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Original article

Behavior of corn (*Zea mays*) grown under controlled deficit irrigation strategies and in two agroclimatic conditions

Comportamiento del maíz (*Zea mays*) cultivado bajo estrategias de riego deficitario controlado y en dos condiciones agroclimáticas

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ABSTRACT: Maize is considered one of the priority crops in the import substitution program carried out by the Cuban state. Water stress is the most limiting factor for corn productivity. The research was carried out at the National Institute of Agricultural Sciences located in the province of Mayabeque, Cuba. At two sowing times, on April 20, Trial 1 (A1) and on October 29, 2021, trail 2 (A2). Under semi-controlled conditions, seeds of the corn cultivar P7928 were sown in concrete containers and three controlled deficit irrigation (CDI) treatments were studied, with suspensions of irrigation for 15 days in three stages of crop development, growth (GS), flowering (FS) and grain filling (GFS) and a control irrigated at 100% of the standard crop evapotranspiration (ETc). At the conclusion of the irrigation suspension in each of the stages, soil moisture, physiological traits, yield, and their components were evaluated. The results showed that in GS in E2 the stem length, the number of leaves and the leaf area were reduced and in both assays the aerial dry mass, the mass of 100 grains and grams per plant decreased. In FS, the stem length, the relative chlorophyll content (RCC), the mass of 100 grains and the yield in grams per plant were reduced and in SGF, only the RCC.

Key words: water stress, soil moisture, growth, yield.

RESUMEN: El maíz está considerado como uno de los cultivos prioritarios en el programa de sustitución de importaciones que lleva a cabo el estado cubano. El estrés hídrico es el factor más limitante para la productividad del maíz. Las investigaciones se realizaron en el Instituto Nacional de Ciencias Agrícolas ubicado en la provincia de Mayabeque, Cuba. En dos momentos de siembra, el 20 de abril el ensayo 1 (E1) y el 29 de octubre de 2021 el ensayo 2 (E2). En condiciones semi-controladas, semillas del cultivar de maíz P7928 se sembraron en canaletas de hormigón y se estudiaron tres tratamientos de riego deficitario controlado RDC, con suspensiones del riego por 15 días en tres etapas del desarrollo del cultivo, crecimiento (SC), floración (SF) y llenado del grano (SLL) y un control regado al 100 % de la evapotranspiración estándar del cultivo (ETc). Al concluir la suspensión del riego en cada una de las etapas, se evaluó la humedad del suelo, indicadores fisiológicos y el rendimiento y sus componentes. Los resultados mostraron que en SC en E2 se redujo la longitud del tallo, el número de hojas y el área foliar y en ambos ensayos disminuyó la masa seca aérea, la masa de 100 granos y los gramos por planta. En SF, se redujo la longitud del tallo, el contenido relativo de clorofilas (CRC), la masa de 100 granos y el rendimiento en gramos por planta y en SLL, solamente el CRC.

Palabras clave: estrés hídrico, humedad del suelo, crecimiento, rendimiento.

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INTRODUCTION

The rapid increase in the global population has made the efficient use of water an urgent necessity (1). Similarly, food production at the international level has been severely limited by high temperatures and drought conditions (2). Climate change is one of the most important and widely studied phenomena today, and it can have a profound impact on agriculture, primarily due to the occurrence of low precipitation levels (3).

The productivity and growth of major cereal crops-including maize (*Zea mays*), wheat (*Triticum aestivum*), and rice (*Oryza sativa*) are inhibited to varying degrees by abiotic stress conditions such as high temperatures and drought, which in the case of maize can lead to total crop failure (4).

Maize is a cornerstone of food and nutritional security (FNS) for the Mesoamerican population, accounting for 61 % of consumed calories and serving as a significant source of protein (5). Moreover, maize is a multipurpose crop with high adaptability to diverse agroclimatic conditions (6).

Irrigation management determines when and how much to irrigate, based on crop water requirements, soil characteristics, and climatic conditions. However, the lack of irrigation scheduling tailored to climate, soil, and crop characteristics is one of the main causes of excessive irrigation water use (7).

