TERRA LATINOAMERICANA

Effect of Maximum Seasonal Temperature on Yield and Water Use Efficiency in Forage Corn in Consecutive Growing Seasons
Efecto de Temperatura Máxima Estacional sobre el Rendimiento y la Productividad del Agua en Maíz Forrajero en Ciclos Consecutivos

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SUMMARY

High temperature negatively affects plant growth and crop yield. The aim was to evaluate the effect of maximum temperature on yield and water use efficiency in forage corn with subsurface drip irrigation and surface irrigation in five consecutive growing seasons (spring and summer) in the comarca Lagunera. The study was carried out at the La Laguna Experimental Field, of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP) in Matamoros, Coahuila. The research was carried out during summer 2019, spring 2020, summer 2020, spring 2022, and summer 2022 growing seasons. The variables were: maximum temperature, plant height, dry forage, water depth, and water use efficiency. The highest temperatures were recorded in spring 2022 and the lowest in the summer growing season of the same year. Overall, the highest plant heights occurred in the coolest growing season (summer 2022). A higher yield of dry forage (19 Mg ha^{-1}) was in the 2022 summer growing season. The highest water depth was applied in the spring 2022 growing season (71 cm) and the lowest in summer 2020 (55 cm). This resulted in higher water use efficiency in summer. The variation in water use efficiency between growing seasons was due to higher temperatures in spring. Finally, water use efficiency tended to decrease by 19% as temperature increased from 30 to 38 degrees Celsius.

Index words: *climate, Comarca Lagunera, drip irrigation.*

RESUMEN

La alta temperatura ambiental afecta de manera negativa el crecimiento de la planta y el rendimiento del cultivo. El objetivo fue evaluar el efecto de temperatura máxima estacional sobre el rendimiento y la eficiencia en el uso del agua en maíz forrajero con riego por goteo subsuperficial y riego superficial por melgas en cinco ciclos consecutivos (primavera y verano) en la Comarca Lagunera. El estudio se llevó a cabo en el Campo Experimental La Laguna, del Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP) en Matamoros, Coahuila. La investigación se realizó durante los ciclos: verano 2019, primavera 2020, verano 2020, primavera 2022 y verano 2022. Las variables fueron: temperatura ambiental máxima, altura de planta, forraje seco, lámina de riego y eficiencia en el uso del agua. Las mayores

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temperaturas se registraron en la primavera de 2022 y las menores en el ciclo de verano del mismo año. En general las mayores alturas de planta se presentaron en el ciclo más fresco (verano 2022). Se observó mayor rendimiento de forraje seco (19 Mg ha^{-1}) en el ciclo de verano 2022. La mayor lámina de riego fue en el ciclo de primavera 2022 (71 cm) y la menor en verano 2020 (55 cm). Esto dio como resultado que la eficiencia en el uso del agua fuera mayor en verano. Esta variación de eficiencia en el uso del agua entre ciclos se debió a mayores temperaturas en primavera. En conclusión, la eficiencia en el uso del agua tendió a disminuir en 19% al incrementarse la temperatura de 30 a 38 grados centígrados.

Palabras clave: *clima, Comarca Lagunera, riego por goteo.*

INTRODUCTION

The population is increasing, while the water available for agriculture is decreasing (Dharaiya, Solanki, Jadav, Damor, and Malam, 2022). This means that water resource management in agriculture will have to be more efficient to ensure food security (Fatahi *et al*., 2021). A viable option to improve food production is to switch from conventional irrigation (surface) to drip irrigation (Chauhdary, Bakhsh, Arshad y Maqsood, 2017); as the problems related to water availability will be further aggravated in the future. So, farmers should protect water resources by using efficient irrigation methods (Tari, 2022). Drip irrigation is a modern method that improves water resource efficiency by applying water and nutrients directly to the root zone of the plant, which contributes to improving crop yields (Amini, Fatahi, Salami, Raeisi, and Ostad, 2023).

Climate change is one of the biggest challenges in this century as it influences crop water demand (Harina *et al*., 2022). With the effects of climate change, precipitation is expected to decrease by 10% and temperature is expected to increase by 3 to 4 °C in Mexico's semi-desert regions (SEMARNAT-INECC, 2016); this could make irrigated agriculture vulnerable in regions where water scarcity already exists. Extreme temperatures negatively affect plant growth and productivity and ultimately yields (Vega, 2018[1]). Cheikh and Jones (1994) found that temperatures above 35 °C caused stigma desiccation and reduced pollen viability in maize, which led to a reduction in crop grain yield. A 74% reduction in maize yield was found when plants were subjected to temperatures above 35 °C for more than eight days during the reproductive stage (Rincón-Tuexi *et al*., 2006). It is then evident that maize has an unfavorable response when temperatures exceed 35°C (Lobell *et al*., 2013). Therefore, in areas where temperature is high, irrigation should be applied with greater precision (Amini *et al*., 2023).

