pySolanum: A Python Implementation of the SOLANUM Potato Crop Model for Andean Conditions

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Abstract

The SOLANUM model is a potato crop model capable of estimating tuber yield under water stress, frost, variations in atmospheric CO_2 concentration, and thermal stress. This document presents the main equations of the model, the biomass dynamics, and the soil water balance, as well as the indices related to stress and water use efficiency.

Contents

1 Introduction

SOLANUM is a potato crop model modified from LINTUL-POTATO and adapted for Andean conditions. It requires daily agrometeorological data (precipitation, minimum and maximum temperature, solar radiation, and photoperiod), soil parameters (field capacity FC, permanent wilting point WP, soil depth), and environmental variables such as atmospheric CO_2 concentration.

The model operates with daily time steps and performs iterative calculations in the following order: (a) foliage growth and biomass accumulation, (b) percolation, (c) evapotranspiration, (d) water balance update, (e) effect of water availability on evapotranspiration, and (f) final update of biomass and foliage.

The following figure shows the diagram corresponding to the SOLANUM model.

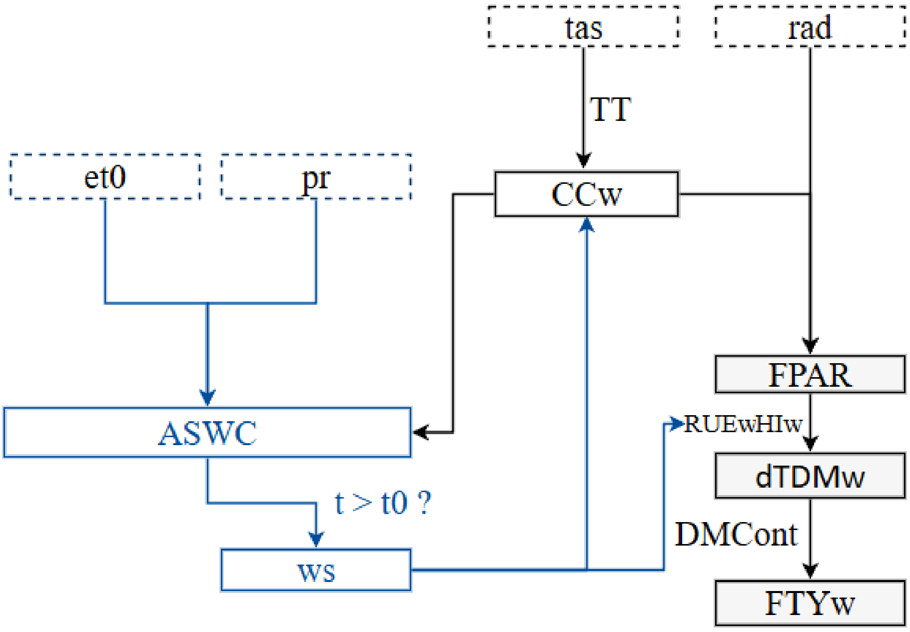

Figure 1: General diagram of the SOLANUM model, showing the main modules for growth simulation and water balance.

2 Biomass Accumulation

The growth rate of a well-watered crop is proportional to the absorbed light and the net assimilation rate. SOLANUM simulates daily dry matter accumulation using the following equation:

$$\mathrm{dTDM}_w = \frac{\mathrm{RUE}_w \cdot \mathrm{CC}_w \cdot \mathrm{PAR}}{100} \cdot \mathrm{HI}_w \tag{1}$$

where:

- dTDM_w is the net assimilation rate of dry matter (t ha^{-1} day^{-1}).
- PAR is the photosynthetically active radiation (MJ m^{-2}), calculated as $\mathrm{PAR} = R_s \times 0.5$.
- RUE_w is the radiation use efficiency for PAR adjusted by stress.
- CC_w is the canopy cover adjusted by water stress.
- HI_w is the tuberization index (fraction of assimilates allocated to the tuber).

