A comparison of two open-source crop simulation models for a potato crop

Comparación de dos modelos de simulación de cultivo de código abierto para un cultivo de papa

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ABSTRACT

An open-source model is a model that makes it possible to modify the source code. This tool can be a great advantage for the user since it allows changing or modifying some of the background theory of the model. World Food Studies (WOFOST) and AquaCropOS open-source crop models were compared using field recorded data. Both models are free open-source tools that allow evaluating the impacts of climate and water on agriculture. The objective of this research was to assess the model's efficiency in simulating the yield and above-ground biomass formation of a potato crop on the cundiboyacense plateau. WOFOST simulates biomass accumulation in the crop organs using partitioning of assimilates to establish the biomass fraction that turns into yield. AquaCropOS simulates total above-ground biomass accumulation using crop water productivity (WP) and considers the Harvest Index (HI) to calculate yield formation. Crop modules for both models were built using information recorded in previous studies by other authors; those works performed a physiological and phenological characterization of some potato varieties. It was found that the WOFOST model simulates yield formation better than AquaCropOS; despite that, AquaCropOS simulates total above-ground biomass better than WOFOST. However, AquaCropOS was as efficient as WOFOST in simulating yield formation.

Key words: crop modelling, crop yield, agrometeorology, *Solanum tuberosum* L.

RESUMEN

Un modelo de código abierto permite modificar el código fuente. Esto puede ser una gran ventaja para el usuario, pues permite modificar o cambiar parte de la teoría en la que se sustenta el modelo. Los modelos de código abierto WOFOST y AquaCropOS fueron comparados usando información medida en campo. Ambos modelos son herramientas gratuitas de código abierto que permiten evaluar los impactos del clima y el agua en la agricultura. El objetivo de esta investigación fue evaluar la eficiencia de los modelos para simular el rendimiento y la formación de acumulación de biomasa sobre el suelo para un cultivo de papa en el altiplano cundiboyacense. WOFOST simula la acumulación de biomasa en los órganos del cultivo utilizando la partición de asimilados para establecer la fracción de biomasa que va al rendimiento. AquaCropOS simula la acumulación total de biomasa sobre el suelo usando la productividad de agua del cultivo (PA) y tiene en cuenta el índice de cosecha (IC) para calcular la formación del rendimiento. Los módulos de cultivo para ambos modelos fueron construidos usando información recolectada en estudios previos hechos por otros autores; estos trabajos hicieron una caracterización fisiológica y fenológica de algunas variedades de papa. Se encontró que el modelo WOFOST simula la formación del rendimiento mejor que AquaCropOS; a pesar de esto, AquaCropOS simula la acumulación total de biomasa sobre el suelo mejor que WOFOST. Sin embargo, AquaCropOS fue tan eficiente como WOFOST simulando la formación del rendimiento.

Palabras clave: modelización de cultivos, rendimiento de cultivos, agrometeorología, *Solanum tuberosum* L.

Introduction

Crop modeling is increasingly being used to describe agricultural systems, helping scientists to incorporate their understanding of the interactions among components in predicting performance of agricultural systems for better goal achievement of farmers and society (Wallach *et al.*, 2014). Predicting the performance of agricultural systems has also been used as a tool for decision support in crop production, involving topics such as sowing dates, irrigation amounts and fertilization management (Graeff *et al.*, 2012). Crop model calibration is necessary for using crop models since the quality of the simulation depends on the quality of the parameters of the crop. Although this study is not about model calibration, it is about crop parameter estimation. For crop parameter assessment, we used data recorded in the field by other authors in previous studies (Ñústez *et al.*, 2009; Valbuena *et al.*, 2010).

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Teh (2006) defines crop modeling as describing and translating a real agricultural system into a mathematical form, finding the patterns in the behavior or action of the crop system and translating those patterns into an equation or set of equations. A system is a limited part of reality that contains interrelated elements, and a model is a simplified representation of a system where the variables that govern the system are described. These variables may be interacting with each other. Simulation is the building of mathematical models, and the study of their behavior in reference to that of the system they represent (Boogaard *et al.,* 2014).

