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Article

Simulation of CIRNO-C2008 wheat yield in the Yaqui Valley using AquaCrop

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Abstract

Worldwide, wheat is one of the most widely used cereals in the human diet and, in Mexico, it ranks second in production after corn. Nevertheless, its productivity is affected by the low efficiency of chemical fertilizers and the loss of nutrients in the soil, leading to environmental problems. It is necessary to look for alternatives to reduce the use of inorganic fertilizers and maintain or improve crop yield without affecting grain quality. This study calibrated and validated the AquaCrop simulation model for wheat crop development and yield. Experiments were carried out in the Yaqui Valley, Mexico, during the 2019-2020 cycle with the wheat (*Triticum turgidum* L.) variety CIRNO C2008 under different doses of nitrogen using urea (240, 120, and 0 kg N ha^{-1}) to evaluate the impact of nutritional stress on crop development and yield. The analysis of variance showed that there were no significant differences (p< 0.05) between the simulated yields (7 189 t ha^{-1}, 6 638 t ha^{-1} and 4 436 t ha^{-1} for the doses of 240, 120 and 0 kg N ha^{-1}, respectively) and the observed yields (7.2 ±0.007 t ha^{-1}, 6.6 ±0.02 t ha^{-1}, 4.21 ±0.16 t ha^{-1}, respectively). The results demonstrated that the yield simulation model for wheat crops was successfully calibrated using AquaCrop.

Keywords:

plant physiology, soil fertility, stress, sustainability.

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Introduction

The accelerating pace of climate change as well as population growth threatens food security around the world. On the other hand, unsustainable intensive agricultural practices together with environmental pollution and the depletion of natural resources (Ochoa-Noriega, 2022) give a broader perspective of the challenge of the agricultural sector.

In this context, it is crucial to consider the importance of crops such as wheat, which is one of the most important globally and the most widely used cereal in the human diet. In northwestern Mexico, mainly in the Yaqui Valley in Sonora, wheat is grown under irrigated conditions (Félix-Fuentes, 2010). Thus, there are several challenges to the production of this crop, such as low water availability and fertilizer leaching, which significantly reduces yields and the soil's capacity to store and complete the nutrient and water cycles (FAO, 2009).

On the other hand, changes in rainfall patterns increase the likelihood of low yields in the short and long term (Nelson *et al*., 2009). Thus, the need arises to develop tools that integrate crop information and that allow the analysis and quantification of the relationships that exist between biotic and abiotic factors in agroecosystems.

These tools could also be used to evaluate different productive management or analyze one or more factors of interest while keeping the others constant, for example, management such as irrigation scheduling, fertilization, sowing dates, as well as the simulation of the impact of climate change on the crop (Hernández *et al*., 2011); these tools are now known as simulation models.

In this sense, the AquaCrop model, a crop model to simulate the response of yield to water, of the Food and Agriculture Organization of the United Nations (FAO) arises, which allows the simulation of crop yield through a water productivity model, which, in turn, simulates the production of biomass based on the amount of transpired water from the vegetation cover (González-Robaina, 2019).

A study on BM709 corn in Altillanura, using AquaCrop 5.0 adapted to the area, showed high accuracy (> 90%) in the simulation of growth and yield. The efficiency in dry matter production depended on the crop's ability to use solar radiation, favorable in Altillanura, concluding that, at 40 °C, corn can maintain or increase its productivity thanks to the high concentration of CO_2 (Cantillo *et al*., 2019).

This is an example of the current focus on developing alternatives to improve the productivity of agroecosystems and provide more nutritious food. In addition, it is sought to reduce pollution derived from the increased application of agro-inputs, their health risks, and soil degradation. The objective of this work was to simulate and correlate the yield of wheat (*Triticum turgidum* L.) variety CIRNO C2008 under different doses of urea as nitrogen fertilization by validating the AquaCrop model.

Materials and methods

Study site and experimental design

The study was developed during the winter cycle, December 2019-May 2020, at the Experimental and Technology Transfer Center (CETT, for its acronym in Spanish) of the Technological Institute of Sonora (27° 22' 01.3" north latitude, 109° 54' 55.1" west longitude) located in the municipality of Cajeme, Sonora. The soil type was vertisol and presented a clay-sandy texture in the first 25 cm, sandy clay-loam up to 100 cm deep, and loam from 100 to 170 cm (Valenzuela-Aragon *et al*., 2019). The soil pH was 7.9, 0.8% organic matter, and a bulk density of 1.15 g cm^{-3} (Zepeda *et al*., 2024).