Total accumulated biomass is obtained by integrating the rate over time:

$$\mathrm{DTY}_w = \int_{TT=0}^{TT=n} \mathrm{dTDM}_w \, dt \tag{2}$$

Fresh yield FTY_w is calculated as a function of tuber dry matter content DMContent:

$$\mathrm{FTY}_w = \frac{\mathrm{DTY}_w}{\mathrm{DMContent}} \tag{3}$$

3 Effect of CO_2 Concentration

The relative effect of CO_2, CO2relatEffect, on radiation assimilation efficiency depends on the atmospheric CO_2 concentration (ppm) and is defined in ranges:

$$\text{CO2relatEffect} = \begin{cases} 0.0031 \cdot \text{CO2AirConcent} + 0.0093, & \text{if CO2AirConcent} < 330, \\ 0.0007 \cdot \text{CO2AirConcent} + 0.79, & \text{if } 330 \le \text{CO2AirConcent} < 880, \\ 0.000008 \cdot \text{CO2AirConcent} + 1.4223, & \text{if CO2AirConcent} \ge 880. \end{cases} \tag{4}$$

The radiation use efficiency adjusted for CO_2 is given by:

$$\text{RUE}_{CO2} = \begin{cases} \text{RUE}_w \cdot 1.5, & \text{if CO2relatEffect} \ge 1.5, \\ \text{RUE}_w \cdot \text{CO2relatEffect}, & \text{if CO2relatEffect} < 1.5. \end{cases} \tag{5}$$

4 Development and Tuberization

Canopy growth and tuberization depend on accumulated thermal time (TT). Thermal time accumulates daily as:

$$TT_i = TT_{i-1} + k \cdot (T_a - T_{base}) \tag{6}$$

where $T_a = (T_{\min} + T_{\max})/2$ is the daily mean temperature and T_{base} is the crop base temperature.

4.1 Canopy Cover (CC)

The dynamics of leaf expansion are described by the following function (form proposed in the original document):

$$\text{canopy} = w_{max} \cdot \exp\Big(- \Big(\frac{t_m}{TT} \cdot \text{PDEN} \Big) \Big) \cdot \Big(1 + \frac{t_e - TT}{t_e - t_m} \Big) \cdot \frac{TT}{t_e} \Big(\frac{t_e}{t_e - t_m} \Big) \tag{7}$$

(Note: the equation is presented here following the original structure; implementation must confirm the exact functional form and exponents.)

This variable is adjusted by a growth coefficient:

$$CC_{raw} = rdm \cdot v \cdot \text{canopy} + \text{canopy}$$

Days After Emergence (DAE) are calculated as:

$$DAE = PD_{ay} - ED_{ay} \quad \text{if } PD_{ay} \ge ED_{ay}.$$

Finally, the canopy cover index CC is:

$$CC = \begin{cases} 0, & \text{if } DAE \le 0, \\ canopy, & \text{if } canopy > 0. \end{cases} \tag{8}$$

4.2 Tuberization

The harvest index HI, which determines the fraction of biomass allocated to tubers, is modeled by a Gompertz function:

$$HI = A \cdot \exp\Big(- \exp\big(\tfrac{TT - t_u}{b} \big) \Big) \tag{9}$$

where A is the maximum harvest index, t_u is the thermal time of maximum partitioning, and b is a scaling constant.

5 Water Processes

The water module simulates the balance in a single soil layer. Soil water is lost through transpiration (T), evaporation (E_0), and percolation (D); and gained through precipitation (P) and irrigation (I). The mass conservation equation is:

$$ASWC_i = ASWC_{i-1} + P_i + I_i - E_0 - T - D \tag{10}$$

with initial condition $ASWC_0 = ISM$ (initial soil moisture).

5.1 Potential Transpiration (T_0) and Evaporation (E_0)

Potential transpiration is calculated from reference evapotranspiration ET_0 and the canopy curve:

$$T_0 = \frac{w_{max} \times ET_0 \times \left(1 - e^{-0.7 \cdot 4 \cdot CC_w}\right)}{1 - e^{-0.7 \cdot 4 \cdot w_{max}}} \tag{11}$$

And potential evaporation is:

$$E_0 = ET_0 - T_0 \tag{12}$$

5.2 ASWC Update

Soil available water content remains between WP and FC. The discrete update of ASWC is:

$$ASWC_i = \begin{cases} WP, & \text{if } P_i + I_i + ASWC_{i-1} - E_{0,i-1} - T_i \leq WP, \\ FC, & \text{if } P_i + I_i + ASWC_{i-1} - E_{0,i-1} - T_i \geq FC, \\ P_i + I_i + ASWC_{i-1} - E_{0,i-1} - T_i, & \text{otherwise.} \end{cases} \tag{13}$$

The critical threshold CL is defined as:

$$CL = FC - Z \cdot (FC - WP)$$

where Z is the effective root depth.

