

Modeling the yield of forage and grain of irrigated maize using the AquaCrop model

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ABSTRACT

Objective: To calibrate and validate the AquaCrop model for simulating the forage and grain yield of maize cultivated under irrigation in Irrigation District 052 “Durango”.

Design/Methodology/Approach: This study involved the parameterization of the AquaCrop model to simulate maize yield using two commercial hybrids (XR20A and XR21), cultivated under surface irrigation at the Valle del Guadiana Experimental Station of INIFAP, located within Irrigation District 052 “Durango”, during the spring-summer (*S-S*) growing seasons of 2015, 2016, and 2017.

Results: The findings demonstrate the model’s robustness in predicting grain yield, with a root mean square error (*RMSE*) of 0.47 t ha⁻¹ and a Willmott index (*d*) of 0.99.

Limitations/Implications: The model requires calibration and validation under the specific agronomic conditions of the target region. Nevertheless, this research provides a valuable reference for future studies utilizing the AquaCrop model.

Findings/Conclusions: AquaCrop represents a reliable tool for estimating both expected and potential maize yields, thereby supporting more informed decision-making by farmers.

Keywords: Calibration, parameterization, simulation, validation, *Zea mays*.

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INTRODUCTION

Maize (*Zea mays* L.) is one of the most significant crops both nationally and globally, owing to its nutritional, social, and economic relevance (Flores-Gallardo *et al.*, 2017). It has become a staple in global food and industrial markets due to its versatility in animal feed production, human consumption, and industrial applications (FIRA,

2016). Ensuring food security remains a critical global challenge, and in Mexico, it is imperative to produce sufficient quantities of high-quality food at affordable prices. In this context, irrigated agriculture plays a pivotal role in addressing the growing food demand of an increasing population, even though the cultivated area has remained nearly unchanged over the past four decades (Ojeda-Bustamante *et al.*, 2012). Maize usage can be classified into three main categories: (1) human consumption, (2) forage for livestock feed formulation, and (3) input for the production of balanced feeds, edible oils, and starches (SIAP, 2004). In recent years, despite its nutritional importance, maize has also gained prominence as a low-emission biofuel source, particularly ethanol. However, maize productivity in Mexico remains insufficient, with forage and grain yields exhibiting considerable variability depending on the agroecological region and cultivation zone. This variability is primarily due to differences in agronomic management practices and their interaction with the soil and climatic conditions in which the crop is grown. Although maize is cultivated across most irrigated and rainfed areas in Mexico, the country still imports approximately twelve million tons of grain annually roughly one-third of its basic grain needs (SIAP, 2017). Maize is among the most extensively studied crops in agronomic research, with numerous investigations focused on its water response under various management and climatic conditions, including economic evaluations (Gadedjisso-Tossou *et al.*, 2019). The AquaCrop model is no exception; since its release, maize was among the first crops included in its database (Heng *et al.*, 2009; Hsiao *et al.*, 2009; Raes *et al.*, 2009). Consequently, several studies have been conducted worldwide using this model for maize, under diverse regional conditions (Abedinpour *et al.*, 2012; Flores-Gallardo *et al.*, 2013; Ahmadi *et al.*, 2015), and in the context of climate change scenarios (Abedinpour *et al.*, 2014; Arce-Romero *et al.*, 2020). The aim of this research was to parameterize the AquaCrop model using experimental data to simulate maize yield. This was achieved through the calibration and validation of the model's parameters for two commercial hybrids cultivated under surface irrigation at the Valle del Guadiana Experimental Station of INIFAP, located in Irrigation District 052 "Durango," during the 2015, 2016, and 2017 spring-summer (S-S) growing seasons.

MATERIALS AND METHODS

Location, climatic and edaphic characteristics of the study area

The research was conducted over three consecutive S-S growing seasons 2015, 2016, and 2017 by establishing semi-commercial maize plots at the Valle del Guadiana Experimental Station (INIFAP-Durango), located at 23° 59' 18.6" N, -104° 37' 32.4" W, and an elevation of 1,878 m. Two commercial maize hybrids commonly cultivated in the region were used for this study (Table 1).