According to Boogaard *et al.* (2014), a mathematical model may be a descriptive model or an explanatory model. A descriptive model usually describes the behavior of a system in a relatively simple manner and reflects little or none of the mechanisms that are the cause of that behavior. An explanatory model consists of a quantitative description of the main processes involved. Within an explanatory model, the system processes are related to each other based on comprehension of their interaction.

A descriptive model describes processes that govern crop growth and yield development in a wide way; for example, a direct relation between some weather indicators such as total incoming radiation and yield formation. An explanatory model describes a process in detail; for example, a relation between the total assimilated CO_2 and yield, where the total assimilated CO_2 depends on the photosynthetic rate, the total incoming radiation, and the canopy cover (Marcelis e*t al.,* 1998). A simple relation may involve many sub processes that are interacting with each other. A crop model must take weather, soil, crop and crop management information and use those data for solving the equations of the model.

AquaCropOS and WOFOST models are computer programs that compile equations that then describe the behavior of the water-soil-crop-atmosphere continuum. AquaCropOS and WOFOST are made up of multiple modules, and each of those simulates a specific process. Simulation of a specific process may consist of the interaction of several subprocesses (Raes *et al.,* 2018; De Wit *et al*., 2019). AquaCropOS and WOFOST are open-source models, which means that the user of the model can modify the source code. Therefore, all the equations, theory, and relations that describe the crop's system can be modified. Open-source models are generally executed on the terminal. This characteristic could be harder for beginner users, but executing a model that way is also a great benefit since the user can make several simulations without spending too much time comparing it to other models that must be executed using a graphic user interface (GUI) (Foster *et al.,* 2017; De Wit, 2018a; De Wit, 2018b).

In WOFOST, crop growth is simulated based on ecophysiological processes such as growth and phenological development with a fixed time step of one day. The potential production in the model is limited only by radiation, temperature, atmospheric CO_2 concentration, and crop features. WOFOST growth limiting factors are related to water and/or nutrient limitation. Growth-reducing factors are associated with weeds and pollutants. The major processes simulated by the model are phenological development, leaf development, and light interception, CO_2 assimilation, root growth, transpiration, respiration, partitioning of assimilates to the various organs, and dry matter formation (De Wit *et al*., 2019).

AquaCropOS is a recent model based on the previous AquaCrop model. This tool simulates crop growth based on crop water productivity. Water productivity expresses the above-ground dry matter (kg or g) produced per unit of land area (m^2 or ha) per unit of transpired water (mm) (Foster *et al.,* 2017; Raes *et al.,* 2018). The potential production in the model is only limited by crop transpiration and atmospheric CO_2. AquaCrop growth limiting factors are the same used by WOFOST. Growth-reducing factors are related to weeds and soil salinity. As WOFOST, this model uses a fixed time step of one day.

Condori *et al.* (2016) summarized some of the most relevant works on potato crop modeling in Latin America. They found that the most frequent topic in publications on modeling is evaluating varieties and their calibration in different simulation models. Crop calibration is often focused on fertilizer and irrigation management, as well as the study of the effects of pests and diseases on the potato crop. Almost all crop modeling works collected by Condori *et al.* (2016) were about decision support systems for agrotechnology transfer (DSSAT) and Agro models, but none of them were about AquaCrop or WOFOST.

There are not many studies on the comparison between the WOFOST and AquaCrop models. However, a recent project aims to improve agricultural models, based on their intercomparison and evaluation. The agricultural model intercomparison and improvement project (AgMIP) (Rosenzweig *et al*., 2015) was founded in 2010 and consists of a group of experts in crop modeling and agricultural economy. Despite this, AgMIP does not report any research that compares the two models that are the subject of this work.

Todorovic *et al.* (2009) compared the AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth. They found that although AquaCrop requires less input information than CropSyst and WOFOST, it performed similarly to them in simulating both the total above-ground biomass and yield at harvesting. Furthermore, Huang *et al.* (2017) used the WOFOST and AquaCrop models for a multiple crop model ensemble. They emphasized that each of the models has a specific target parameter for simulation of growth; therefore, instead of using only one of the models, it is better to use both as an ensemble. The weight of each model in the ensemble would depend on the climate characteristics of the location.

Therefore, the objective of this research was to study and compare two open-source crop simulation models for a potato crop, under the agrometeorological conditions of the Cundiboyacense plateau.