5.3 Actual Evapotranspiration (T)

Actual transpiration is limited by available water:

$$T = \begin{cases} 0, & \text{if } ASWC_i < WP, \\ T_0 \cdot \dfrac{WP - ASWC_i}{WP - CL}, & \text{if } WP \leq ASWC_i \leq CL, \\ T_0, & \text{if } ASWC_i > CL. \end{cases} \tag{14}$$

6 Water Stress Index (W_s) Calculation

The daily water stress index W_s modulates the negative effects of moisture deficit and depends on the ratio between T and T_0:

$$W_s = 0 \quad \text{if } T_i > 0.5 \times T_0 \tag{15}$$

$$W_s = \frac{0.5 \times T_0 - T_i}{T_0} \quad \text{if } T_i \leq 0.5 \times T_0 \tag{16}$$

The values of W_s and its cumulative form (CW_s) penalize RUE and the canopy curve:

$$\text{RUE}_w = \text{RUE} \cdot \frac{0.8 - W_s}{0.8} \tag{17}$$

$$CC_w = CC \cdot \frac{0.75 - W_s}{0.75} \tag{18}$$

These adjusted values are used in the biomass equations (Equation 1) and in yield estimation under stress conditions.

7 Output Variables

The main outputs of the SOLANUM model include:

- Fresh tuber yield FTY_w (kg ha^{-1}). Equation 3.
- Total accumulated evapotranspiration $\sum ET$ (mm).
- Daily water balance ($ASWC$) and stress status (W_s over time).
- Total water requirement for the season $WR = \sum T$.
- Water Use Efficiency (WUE), expressed as:

$$\text{WUE}_{ET} = \frac{\text{FTY}_w}{\sum ET} \tag{19}$$

8 Normalized Water Stress Index (WSI)

The normalized index for the whole season is defined as:

$$WSI = 1 - \frac{\sum T}{\sum T_0} \tag{20}$$

This index varies from 0 (no stress) to 1 (total stress).

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Supplementary Material

4.5.1.5. Parameters of the *SOLANUM* Model

The crop parameters used by the *SOLANUM* model (see Table 1) describe the main processes involved in light interception, radiation use efficiency, and tuber partitioning. For a more detailed description, see Condori et al. (2010, 2014) and Quiroz et al. (2017).

Table 1: Crop parameters of the *SOLANUM* model.

Symbol	**Full name**	**Unit**
Management parameters		
EDay	Day of emergence	days
plantDensity	Plant density	plants m^{-2}
Crop parameters		
Wmax	Maximum canopy cover index	–
tm	TT at maximum canopy growth	°Cd
te	TT at maximum canopy cover value	°Cd
A	Maximum harvest index	–
tu	TT at maximum tuber partition index	°Cd
b	TT before the onset of tuberization	°Cd
RUE	Radiation use efficiency	g MJ PAR^{-1}
DMC	Tuber dry matter content	–
Environmental parameters		
Tb	Minimum temperature for the onset of tuberization	°C
To	Optimum temperature for the onset of tuberization	°C
Tu	Maximum temperature for the onset of tuberization	°C
Pc	Critical photoperiod	h
w	Photoperiod sensitivity	–
Low temperature parameters		
Tcr	Lower critical temperature	°C
Tld	Lower limit of lethal cold damage	°C
Trg	Temperature of rapid cold death	°C
Soil parameters		
zsoil	Soil depth	m
Ho	Initial soil water content (as water depth)	mm
FC	Volumetric water content at field capacity	%
PWP	Volumetric water content at permanent wilting point	%
CO_2		
CO2AC	CO_2 concentration in the air	ppm