted line more tolerant). 

**Figure 10.** Effect of %AU on CEHR. UDr indicates the threshold of response in which the coefficient starts to decline affecting EURPot. Uncr indicates the point in which the crops stop growing. And Rs the relative stress.

The equation that describes this relationship is the following.

CEHR = 1 - ((eRrs \* cof.formaR - 1) / (ecoef.formaR - 1 )) (Eq.12)

Where Rrs is the relative stress equation 13 and cof.forma is the parameter that describes the shape of the curve. Both are “input cultivo”; those values for different crops could be found in table 5.

Rrs = (%AU - Uncr) / ((UDr - Uncr)/100) (Eq.13)

## 3.2 Water stress effects on canopy expansion

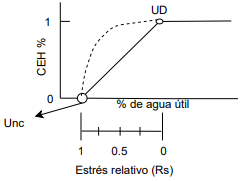
Under water stress the daily canopy expansion is being affected producing a reduced increment of daily CT. This relationship depends on the %AU of the soil in which exist a threshold value (UD) since the value of CHE (%) became smaller affecting to a greater extend the CT (figure 11). so under rain feed conditions a new equation it´s added to the model for take into account these relationships (Eq.12). in the equation, the daily value it’s multiplied by the CEH and added to the value of CT of the day before.

CT% = CT-1 + (CTi \* CEH) (Eq.14)

The magnitude of the CEH will depend on the relative stress (Rs) and shape of the curve (dotted line Fig.11). Rs is the relative value of stress between the two limits (UD and Unc respectively). CEH is calculated as follows.

CEH = 1 - ((eHrs \* cof.formaH - 1) / (ecoef.formaH - 1 )) (Eq.15)

Where Rs is the relative stress (equation 16) and cof.formaH is the parameter that describes the shape of the curve. Both are “input cultivo”; those values for different crops could be found in table 5.



**Figure 11.** Effect of %AU on CEH. UD indicates the threshold of response in which the coefficient starts to decline affecting %CT. Unc indicates the point in which the crops stop growing. And RS (relative stress).

Hrs = (%AU - Unc) / ((UD - Unc)/100) (Eq.13)

**Table 5**. Reference values of Coef.forma and threshold for CEHR and CEH estimation for different crops.

| Crop | Coef.formaH | Coef.formaR | Unc | UD | Uncr | UDr |
| --- | --- | --- | --- | --- | --- | --- |
| Maize | 2.9 | 6.0 | 0.4 | 0.72 | 0 | 0.69 |
| Soybean | 3.0 | 3.0 | 0.15 | 0.65 | 0 | 0.50 |
| Wheat | 5.0 | 2.5 | 0.20 | 0.65 | 0 | 0.65 |

# Catastrophic events coefficients (δi)

## 4.1 Floods

Sat??

## 4.2 Frost

The effect of low temperature is considered in Figure 4. In which as the temperature became lower EURpot is affected producing a reduction in the daily growth.

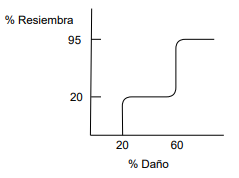
## 4.3 Hail

Once a meteorological event of hail and the % of damage is identified, the % of reseeding is estimated based on the figure 12 and the Equation 15. The % of damage is an “input clima”.

% resiembra = 0% if %Daño < 20%

20 to 95% if 20% < %Daño < 60% (Eq.16)

95% if %Daño > 60%

**Figure 12.** Percentage of “resiembra” as a function of %damage. 

# Appendix

The inputs required for crop simulation are described below.

## 5.1 Input suelo

Those values are obtained by the “Carta de suelos” available online.

https://gn-idecor.mapascordoba.gob.ar/maps/294/view

| **Variable** | **Name** | **Unit** |
| --- | --- | --- |
| Profundidad máxima del suelo | Soil depth | mm |
| Capacidad campo | CC | mm mm-1 |
| Punto de marchitez permanente | PMP | mm mm-1 |
| Potencial evaporativo del suelo | EsPot | mm |
| Factor evaporación suelo | FEs |  |
| Coeficiente drenaje | Coef. Drenaje | % |
| Agua util total | AUT | mm |
| Agua disponible | ADT | mm |
| Porcentaje de agua útil | %AU | % |
| Capa del suelo uno | C1 | -- |
| Capa del suelo dos | C2 | -- |
| Agua util de C1 | AU1 | mm |
| Agua util de C2 | AU2 | mm |
| Agua disponible de C1 | A.disp1 | mm |
| Agua disponible de C2 | A.disp2 | mm |
| Curva número | CN | % |

## 5.2 input clima

| **Variable** | **Name** | **Unit** |
| --- | --- | --- |
| Temperatura máxima | Temperatura máxima | °C |
| Temperatura mínima | Temperatura mínima | °C |
| Precipitaciones | PP | mm |
| Radiación solar diaria | Radiación solar | Mj m-2 |
| Déficit de presión de vapor | DPV | Pa |
| Radiación fotosintéticamente activa | PAR | Mj m-2 |
| % de daño producido por granizo | %Daño | % |

## 5.3 input manejo

| **Variable** | **Name** | **Unit** |
| --- | --- | --- |
|  |  |  |
|  |  |  |

## 5.4 input cultivo

| **Variable** | **Name** | **Unit** |
| --- | --- | --- |
| Cobertura total | CT | % |
| Cobertura máxima | CMax | % |
| Cobertura inicial (%C T). | Cin | % |
| Cobertura incremento diario (%CT) | Ccrec | % día-1 |
| Cobertura decrecimiento diário (%CT) | Csen | % día-1 |
| Días desde siembra dónde se alcanza CMax | DDSmax | Días desde siembra |
| Días desde siembra en dónde comienza a disminuir el %CT | DDSsen | Días desde siembra |
| Eficiencia en el uso de la radiación potencial | EURPot | g MJ m-2 |
| Eficiencia en el uso de la radiación actual | EURAct | g Mj m-2 |
| Temperatura base para EUR | T°base EUR | °C |
| Temperatura optima EUR uno | T° optima EUR 1 | °C |
| Temperatura optima EUR dos | T° optima EUR 2 | °C |
| Temperatura crítica para EUR | T° crítica EUR | °C |
| Indice de cosecha | IC | % |
| Crecimiento diario de raíz | Cre. raíz diario | mm dia-1 |
| Eficiencia transpiratoria | Ef.tanspiratoria | Pa |
| Umbral de no crecimiento radiación | Uncr | %AU |
| Umbral de daño radiación | UDr | %AU |
| Umbral de no crecimiento déficit hídrico | Unc | %AU |
| ºUmbral de daño déficit hídrico | UD | %AU |
| Coeficiente de estrés hídrico para EUR | CEHR | % |
| Coeficiente de estrés hídrico para expansión foliar | CEH | % |