The initial nitrogen content in the soil, prior to the establishment of the experiment, was 123 kg N ha^{-1}. The climate was measured using the HOBO U30 NRC weather station, which indicated a climate of variable rainfall, with an average temperature of 25.5 °C and an average rainfall of 308 mm. The studied variety of crystalline wheat (*Triticum turgidum* L.) was CIRNO C2008 and was sown at a density of 120 kg ha^{-1}.

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The crop management was carried out in the conventional way used by the producers (primary tillage; moldboard plowing, which turns and breaks the soil to significant depths (20-30 cm); subsoiling, which breaks up the deep compacted layers without completely inverting the soil; disc harrowing, which is used after plowing to break up large clods and level the soil; gravity irrigation, and integrated weed management) (Prasad, 2018).

The experimental design consisted of three treatments with four replications each. The field experiment was conducted with an experimental design consisting of 12 plots distributed in three treatments, each with four replications. Each plot measured 10 m x 6.4 m. The treatments evaluated included three levels of nitrogen fertilization with urea: 240 kg N ha^{-1}, 120 kg N ha^{-1} and 0 kg N ha^{-1}, along with 100 kg ha^{-1} monoammonium phosphate (MAP). Each plot had eight furrows (0.8 m wide) 10 m long.

The treatments consisted of applications of 0, 120, and 240 kg N ha^{-1} (equivalent to 0, 50 and 100% nitrogen, respectively) administered in the form of urea. The irrigations carried out were by gravity, including one before sowing and three additional as supplemental irrigations. Nitrogen fertilization (urea) was applied by broadcasting, divided into three stages: 33% at sowing, 33% at the first irrigation, which was 45 days after sowing (das), and 33% at the second irrigation, 80 das (Zepeda *et al*., 2024). Finally, the treatments were harvested for the calculation of grain yield.

Data collection

Climate data

The data used were from a historical database of the Network of Automatic Meteorological Stations of Sonora (REMAS, for its acronym in Spanish), station located in block 910, selecting the time period 1995-2019. At the field level, a HOBO U30 'New CETT' weather station was installed to measure climatic parameters during the experiment, such as air temperature and humidity, wind speed, crop evapotranspiration (Eto), and precipitation. The ETo measurements were obtained from the Eto calculator of the AquaCrop model, using the parameters of air humidity, wind speed, and radiation or sun data, necessary to calculate the Eto (Boudhina *et al*., 2019).

Crop data

The data on crop development were obtained by observation and measurement with the Zadoks scale 'decimal code', based on 10 important stages of development (Boudhina *et al*., 2019). Likewise, the canopy cover was measured with the semi-professional go pro-7 camera, taking photographs 3 times a week to obtain phenology and cover data during the duration of the cycle.

AquaCrop simulation

According to what Raes *et al*. (2009) reported, the AquaCrop model consists of several equations that, with data on climate, population density, genetic characteristics of the crop, soil type, level of fertilization, and level of water deficit, simulate the growth and yield of the crop. Figure 1 shows the simulation scheme used in AquaCrop. In the simulation of crop development, canopy expansion was distinguished from root zone expansion.

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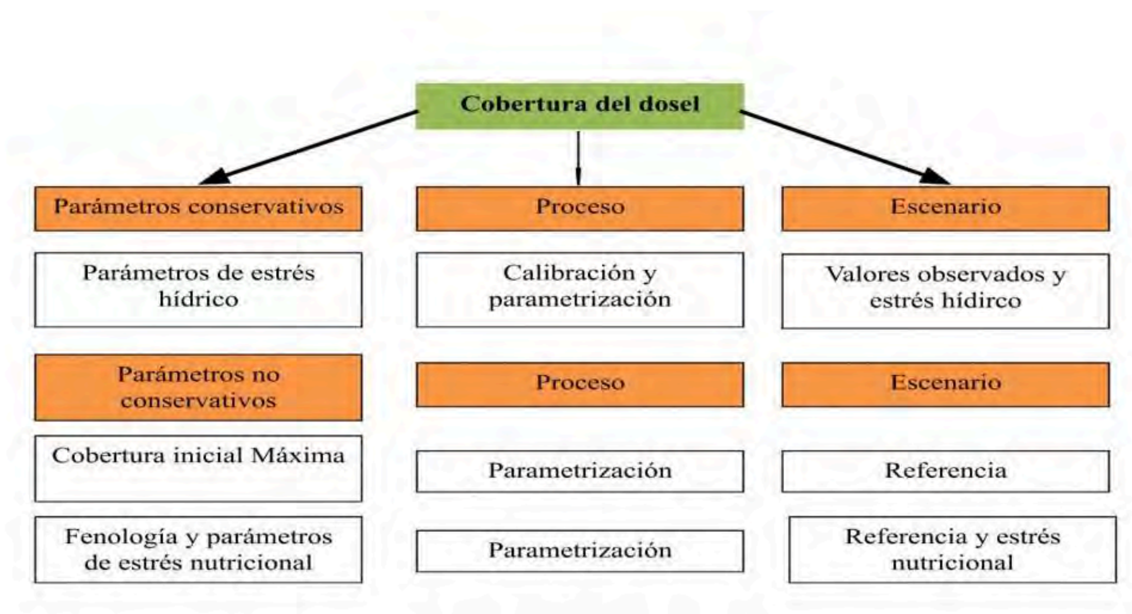
Figure 1. General scheme used in the simulation with AquaCrop.