The predominant climate at the study site is temperate semi-arid, with a summer rainfall regime and pronounced temperature variability [BS1 Kw(w)(e)], with a mean annual temperature of 17.4 °C (García, 1987). Annual accumulated precipitation averages 476 mm, with the highest values occurring between June and September (Medina *et al.*, 2005). The mean annual reference evapotranspiration (ET_o) is 4.9 mm d⁻¹, ranging

Table 1. Characteristics of the maize hybrids used in Durango during the 2015, 2016, and 2017 S-S growing seasons.

Characteristic	XR20A	XR21
Growth cycle (duration)	Intermediate-Early	Intermediate-Early
Days to flowering (d)	65-70	66-68
Days to maturity (d)	132-135	138-140
Days to harvest (d)	160-170	165-175
Ear height (m)	1.14	1.15
Plant height (m)	2.45-2.75	2.80-2.90

from 0.3 to 8.9 mm d⁻¹ (INIFAP, 2017). The soil is classified as sandy loam, with varying particle size distribution for sand (S), silt (Si), and clay (C), as well as bulk density (ρ_b) and organic matter content (OM). The detailed physical and chemical soil properties are presented in Table 2.

Conservative parameters of the aquacrop model

Once the validation plot data were obtained, the conservative parameters of the AquaCrop model (Table 3) were used to simulate maize yield. These parameters were originally reported for three maize experiments conducted in Spain and the United States (Hsiao *et al.*, 2009). However, the values reported by Flores-Gallardo *et al.* (2013) were used as a reference to adapt and appropriately validate the model under the climatic conditions of Durango.

Statistical analysis

Following the parameterization process, the AquaCrop model was calibrated and validated using field-obtained data. Statistical analysis was applied to both observed and simulated values of crop yield and growth cycle duration (Flores-Gallardo *et al.*, 2013). The following statistical indicators were used: root mean square error (*RMSE*) and Willmott's index of agreement (*d*), as proposed by Willmott (1982), calculated using the following equations:

$$RMSE = \left[n^{-1} \sum_{i=1}^n (S_i - O_i)^2 \right]^{0.5} \quad (1)$$

Table 2. Physical and chemical soil properties.

Property	Value
Sand (%)	62
Silt (%)	28
Clay (%)	10
Bulk density (g cm ⁻³)	1.295
Organic matter (%)	0.60
pH	8.15

Table 3. Conservative parameters of the AquaCrop model based on results from other agricultural regions (Hsiao *et al.*, 2009; Flores-Gallardo *et al.*, 2013).

Description	Value	Unit or Measure
Base temperature	8	°C
Upper temperature threshold	30	°C
Canopy cover at 90% emergence (<i>CCo</i>)	6.5	cm ²
Canopy growth coefficient (<i>CGC</i>)	1.3%	Relative increase in <i>CC</i> per growing degree day (°D)
Maximum canopy cover (<i>CCx</i>)	-	Depends on plant density
Crop coefficient for full transpiration at 100% canopy cover	1.03	Full canopy transpiration relative to <i>ETo</i>
Canopy decline coefficient before reaching <i>CCx</i>	0.3%	Decline per day due to leaf aging
Canopy decline coefficient (<i>CGC</i>) until senescence	1.06%	Decline of <i>CC</i> relative to <i>CCx</i> per °D
Water productivity (<i>WP</i>), normalized to the year 2000	33.7	g (biomass) m ⁻² , based on atmospheric CO ₂ concentration
Upper threshold for leaf growth inhibition (p-upper)	0.14	Fraction of total available water (<i>TAW</i>); above this, leaf growth is inhibited
Lower threshold for leaf growth inhibition (p-lower)	0.72	Leaf growth stops entirely at this threshold
Leaf growth stress coefficient (curve shape)	2.9	Moderately convex curve
Upper threshold for stomatal conductance reduction	0.69	Above this, stomata begin to close
Stomatal stress coefficient (curve shape)	6.0	Highly convex curve
Upper threshold for canopy senescence acceleration	0.69	Above this, senescence accelerates
Senescence stress coefficient (curve shape)	2.7	Moderately convex curve
Reference harvest index (<i>HI</i>)	48%	Typical under optimal conditions
°D from 90% emergence to start of anthesis	800	May be lower for short-cycle cultivars
Duration of anthesis in °D	190	-
Leaf growth inhibition coefficient relative to <i>HI</i>	7.0	<i>HI</i> increased due to leaf growth inhibition during anthesis
Stomatal inhibition coefficient relative to <i>HI</i>	3.0	<i>HI</i> decreased due to stomatal inhibition during anthesis
Total °D from emergence to maturity	1510-1840	Lower values for short-cycle cultivars