There are irrigation strategies that allow for reduced frequency and volume of irrigation with minimal impact on conventional yields, provided they are validated at the local scale such as deficit irrigation based on phenological development (8). However, these strategies must be applied with a sound scientific foundation to avoid negative impacts on crop yield (9), as yield results from the interactions within the soil-plant-atmosphere continuum over time. Understanding these interactions and describing the effects of climate on yield requires ongoing efforts to mitigate the negative impacts of climate variability (10).

The objective of this study was to evaluate the performance of maize cultivated under controlled deficit irrigation strategies in two distinct agroclimatic conditions.

MATERIALS AND METHODS

Two trials, E1 and E2, were conducted under semi-controlled conditions in the central area of the National Institute of Agricultural Sciences (INCA), geographically located at 22º58′00″N and 82°09′00″W, at an elevation of 130 m a.s.l. In April (E1) and October (E2) of 2021, twelve concrete containers were planted during each period. Each container measured 2.60 m in length and 0.60 m in width (1.56 m^2) and was filled with Lixiviated Red Ferrallitic soil from the province of Mayabeque (11), a region that forms part of the Habana-Matanzas karstic plain (12).

In each container, seeds of maize cultivar P7928 were sown in two rows, with a spacing of 0.4 m between rows and 0.2 m between plants, totaling 26 plants per container.

Four irrigation treatments, detailed in Table 1, were tested and arranged in a randomized block design with three replications.

Irrigation was applied using an automated micro-sprinkler system, and valves installed along the lateral irrigation lines of each treatment regulated water delivery. The irrigation water during the experimental phase had a pH of 7.8 and an electrical conductivity (EC, dS m^{-1}) of 0.58.

Irrigation consisted of replenishing 100 % of the crop's daily standard evapotranspiration (ETc) three times per week (Monday, Wednesday, and Friday). Plants received 100 % of ETc immediately before and after each irrigation suspension period (IS).

Reference evapotranspiration (ETo, mm), crop evapotranspiration (ETc, mm), and irrigation requirements (ETc = ETo × Kc) were estimated using CropWat 8.0. The model was updated with a 31-year (1990-2021) meteorological dataset from the Tapaste station (National Institute of Meteorology), located approximately 300 m from the experimental site. Monthly average values of all required climatic variables were used for the calculations.

The crop coefficients (Kc) applied were: Initial Kc = 0.62, Mid-season Kc = 1.00, Final Kc = 0.93 as proposed for the region (13).

Evaluations Conducted

All measurements were taken at 35, 55, and 75 days after sowing (DAS), coinciding with the end of the irrigation suspension periods in the vegetative (GS), flowering (FS), and grain-filling (GFS) stages.

Soil moisture was monitored at a depth of 20 cm using an HD2 Precise Moisture Measurement device equipped with a TRIME®-PICO TDR sensor (Germany), calibrated with internal calibration No. 2. Fifteen replicates were recorded per treatment.

Table 1. Description of the deficit irrigation treatments evaluated

Treatments	Description
100 %	Control: Irrigated at 100% of the crop's standard evapotranspiration (ETc) throughout the entire growth cycle.
GS	Growth Stage Deficit: Irrigation suspended for 15 days during the vegetative growth stage (between 20-35 days after sowing, DAS).
FS	Flowering Stage Deficit: Irrigation suspended for 15 days during the flowering stage (between 40-55 DAS).
GFS	Grain Filling Stage Deficit: Irrigation suspended for 15 days during the grain filling stage (between 60-75 DAS).

DAS = days after sowing. During the irrigation suspension periods, the concrete containers were covered with a transparent polyethylene roof to prevent rainfall

Growth Evaluations

- Stem length (cm), measured with a graduated ruler
- Stem diameter (cm), measured with a caliper

Leaf Number

- Leaf Area (cm²) = (Length × Average Leaf Width) × 0.75 (14)
- Aboveground Dry Mass (g) measured using a precision balance.

Relative water content (%) (RWC) and chlorophyll content (SPAD), along with growth evaluations, were assessed using nine replicates per treatment.