AquaCrop uses the green canopy cover to describe the development of the crop; through its expansion, maturity, conductance, and senescence, it determines the amount of transpired water, which, in turn, determines the amount of biomass produced and the final yield (Porras-Jorge, 2019). If there is water stress, the simulated canopy cover (CC) will be less than the potential canopy cover (CCpot) for non-stress conditions and the maximum rooting depth may not be reached.

Canopy cover calibration in AquaCrop

The process of calibrating canopy cover is shown in Figure 2.

Figure 2. Calibration and simulation of canopy cover in wheat crops under three doses of nitrogen fertilization.



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Results and discussion

Parameterization of crop variables

To simulate the yield of wheat crops, the various non-conservative parameters in the treatments were first determined with the different fertilization doses, which are observed in Table 1.

Table 1. Parameterized values of CIRNO C2008 wheat (*Triticum turgidum* L.) crops.

Non-conservative parameters	240 (kg N ha^{-1})	120 (kg N ha^{-1})	0 (kg N ha^{-1})	Mean value	Unit
Minimum temperature	0.4	0.4	0.4	0.4	°C
Maximum temperature	38	38	38	38	°C
Initial canopy cover	0	0	0	0	%
Maximum canopy cover	98	75.63	93.5	89.04	%
Crop transpiration coefficient	1	1	1	1	°C
Normalized water productivity	19.5	19.5	19.5	19.5	g m^{-2}
Harvest index	50	56	50	52	%
Maturity date	126	126	126	126	DDS
Maximum root depth	1.25	1.25	1.25	1.25	m
Sowing density	126	126	126	126	kg ha^{-1}

Water productivity

C3 crops, such as wheat, have WP (water productivity) values in the range of 13-20 g m^{-2}. The model has a default value of 15 g m^{-2} for normalized water productivity. However, in this particular work, water productivity was adjusted using AquaCrop to consider the concentration of atmospheric CO_2, so the value used was 19.5 g m^{-2}.

Canopy cover

Canopy cover is expressed as the percentage of the total crop area covered by the vertical projection of the plants (Farfán, 2019). The results indicated a 98% soil cover in the maturity stage of the crop, as expressed in Figure 3, where the black squares indicate the canopy cover observed in the field and the values presented in the green graph are the values simulated by the AquaCrop model, with initial coverage values of 2.6%.

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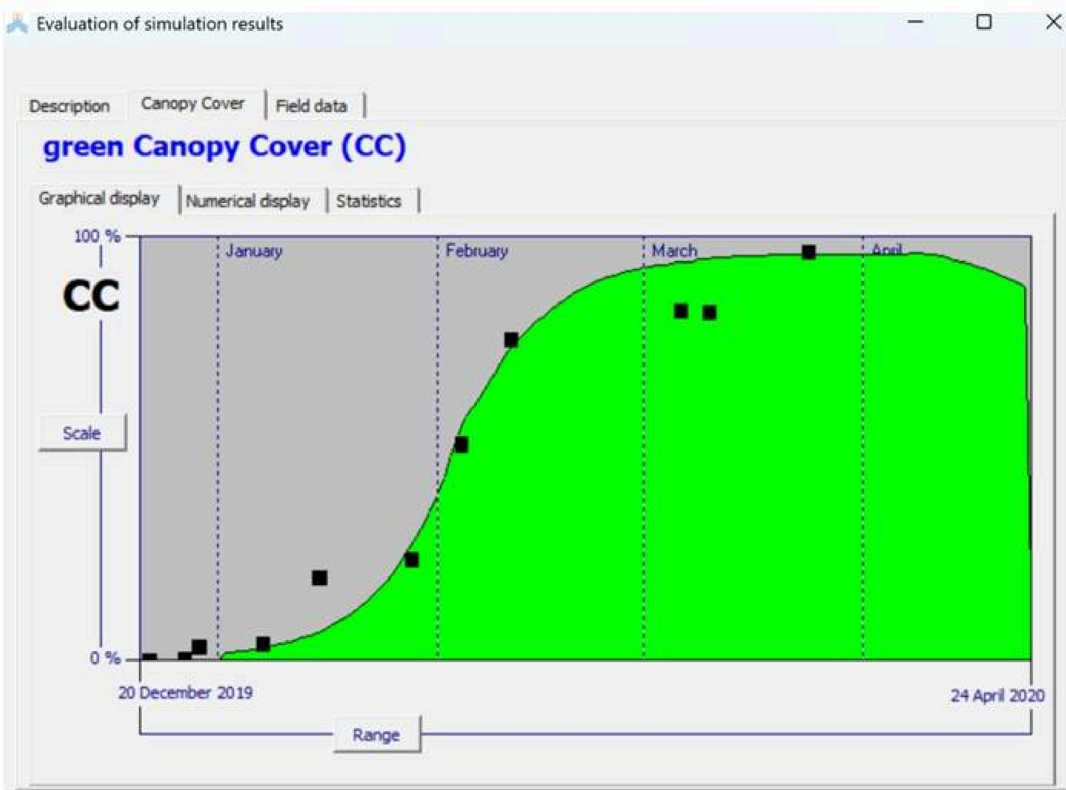
Figure 3. Simulation of the canopy cover of wheat crops and its correlation with experimental data (black squares).