Materials and methods

A potato crop cycle was simulated with limiting water conditions during the second semester of 2004. The simulation period and weather data provider station were selected according to details found on Ñústez *et al.* (2009) about the location and date of execution of the experiments. Observed data were recorded at a farm located in the municipality of Zipaquira (5°0.133' N and 73°59.529' W, and altitude of 2580 m a.s.l.).

The observed data recorded by Ñústez *et al.* (2009) and a phenological description performed by Valbuena *et al.* (2010) were used to estimate some crop parameters of the WOFOST and AquaCropOS models. Both authors collected their data in the field for various potato varieties at the Cundiboyacense plateau. Some parameters cannot be estimated using those data, and for that reason, default potato crop parameters were adopted for both models. For this work, the potato variety selected was Diacol Capiro. Both models were run for the same period when data was recorded. The results obtained for the two models were compared to the observed data, using the root-mean square error (RMSE) and an efficiency coefficient of a model.

The results for the two models were compared to the observed data. RMSE, Pearson correlation, and an efficiency index were obtained for both models. The efficiency index of the model was calculated according to Equation 1, which was proposed by Confalonieri *et al.* (2009) for assessing the efficiency of crop models. Model efficiency (EF) ranges from negative infinity to one. Negative values of EF indicate that the average value of all observations is a better estimator than the model. If the EF value equals one, it means that the model simulates almost perfectly that system.

$$EF = 1 - \frac{\sum_{i=1}^{n}(D_i)^2}{\sum_{i=1}^{n}(O_i-\overline{O})^2} \quad (1)$$

where: D_i is the model's residual for observation i, O_i is the value of observation i, Õ is the average of observations, and n is total number of observations. The efficiency of the model (EF) ranges from negative infinity to one. Negative values of EF indicate that the average value of all observations is a better estimator than the model. If the EF value is one, it means that the model simulates almost perfectly that system.

RMSE (Eq. 2) is indicates the mean difference between simulated values by the model and observed values.

$$RMSE = \left[\frac{1}{n}\sum_{i=1}^{n}(E_i - O_i)^2\right]^{1/2} \quad (2)$$

where: E_i is the estimated value, O_i is the observed value and n is total number of observations.

The AquaCropOS model was executed using GNU Octave version 4.2.2, and the WOFOST model was executed in Python 2.7.15. The Python crop simulation environment library (PCSE) was used for running the WOFOST model. PCSE (De Wit, 2018a) is a Python package for building crop simulation models, in particular the crop models developed at Wageningen University (Netherlands).

The model can distinguish an entire crop system in three subsystems, crop, soil and atmosphere. When it comes to the crop subsystem, AquaCropOS simulates it by using four different submodules: roots, canopy cover, phenology, yield, and biomass. All these submodules are affected by stress coefficients at any step (Raes *et al.*, 2018). On the other hand, WOFOST uses nine submodules for simulating plant growth and yield: phenology, radiation fluxes, assimilation rates, maintenance respiration, dry matter partitioning, carbon balance check, senescence, net growth, and root growth (De Wit, 2018a).

Either for AquaCropOS or WOFOST it is necessary to define some parameters that will determine soil, plant, and atmosphere behavior and interactions. According to this, it is required to define soil, crop, and weather parameters which vary according to the location, crop species and variety, soil texture, etc.

Crop: WOFOST crop file included information about crop phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs. Phenology and partition of assimilates parameters were estimated from the studies by Ñústez *et al.* (2009) and Valbuena *et al.* (2010).

Assimilation and respiration parameters were obtained from De Wit (2018b), who had calibrated the WOFOST model for a potato crop under the conditions of central Europe. Although the assimilation and respiration parameters defined by De Wit (2018b) were obtained for a different variety, they were used due to the difficulty in obtaining those parameters for local potato varieties since it requires years of research and field experiments under very controlled environments. AquaCropOS crop file included information about crop phenology and crop water productivity. AquaCropOS crop parameters were obtained from Cortés *et al.* (2013), who estimated crop parameters based on Ñústez *et al.* (2009).