$$d = 1 - \left[\frac{\sum_{i=1}^n (S_i - O_i)^2}{\sum_{i=1}^n (|S_i| + |O_i|)^2} \right], 0 \leq d \leq 1 \quad (2)$$

Where: n is the number of observations, S_i and O_i represent the simulated and observed values, respectively. Since *RMSE* provides a global measure of the difference between observed and simulated values, it is considered an indicator of uncertainty, as it shares the same units as the simulated variable. Therefore, values closer to zero indicate better simulation performance.

The d value (Equation 2) ranges from zero to one; hence, both statistical analyses were sequentially applied to the observed and simulated data.

Finally, to statistically compare S_i values against O_i values, the coefficient of variation (*CV*) and standard deviation (σ) were calculated using the following equations:

$$CV = \frac{\sigma}{|\bar{X}|} \quad (3)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (X_i - \bar{X})^2} \quad (4)$$

Where: σ is the standard deviation, \bar{X} is the mean value, and X is each recorded observation.

RESULTS AND DISCUSSION

For the calibration of the AquaCrop model, data from the plots corresponding to the 2015 S-S growing season were used. Subsequently, the model was validated using data from the 2016 and 2017 S-S seasons. The grain yield simulation yielded an *RMSE* of 0.47 t ha^{-1} and a Willmott index (*d*) value of 0.99 for the same variable. Additionally, other statistical analyses were performed, resulting in an R^2 of 0.95 between observed (O_i) and simulated (S_i) grain yield data using the AquaCrop model (Figure 1).

Similar statistical values for maize yield simulations have been reported in studies conducted in other regions, such as those by Flores-Gallardo *et al.* (2013) and He *et al.* (2021). However, when using other models like CROPWAT and EPICphase, significantly different results were obtained, with *RMSE* values as high as 5.25 t ha^{-1} . Such discrepancies render the results less reliable for simulations under conditions of high climatic variability (Cavero *et al.*, 2000). Regarding forage production by the maize crop, the biomass (*B*) values estimated by the AquaCrop model were analyzed. Field-observed values (O_i) ranged from 14.6 to 25.6 t ha^{-1} , while simulated values (S_i) from AquaCrop ranged from 13.5 to 22.8 t ha^{-1} closely aligning with the ranges reported by Greaves and Wang (2016), which were between 15.8 and 21.9 t ha^{-1} . Nevertheless, the coefficient of determination (R^2) between observed and simulated biomass values was 0.65 (Figure 2).

The phenological data expressed in growing degree days ($^{\circ}D$) simulated (S_i) by the AquaCrop model showed a slight overestimation compared to the field-observed