Those parameters related to the duration of the different stages of crop development underwent variations compared to those used as starting values to begin calibration, with the parameter of days after sowing (DAS) to achieve maximum coverage (77 DAS), the beginning of flowering (81 DAS), and senescence (112 DAS) standing out.

Figure 4 shows the statistical indicators of the simulations of canopy cover in relation to what was observed in the field, obtaining a Pearson's correlation coefficient, r, of 0.99, being the same order in the two variables. Similarly, the root mean square error (RMSE), which is the standard deviation of the residual values (prediction errors), was analyzed. The values obtained indicated that the AquaCrop model has a high sensitivity when simulating the real canopy cover of CIRNO C2008 wheat crops.

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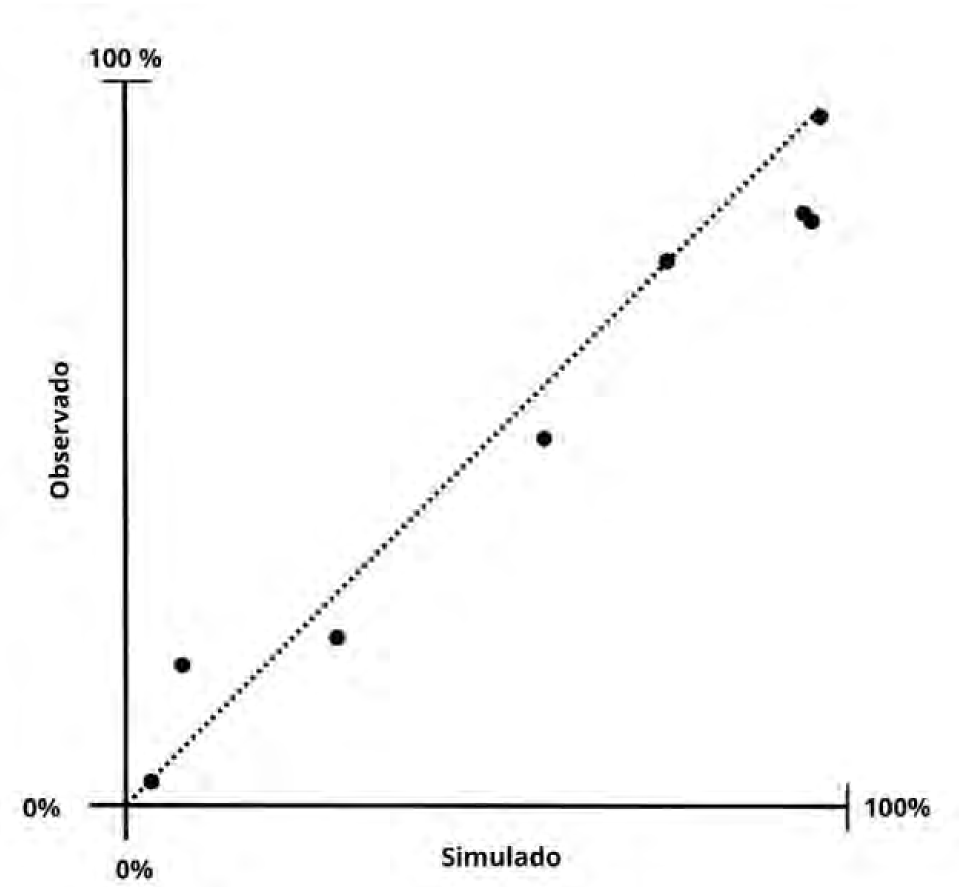
Figure 4. Line graph of canopy cover calibration, simulated vs. observed in the field.