For RWC, leaf apices from the upper third of fully developed plants were collected at 7:00 a.m., weighed (fresh mass), and placed in a hydration chamber for 24 hours in darkness at 8 °C. Subsequently, their turgid mass was measured, and samples were dried in a forced-air oven at 65 °C for 72 hours until reaching constant dry mass. RWC was calculated using Equation [1]:

$$RWC = [(fresh\ mass - dry\ mass) / (turgid\ mass - dry\ mass)]\ x\ 100\ (\%) \qquad [1]$$

Relative chlorophyll content (RCC) was measured using a MINOLTA SPAD 502 Plus Portable Chlorophyll Meter.

For yield and its components, the following variables were measured in 10 ears per treatment: rows per ear, kernels per row, kernels per ear, mass of 100 kernels, kernels per plant, and grams per plant.

Confidence intervals of the means and their comparisons were calculated using IBM SPSS Statistics 19, and graphical representations of the results were generated using Sigma Plot 11.0.

RESULTS AND DISCUSSION

The accumulated values of reference evapotranspiration (ETo) and effective rainfall recorded during the implementation of both trials are shown in Figure 1.

The difference in ETo between the two trials was 372.23 mm, representing a 41 % higher value in Trial 1 (E1). Regarding effective rainfall, the difference was 522.96 mm in favor of E1, which corresponds to a 71 % increase. By analyzing the differences between ETo and effective rainfall in both trials, it was found that in E1 the difference was 120.69 mm (1207 m³ ha⁻¹), and in E2 it was 301.36 mm (3014 m³ ha⁻¹). These results clearly indicate that the climatic water deficit was greater in E2.

Soil moisture content variations under different treatments are shown in Figure 2. In both trials, when irrigation was suspended during the vegetative growth stage (GS), soil moisture decreased by 36.6 and 36.1 %, respectively, compared to the control treatment (100 % of ETc). During the flowering stage (FS), the reduction was 33.45 and 39 %, and during the grain-filling stage (GFS), it reached 44.45 and 38 %, respectively.

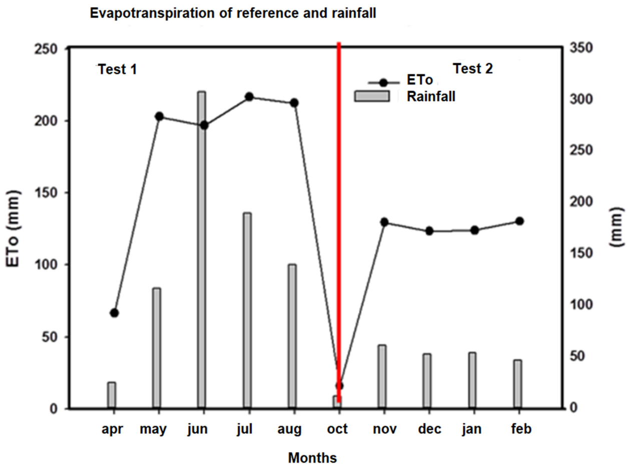
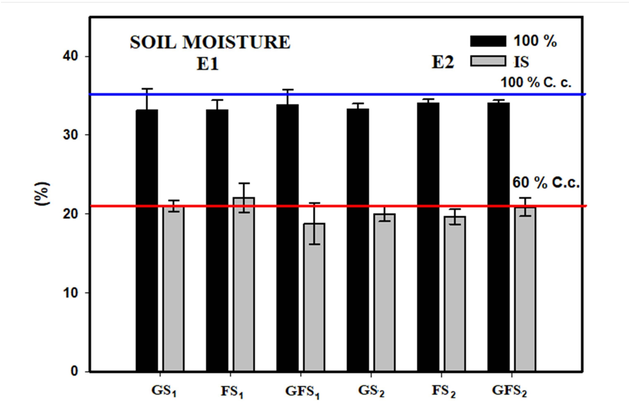


Figure 1. Values accumulated monthly of reference evapotranspiration (ETo) and effective rainfall in both trials



Bars over the mean values represent the confidence interval of the means, α = 0.05. IS = Irrigation suspension. E1 and E2 = Trials 1 and 2. 60 % and 100 % of field capacity (F.C.). GS = irrigation suspension during the growth stage; IS = irrigation suspension during the flowering stage; GFS = irrigation suspension during the grain filling stage

Figure 2. Variation in soil moisture percentage under the treatments studied at a depth of 20 cm

In general, these values confirm the effectiveness of the applied irrigation strategies in terms of soil moisture retention at each of the studied stages, with levels around 60 % of field capacity, which is considered moderate water stress.