Soil: Soil texture was defined using a general soil study for the province of Cundinamarca carried out by the Instituto Geográfico Agustin Codazzi (IGAC, 2000). The defined soil texture was sandy clay loam. Hydrodynamic soil parameters, such as field capacity and permanent wilting point moisture contents, were estimated using the RETC sofwtware (Van Genuchten *et al.*, 1998). RETC uses pedo-transfer functions to compute hydrodynamic soil parameters from soil texture.

Atmosphere: Meteorological data for the second half of 2004 was obtained from the Instituto de Meteorología,

FIGURE 1. Detailed location of the experiments from Ñústez *et al.* (2009) and the weather station that was used as data source.

Hidrología y Estudios Ambientales (IDEAM) database. "La cosecha" station was selected for requesting meteorological data. This station is located at 74.0012° W and 4.989° N and was selected because it is the nearest station to the place where data was collected (approximately 1.8 km away). Figure 1 depicts the locations of the weather station and the experiments from Ñústez *et al.* (2009). The weather and soil conditions can be considered as equal for both locations.

Table 1 shows the principal characteristics of both models; some of those characteristics are about required data.

TABLE 1. Main characteristics of WOFOST and AquaCropOS crop models (adapted from Raes *et al.* (2018) and De Wit *et al.* (2019)).

Model characteristic	Model	
	WOFOST	AquaCropOS
Developer	Timothy Foster (University of Manchester)	Allard De Wit (Wageningen University & Research)
Kind of model	Explanatory	Descriptive
Programming language	Python / FORTRAN	MATLAB / OCTAVE
Installation and operation difficulty	High (It requires medium - advanced knowledge of the programming language)	Medium (It requires basic knowledge of programming)
Crop Calendar	Growing degree days (GDD)	GDD / calendar days
Hydrodynamic soil parameters required	Soil humidity and soil hydraulic conductivity as a function of soil matrix potential	Soil humidity at field capacity, permanent wilting point and saturation. Saturated hydraulic conductivity
Crop management	Irrigation, fertilizer application	Mulches, irrigation
Meteorological data required	Maximum and minimum temperature, total incoming radiation/total sunshine hours, average vapor pressure, wind speed and precipitation	Maximum and minimum temperature, reference evapotranspiration, precipitation
Minimum files required for its execution	3	16
Yield calculation	Partitioning of assimilates	Harvest Index
Main crop parameters required	Parameters for: Crop phenology (growing degree days), CO_2 assimilation, conversion efficiency of assimilates, respiration, assimilate partitioning, leaf death rates, root depth, water, temperature and nutrient stress	Water productivity index, canopy growth parameters, crop yield index, root growth parameters, water and temperature stress parameters

Results and discussion

Tuber biomass simulated by both models was very well adjusted to the observed data (yield or harvestable biomass, Fig. 2). Both models achieved a quite good approximation to tuber biomass through crop development. Simulated final tuber biomass by WOFOST and AquaCropOS was 10.48 t ha^{-1} and 10.73 t ha^{-1}, respectively, whereas the observed final tuber biomass was 10.45 t ha^{-1}. The simulated total above-ground biomass by the two models did not strictly follow the observed data (Fig. 3). However, AquaCropOS exhibited a better fit. Simulated final total above-ground biomass by WOFOST and AquaCropOS was 17.92 t ha^{-1} and 12.90 t ha^{-1}, respectively, whereas the observed final total above-ground biomass was 12.29 t ha^{-1}.

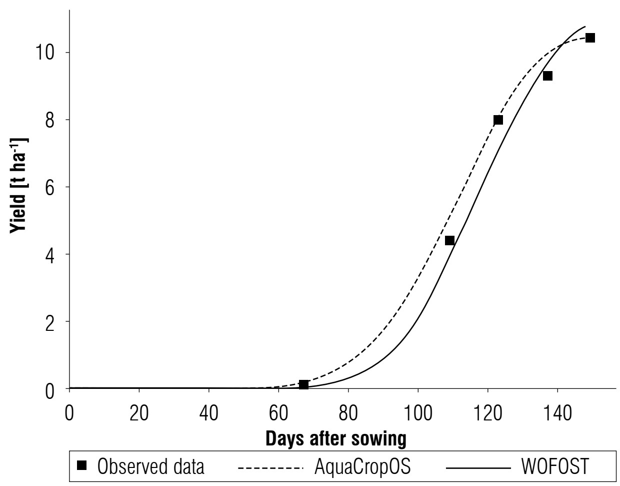

FIGURE 2. Tuber biomass (yield) simulated by AquaCropOS and WOFOST models, and observed tuber biomass.