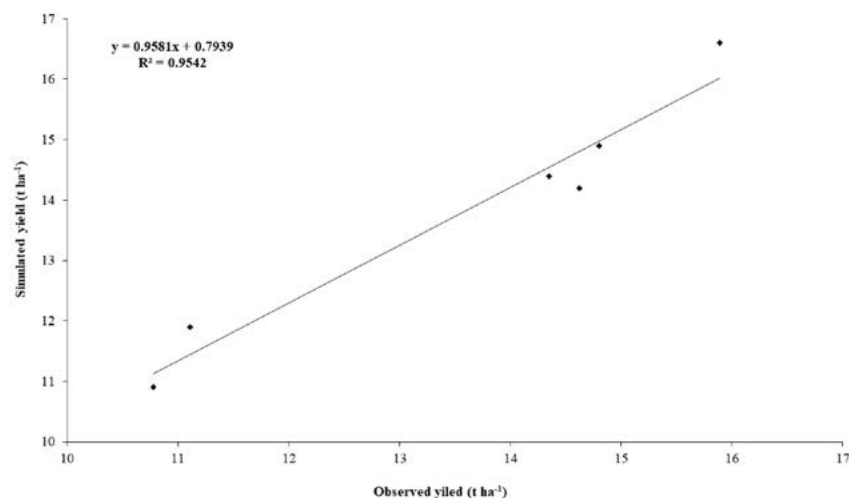


Figure 1. Coefficient of determination (R^2) between observed (O_i) and simulated (S_i) grain yield values using the AquaCrop model.

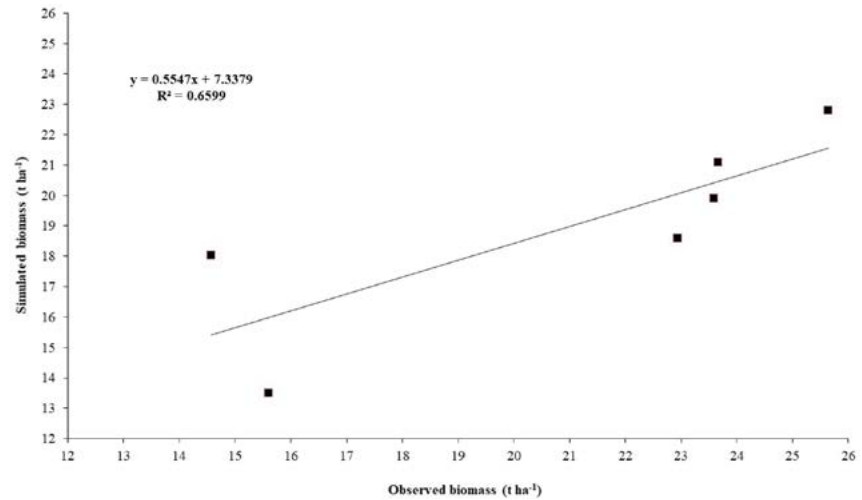


Figure 2. Coefficient of determination (R^2) between observed (B_{Oi}) and simulated (B_{Si}) biomass values using the AquaCrop model.

values (O_i). Figure 3 presents the average $^{\circ}D$ values for each of the S-S growing seasons analyzed.

Both maize hybrids used in the study exhibited similar accumulation of growing degree days ($^{\circ}D$). However, the AquaCrop model showed a slight overestimation of values, attributed to methodological differences in calculation. A similar pattern was observed for the crop’s canopy development, with simulated data (S_i) slightly exceeding the field observations (O_i) across all S-S growing seasons analyzed (Figure 4).

It is important to note that yield values obtained under irrigated conditions are higher, whereas those under rainfed conditions tend to be lower. This difference is expected due to the limitations and lack of water supply control in the latter system (Greaves and Wang, 2017).