Table 2 presents the results of the application of regulated deficit irrigation (RDI) strategies on crop growth variables in both trials.

In this process, it was found that under GS in Trial 1 (E1), moderate water stress did not negatively affect the growth of any of the three evaluated variables. However, in Trial 2 (E2), reductions were observed in stem length and leaf number.

Water stress induced by irrigation suspension during flowering (FS) led to decreases in stem length and diameter only in E1.

Table 2. Effect of regulated deficit irrigation (RDI) treatments during the three developmental stages of maize plants on various growth indicators

Variable	Test	100 %	GS	E.s.X	100 %	FS	E.s.X	100 %	GFS	E.s.X
Stem Length (cm)	1	71.75	83.00	4.49 ns	**138.87**	124.25	**3.67***	121.75	136.00	9.90ns
	2	**95.90**	46.62	**3.560***	123.75	129.0	9.65 ns	**247.70**	160.10	**7.143***
Stem Diameter (cm)	1	1.37	1.32	0.05 ns	**1.69**	1.31	**0.1109***	1.19	**1.67**	**0.125***
	2	1.12	0.90	0.10 ns	1.90	2.10	0.12ns	2.04	2.03	0.05ns
Nº of leaves	1	7.5	7..25	0.37 ns	11.25	11.25	0.61 ns	10.50	12.00	0.75 ns
	2	**7.25**	6.25	**0.250***	9.50	9.25	0.86 ns	**13.5**	9.50	**0.288***

GS = irrigation suspension during the growth stage; FS = irrigation suspension during the flowering stage; GFS = irrigation suspension during the grain filling stage. ($P < 0.05$)

Under GFS, the mean values of the three variables in E1 plants were higher, although statistically significant differences compared to control plants were observed only in stem diameter. In contrast, in E2, substantial reductions in stem length and leaf number were recorded compared to plants irrigated at 100 % of crop evapotranspiration (ETc).

The comparison of plant responses in both trials under identical RDI treatments suggests a notable influence of the higher climatic demand observed in Trial 2 (E2) on treatment effects, which led to reduced stem length and leaf emergence in GS2 and GFS2 compared to control plants.

Regarding the effects of different RDI treatments, (9) working on the same crop with four RDI treatments and a control, reported reduced stem length when water stress was applied during the growth and maturation stages. In contrast, (15) found no differences in stem growth between maize plants irrigated at 100 and 25 % of field capacity (FC) under a climatic water deficit of 471.5 mm. However, when the deficit reached 607 mm, stem length decreased in all plants receiving less irrigation than those under the 100 % FC treatment.

As for leaf area and aboveground dry biomass of maize plants subjected to RDI at different developmental stages, results are shown in Figure 3. It was found that under GS, leaf area was negatively and significantly affected only in E2, while aboveground dry biomass was slightly reduced in both E1 and E2 compared to control plants.

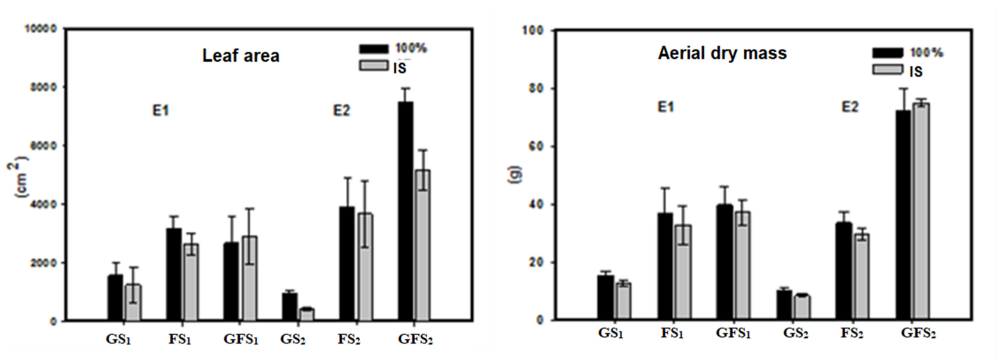
Irrigation suspension during FS had virtually no negative effects on either leaf area or aboveground dry biomass. However, under GFS, leaf area was significantly reduced only in plants corresponding to E2.