Table 2 shows the efficiency of the model (EF) and RMSE values for the simulation of yield and total above-ground biomass for the two models. The obtained results agree with Todorovic *et al.* (2009), who concluded that both models are a good approximation to real yield, although WOFOST showed the best performance. Both RMSE and EF values show that WOFOST is the best model at simulating yield. The efficiency index of both models suggests that the two of them can simulate yield formation with a very high precision. However, WOFOST simulated yield formation with higher accuracy and with a lower error. On average, WOFOST and AquaCropOS error at simulating yield formation was 0.391 t ha^{-1} and 0.614 t ha^{-1}, respectively. The efficiency index of the model in simulating total above-ground biomass was higher for AquaCropOS. Nevertheless, Figure 3 shows that in the last stages before the peak of biomass, WOFOST simulation fits better the observed values.

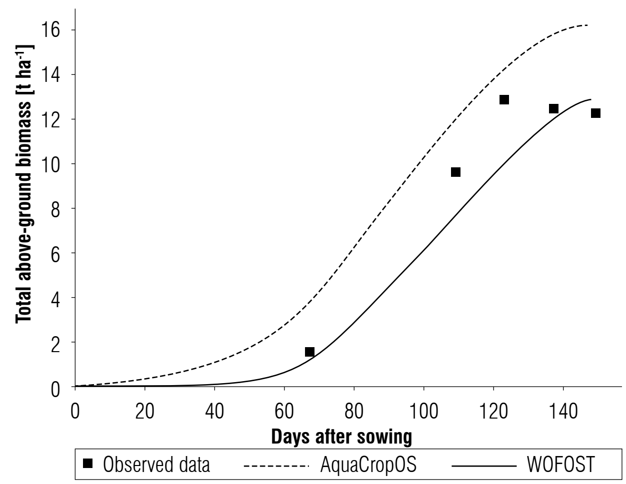

FIGURE 3. Total above-ground biomass simulated by the AquaCropOS and WOFOST models and observed total above-ground biomass.

WOFOST, as a physiological model that considers processes like photosynthesis and biomass partition in detail, showed a better performance than AquaCropOS. The former considers crop transpiration and atmospheric CO_2 as the only yield-defining factors. Despite this, the performance of WOFOST for total above-ground biomass was poor in comparison to AquaCropOS. This discrepancy between observed and simulated above-ground biomass for both models was due to the model's inability of simulating drop of leaves. WOFOST can simulate the death of leaves; however, even though leaves undergo senescence, they are not falling. In the model, the process of leaf death only implies that they are not contributing to physiological processes such as photosynthesis and transpiration anymore. AquaCropOS

TABLE 2. Efficiency of the models, root-mean square error (RMSE), and correlation (r^2) in yield and total above-ground biomass simulated by AquaCropOS and WOFOST models.

	Model	Efficiency	RMSE (t ha^{-1})	Correlation
Harvestable biomass (Yield)	AquaCropOS	0.974	0.614	0.990
	WOFOST	0.991	0.391	0.997
Total above-ground biomass	AquaCropOS	0.828	1.778	0.951
	WOFOST	0.615	2.658	0.979

Highlighted cells show the best result.

simulates canopy cover decline, but it is not associated with a biomass loss due to death and drop of leaves.

Conclusions

Although WOFOST shows the best performance in simulating tuber biomass, AquaCropOS's performance is nearly as good. Due to its lower complexity and the smaller number of parameters, AquaCropOS is the best option for simulating the yield of the potato crop. AquaCropOS is better in simulating above-ground biomass. Less efficiency in simulating above-ground biomass for the two models is due to difficulty at simulating the death of leaves and their consequential fall.

Crop modeling is a powerful tool to develop data-driven and climate-smart platforms in agriculture. Studies on the calibration and validation of crop models result in an important advance in the endless effort to achieve a more sustainable and efficient agricultural production. To represent local conditions for different crop varieties, it is necessary to perform new calibration works.

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