Biomass calibration and simulation

The accumulated amount of transpired water translates into a proportional amount of biomass produced, so the productivity of water for atmospheric demand and CO_2 concentrations in the air expresses the strong relationship between photosynthetic CO_2 assimilation, biomass production, and transpiration regardless of climatic conditions, as shown in Figure 5 (Ordoñez-Paz, 2016).

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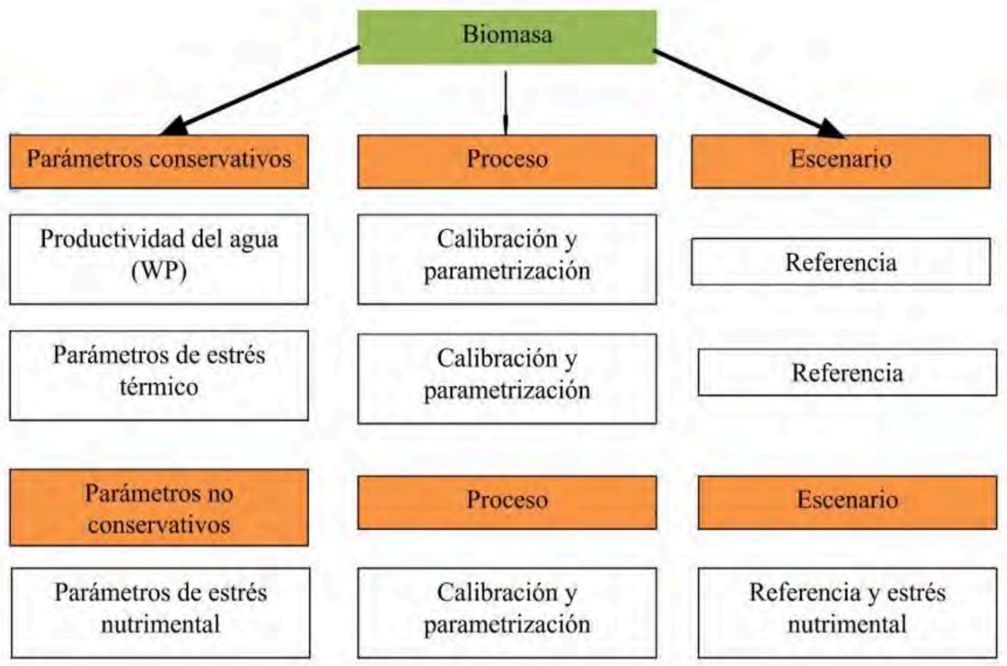
Figure 5. Calibration and simulation of the biomass observed in the field vs. the biomass simulated in Aquacrop.



In the simulation of dry biomass, AquaCrop uses a highly contrasted linear model where dry biomass is related to crop transpiration through the variable of water productivity (WP) (Steduto *et al*., 2009). Reference evapotranspiration (ET_0) was included in this relationship with the intention of normalizing this variable. In general, it is considered that the simulation of the development phases was satisfactory since the statistical indicators for ET_0 are significant.

Regarding the values of the biomass, an r^2 of 0.99 was obtained; the normalized root means square error (NRMSE), also known as the dispersion index, was within the limits of ±20%. The values of EF (model efficiency) and d (Willmott's index) are high according to Moriasi *et al*. (2007) criteria. Thus, using the information provided in the previous sections, it was possible to calibrate the model, which allowed us to obtain a set of non-conservative standard parameters for CIRNO C2008 wheat crops.

Observed yields vs. yields simulated in Aquacrop

The yields obtained in the field are shown in Table 2, where they can be compared with the values simulated in Aquacrop for the three study treatments; that is, for the treatment under 240 kg N ha^{-1}, the yield obtained was 7.2 t ha^{-1}, whereas the simulated yield was 7.189 t ha^{-1}. In the treatment under 120 kg N ha^{-1}, the simulated yield was 6.638 t ha^{-1} and the yield obtained in the field was 6.6 t ha^{-1}. The simulated yield for the 0 kg N ha^{-1} treatment was 4.436 t ha^{-1}, compared to the yield obtained in the field of 4.2 t ha^{-1}.

Table 2. Yields obtained and simulated in the three treatments under study.