This plant behavior clearly indicates that leaf area was more susceptible to irrigation suspension during the growth (GS) and grain filling (GFS) stages than shoot dry mass, especially in E2. In this regard, the results are consistent with those of (16), who, when evaluating the sequence of changes in maize plants in response to soil water deficit, found that leaf area was more sensitive to soil moisture deficiency, which in turn did not have a significantly direct effect on total biomass production. Some authors have identified drought tolerance traits such as limiting the growth of organs that increase transpiration and allocating more resources to the root system to improve water and nutrient uptake (4).

It is noteworthy that the moderate stress induced by the CDI treatments had a greater negative effect in E2, as observed in the previously analyzed variables.

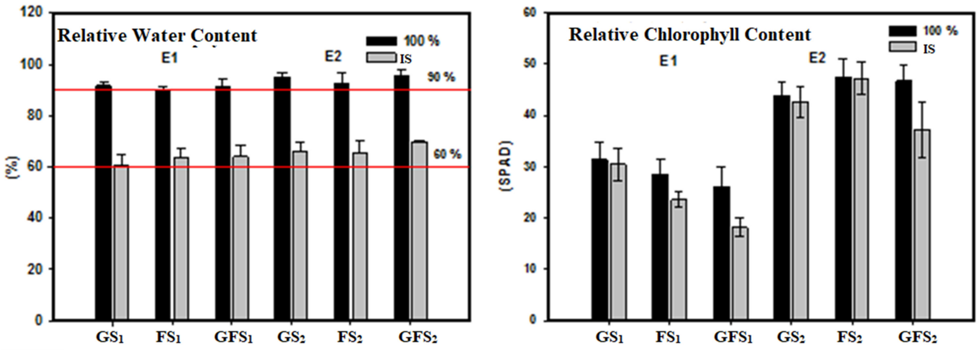
Variations in RWC (Relative Water Content) and RCC (Relative Chlorophyll Content) of the plants under different treatments are shown in Figure 4. Plants that received 100 % of the crop evapotranspiration (ETc) showed RWC values between 89 and 95 %, while those under the three CDI treatments showed RWC values between 60 and 70 %, with statistically significant differences compared to the fully irrigated plants in both trials.

In GS, RCC values did not decrease compared to the control in either trial. In SF, RCC decreased only in E1, and in GFS, it decreased considerably in E1 and slightly in E2.



Bars above the mean values represent the confidence intervals of the means, α = 0.05. GS = irrigation suspension during the growth stage, FS = irrigation suspension during the flowering stage, GFS = irrigation suspension during the grain filling stage

Figure 3. Effect of irrigation suspension (IS) at different stages of maize plant development on leaf area and shoot dry mass



Bars above the mean values represent the confidence interval of the means, α = 0.05. GS = irrigation suspension during the growth stage, FS = irrigation suspension during the flowering stage, GFS = irrigation suspension during the grain filling stage

Figure 4. Effect of irrigation suspension (IS) at different stages of maize plant development on Relative Water Content (RWC) and Relative Chlorophyll Content (RCC)

These results indicate that irrigation suspension at all three stages led to a significant reduction in RWC, mainly due to lower soil moisture affecting the plants under the CDI treatments.

Regarding CCR, the most unfavorable treatment for this variable was GFS in both E1 and E2. This behavior is mainly associated with the fact that GFS corresponds to the final stages of crop development, during which RCC naturally begins to decline. Furthermore, as noted by (14, 17), the reduction in chlorophyll content under water stress conditions is a typical symptom of oxidative stress and may result from pigment photooxidation and degradation, leading to damage in the photosynthetic membrane, lower chlorophyll content, and consequently less efficient use of radiation.