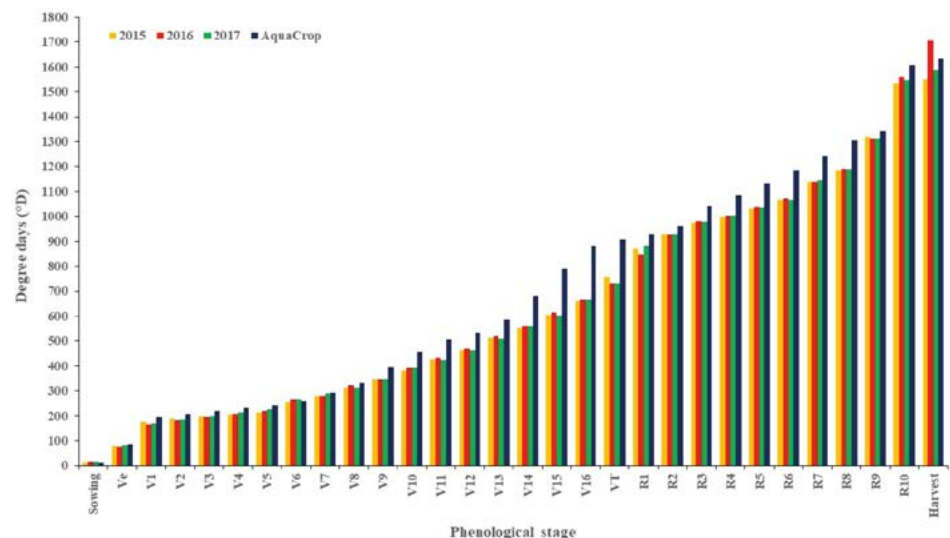


Figure 3. Maize phenology behavior expressed in $^{\circ}D$, observed in the field (O_i) and simulated (S_i) with the AquaCrop model.

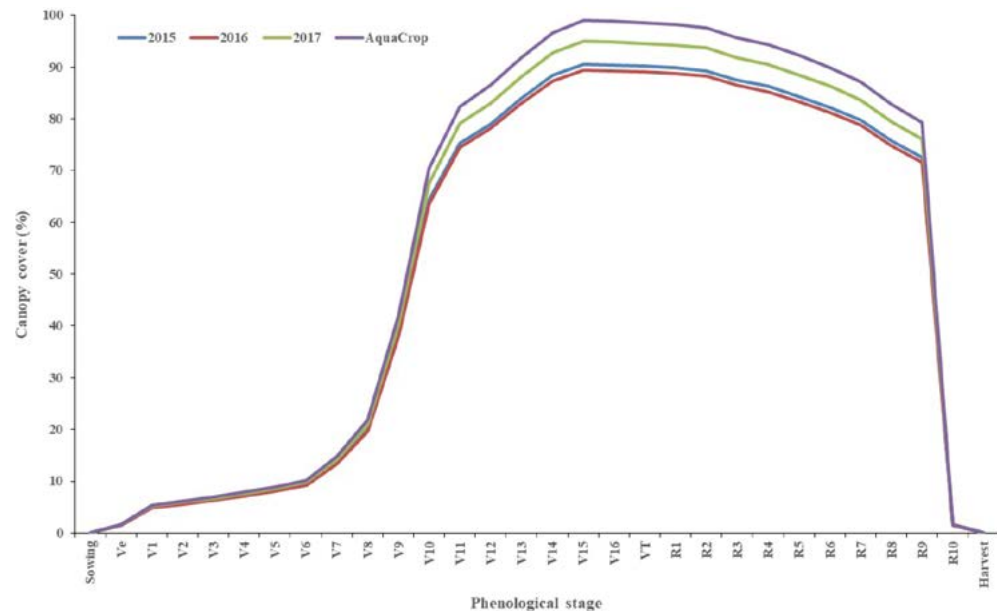


Figure 4. Behavior of the canopy cover observed in the field (O_i) and simulated (S_i) with AquaCrop expressed as a percentage in comparison with the phenology of the maize.

CONCLUSIONS

The statistical analyses demonstrate the strong performance of the AquaCrop model under the prevailing conditions in Durango, showing a slight overestimation of grain yield with an $RMSE$ of 0.47 t ha^{-1} and a Willmott index (d) of 0.99. The AquaCrop model can be replicated in other maize-growing regions within the state, offering alternative management strategies to farmers and supporting agronomic decision-making. Due to its robust statistical outputs, AquaCrop proves to be a reliable tool for simulating maize yield at the field level under varying climatic conditions, agronomic management practices, and water availability conditions likely to occur in Irrigation District 052 “Durango”.

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