Treatment	Simulated yield (t ha^{-1})	Yields obtained in the field (t ha^{-1})
240 kg ha^{-1}	7.189	7.2 ±0.7
120 kg ha^{-1}	6.638	6.6 ±0.02
0 kg ha^{-1}	4.436	4.2 ±0.16

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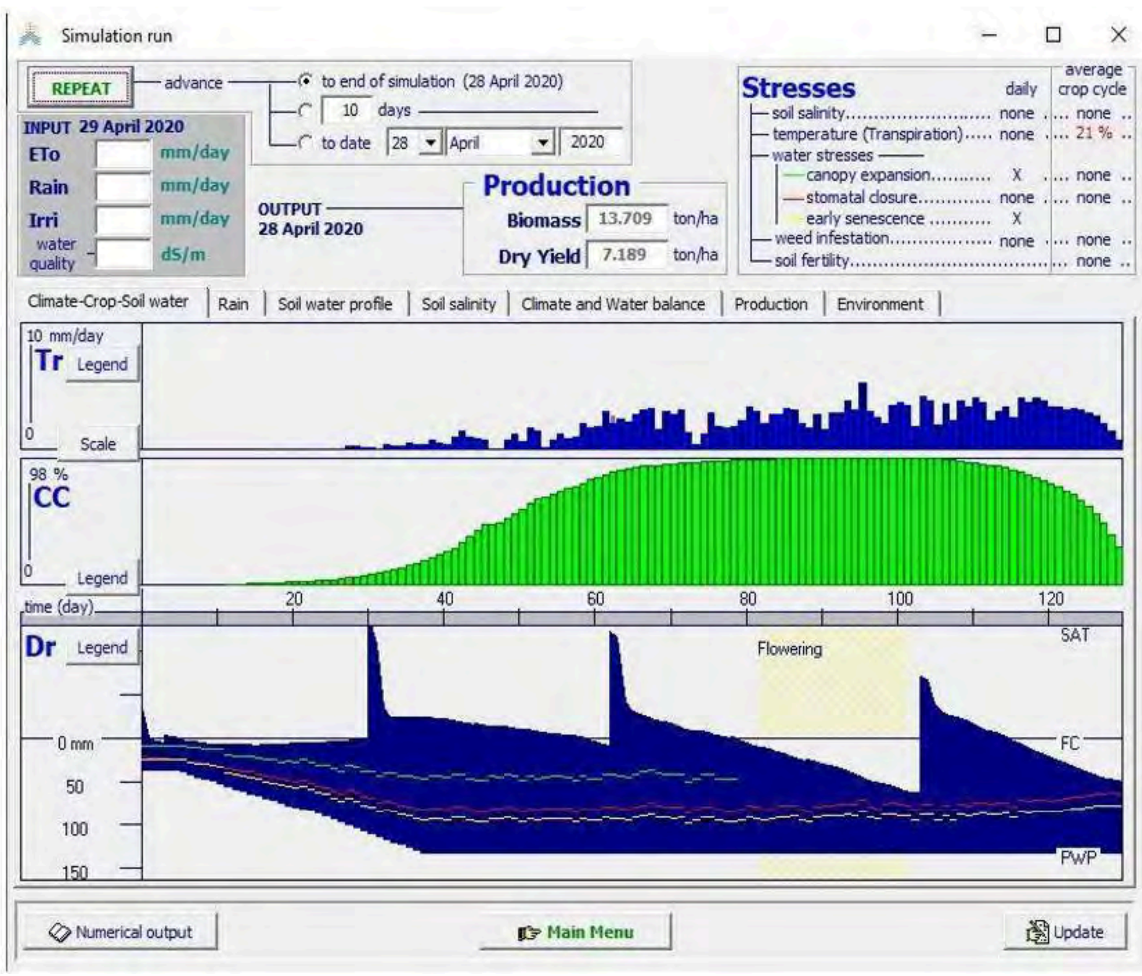
The simulated production of CIRNO C2008 wheat crops under 240 kg N ha^{-1} showed a yield of 7.189 t ha^{-1}. It has been reported that the application of chemical fertilizers has a positive and significant effect on grain production, contributing to both the increase in yields and their quality (Nahar *et al*., 2017; Grageda-Cabrera *et al*., 2018).

In addition, heat stress modified the crop's water ratios and transpiration rate. On the other hand, stomata closure did not occur, as they opened with the increase in nutrient concentration (Zahra, 2023). Finally, there was no nutrient deficit since the proportion of nutrients was correct, following the 4R principle, which means that fertilization was with the right source, at the right rate, right time, and in the right place (Figure 6) (Baseca, 2020).

Figure 6. Simulation of the yield of CIRNO C2008 wheat crops under 240 kg N ha^{-1}.



Nitrogen insufficiency triggers a series of modifications in various physiological processes in plants, with special emphasis on photosynthesis, sugar metabolism, and the distribution of photoassimilates depending on the corresponding sources and requirements (Sun, 2020). This nutritional deficiency reduces the photosynthetic capacity of plants, affecting their ability to capture and transform solar energy into organic compounds essential for their growth and development (Acevedo, 2020).