By analyzing the values of the yield components (Table 3), it was found that in SC, both in E1 and E2, the 100-grain weight decreased, and in E1, the yield in grams per plant also declined. In SF plants, reductions were observed in both the 100-grain weight and grams per plant in both trials. As for GFS, moderate stress only caused a decrease in the 100-grain weight in E1 and in the number of rows per cob in E2.

With the application of CDI treatments at different stages, affecting yield variables and their components, it was found that the most sensitive stages to moderate water stress were, in general, the vegetative growth stage (GS1) and the flowering stage (FS1 and FS2), which caused significant reductions in 100-grain weight and yield in grams per plant.

Despite the considerably lower rainfall in E2, the impact of CDI treatments on yield-related variables and their components was lesser pronounced, especially in GS2 and GFS2. Studies conducted on the same crop indicated that reducing irrigation after the critical flowering period had little effect on maize yield (18).

Table 3. Indicative yield values of maize plants treated with different CDI strategies

Treatment	Trial	Rows - cob	Grains- row	Grain-cob	100-grain weight	Grams-plant
100 % ETc	**1**	12.30	22.80	278.90	17.78	50.06
GS	**1**	13.20	18.55	248.90	14.79	38.64
E.S.X		0.497 ns	2.22 ns	31.54 ns	0.168 *	1.473 *
100 % ETc	**2**	13.10	23.47	312.42	18.37	57.39
GS	**2**	12.40	20.54	251.70	16.85	42.29
E.S.X		0.378 ns	2.99 ns	24.697 ns	0.254*	4.528 ns
100 % ETc	**1**	12.30	22.80	278.90	17.78	50.06
FS	**1**	13.30	17.90	238.60	14.14	33.90
E.S.X		0.746 ns	2.220 ns	25.55 ns	0.225 *	2.084 *
100 % ETc	**2**	13.10	23.47	312.42	18.37	57.39
FS	**2**	13.10	18.90	251.98	14.91	38.00
E.S. X		0.289 ns	2.134 ns	22.913 ns	0.287*	4.377*
100 % ETc	**1**	12.30	22.80	278.90	17.78	50.06
GFS	**1**	13.10	20.40	269.30	16.51	47.07
E.S. X		0.746 ns	2.220 ns	18.113 ns	0.169 *	1.473 ns
100 % ETc	**2**	13.10	23.47	312.42	18.37	57.39
GFS	**2**	14.30	22.10	315.43	17.65	55.93
E. S. X		0.282 *	1.629 ns	20.081 ns	0.290 ns	6.239 ns

GS = irrigation suspension during the growth stage FS = irrigation suspension during the flowering stage GFS = irrigation suspension during the grain filling stage. ($P < 0.05$)

Regarding the potential effects of climatic water deficit (15), it was found that when the deficit was 471.5 mm, there were no statistical differences in 100-grain weight between control plants (irrigated at 100 % of field capacity) and stressed plants (irrigated at 25 % of field capacity), nor in yield between the control and those irrigated at 50 % of field capacity. However, when water demand reached 607 mm, the 100-grain weight was higher in plants irrigated at 100 % of field capacity than in those at 25 %, and yield was greater in the 100 % treatment compared to the other treatments (75, 50, 25, and 0 % of field capacity).

CONCLUSIONS

The higher climatic demand observed in E2 had a negative effect primarily on the behavior of growth-related variables. The application of CDI strategies, involving a 15-day irrigation suspension during the three stages (GS, FS, and GFS) in maize cultivar P7928, led to significant reductions in soil moisture and Relative Water Content (RWC). Additionally, in GS, across both trials, the 15-day irrigation suspension caused reductions in shoot dry mass, leaf area, and 100-grain weight. In SF, there was a decrease in Relative Chlorophyll Content (RCC), 100-grain weight, and yield in grams per plant. In GFS, leaf area, RCC, and the number of rows per ear were reduced. Clearly, the growth stage (GS) was the most susceptible to irrigation suspension, while the grain filling stage (GFS) showed the least sensitivity to moderate water stress.

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