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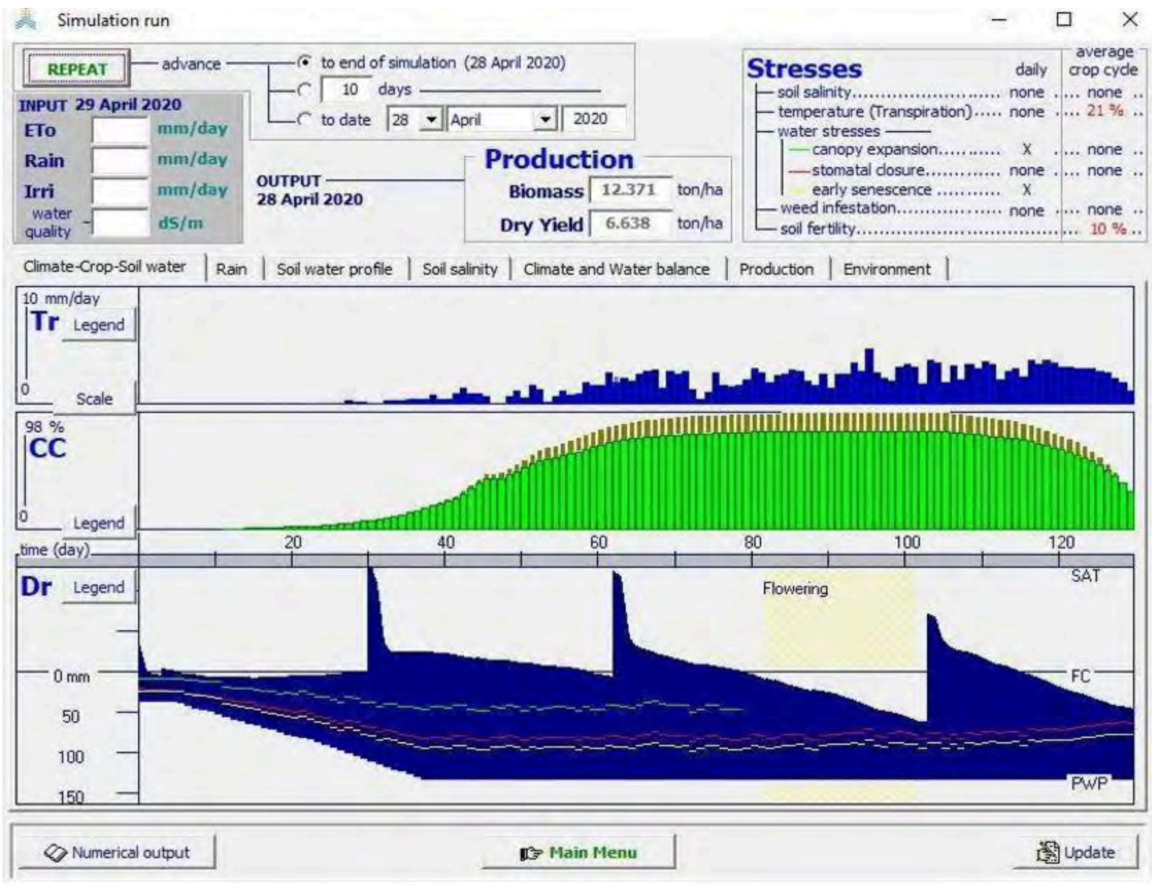
In addition, the alteration in the metabolism of sugars influences the production of carbohydrates and other compounds vital for the optimal functioning of plants. The disturbed allocation of photoassimilates, as a result of nitrogen deficiency, can affect nutrient distribution and response to metabolic demand in different parts of the plant, thus influencing its overall growth and yield (Alcántara-Cortés, 2019). These interconnected physiological effects denote the crucial importance of nitrogen as an essential nutrient for healthy and productive plant development, as observed in the yield obtained vs. the yield simulated for wheat crops under a dose of 120 kg N ha^{-1} (Table 2 and Figure 7).

Figure 7. Simulation of the yield of CIRNO C2008 wheat crops under 120 kg N ha^{-1}.



In this treatment, water ratios, transpiration rate, photosynthesis-respiration balance, water use efficiency, protein synthesis, and enzyme activity were modified, and consequently, agricultural yields decreased (Martínez *et al*., 2017). Baseca (2020) reported that the identified deficiency causes the dysfunction of vital components within the structure of the plant or the absence of these elements, which results in poor development, manifesting itself in growth patterns, the appearance of yellowish tones, and the predisposition of plants to be more susceptible to diseases.

In situations of nutrient deficiency, such as in the treatment of CIRNO C2008 wheat crops under 0 kg N ha^{-1} (Figure 8), the plants experienced a significant decrease in cell growth and elongation, along with a reduction in protein synthesis, which are essential factors that influence their proper growth and optimal functioning. In situations of more acute nitrogen deficiency, wilting of the lower leaves and general chlorosis are observed throughout the plant (Díaz-Franco, 2018).

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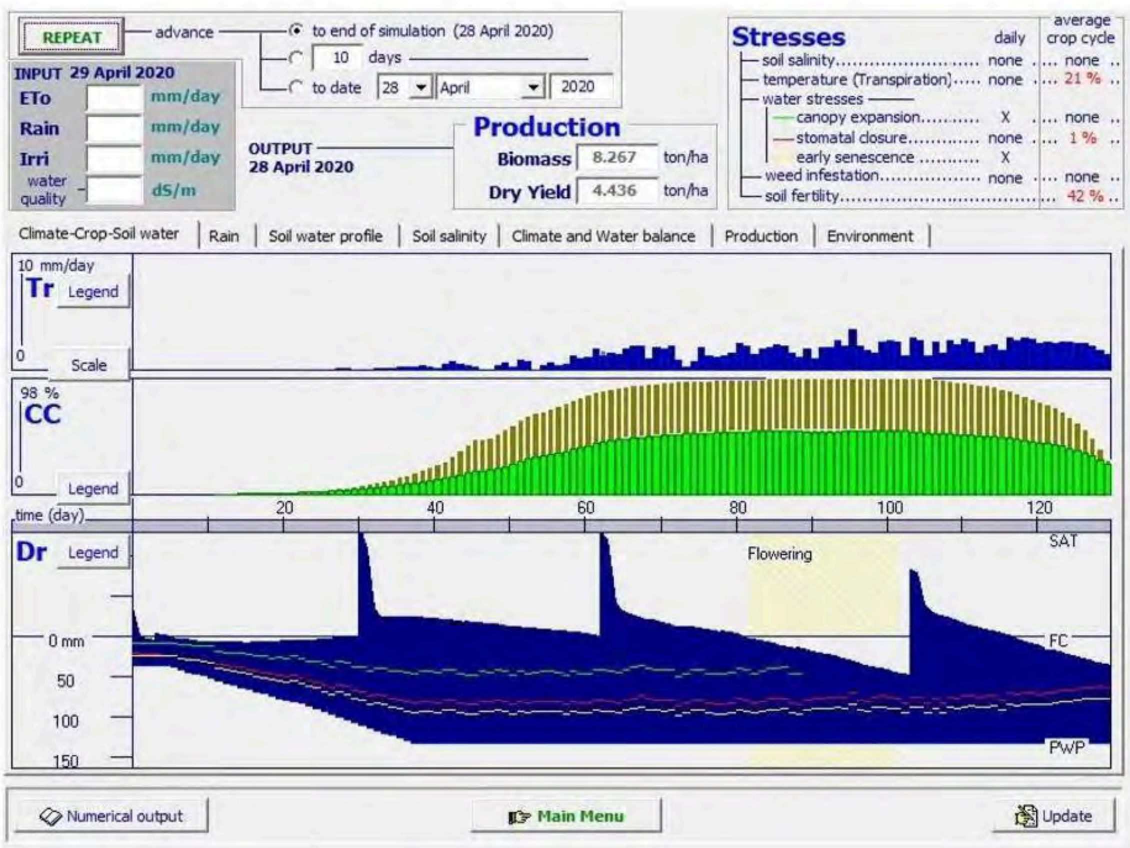
Figure 8. Simulation of the yield of CIRNO C2008 wheat crops under 0 kg N ha^{-1}.



The closure of the stomata in the presence of abscisic acid (ABA) and the activities of calcium channels during the stress response are important for calcium variations since in the guard cells, Ca^{2+} oscillations regulate the opening of the stomata. Drought is one of the biggest stress problems in agriculture. Its deficiency causes significant decreases in plant growth and if this persists, many plants show symptoms of chlorosis, especially in mature leaves (Taiz *et al*., 2020).

Conclusions

The calibration and validation of the AquaCrop model for the crop of wheat (*Triticum turgidum* L.) variety CIRNO C2008, under the conditions of the Yaqui Valley, Mexico and using three doses of nitrogen fertilization, was successfully carried out through the use of experimental data. This represented an effective and reliable tool for the evaluation and prediction of wheat crop yield for the determination of management practices, such as the optimal choice of sowing dates, and design of irrigation and fertilization strategies, among others.

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