Irrigation should be applied according to crop water requirements, depending on its phenological stage and climatic conditions (Reyes-González *et al*., 2023). Irrigation water not only benefits crops by meeting their water demand but also creates transpiration cooling that mitigates crop heat stress (Li *et al*., 2020; Zhu and Burney, 2022). Besides, irrigation makes crop yield less dependent on climate (temperature), buffering yield variability in the face of climate fluctuations (Li, Guan, Schnitkey, DeLucia, and Peng, 2019). In addition, under extreme conditions, surface air temperature decreases due to proper irrigation scheduling and application (Thiery *et al*., 2017). Zhu and Burney (2022) found that irrigation obtained significant cooling on corn plants, specifically during the grain-filling period. These same authors reported that grain corn yield can be improved by 65 and 35% by reducing water stress and high temperatures, respectively, with proper irrigation application.

Corn is used as green fodder or silage, which serves as food for cattle (Piccioni, 1970). In the United States, Argentina and some European countries, the use of corn for silage is common, due to its high yield that ranges between 40 to 95 tons per hectare (Wang *et al*., 1995). In the Comarca Lagunera, forage corn has been the main crop in the last five years with a current area of almost 50 thousand hectares (El siglo de Torreón, 2023).

The aim of this study was to evaluate the effect of maximum seasonal temperature on yield and water use efficiency in forage maize with subsurface drip irrigation and surface irrigation in five consecutive growing seasons (spring and summer) in the Comarca Lagunera, Mexico.

[1] Vega, C. S. G. (2018). *Efecto de las altas temperaturas en plantas de interés agrícola de ecuador y su relación con el cambio climático*. Tesis para obtener el grado de Ingeniera en Gestión Ambiental, Universidad técnica estatal de Quevedo. Ecuador. Disponible en: https://repositorio.uteq.edu.ec/server/api/core/bitstreams/6f5a94ac-b7b4-4bc9-b262-391ab6fd1474/content

MATERIALS AND METHODS

Study Area

The study was carried out at La Laguna Experimental Field of the National Institute of Forestry, Agriculture and Livestock Research (INIFAP); located at 25° 32' N, 103° 14' W; and at 1150 m of altitude (Figure 1). The maximum temperature is up to 45 °C, the minimum temperature fluctuates from 0 to 8 °C, the average annual temperature is 24 °C, the average annual precipitation is 242 mm, and evapotranspiration (ET) is 2000 mm (Villa, Catalan, and Inzunza, 2005). The Comarca Lagunera is characterized by its arid climate, scarce water resources, and cold winters.

Agronomic Management and Crop Establishment

The study was carried out during the growing seasons of summer 2019, spring 2020, summer 2020, spring 2022 and summer 2022. Land preparation consisted of plowing, harrowing, leveling, and irrigation tape placement. Planting was done in mid-April for the spring growing season and mid-July for the summer growing season. Planting was done manually, at a distance of 0.13 m between plants and 0.76 m between rows to obtain about 100 000 plants per hectare.

The maize hybrid SB-302 of the intermediate growing season (~100 days), tolerant to high temperatures and suitable for spring and summer planting, was used. The fertilization rate used was: 200-100-00 (N, P_2O_5, K_2O), which corresponds to 200 kg of nitrogen, 100 kg of phosphorus, and zero kg of potassium per hectare. The fertilization rate was 200 kg ha^{-1} of N and 100 kg ha^{-1} of phosphorus using urea and monoammonium phosphate as main sources. All the phosphorus and half of the nitrogen were applied at planting; the rest of the nitrogen was applied every 15 days according to phenological development and crop needs using a drip irrigation system and a Venturi injector. In the surface control treatment, the other half of the nitrogen was applied manually at 35 days after planting (DAP).

The experiment was arranged as a randomized complete blocks design with four replicates. The experimental units were eight rows of 6 m long and 0.76 m separation between rows (36.48 m^2). The irrigation treatments were: sub-surface drip irrigation (SDI), in which 100, 80, and 60% of evapotranspiration (ET) were applied, and a control treatment, which was irrigation with surface irrigation. The 100% of ET treatment was multiplied by the crop coefficient (Kc) to obtain the ETr crop. The Kc used was generated locally by Reyes-González *et al*. (2019) for forage corn. The reference ET was taken from an atmometer (ETgage, model A marketed by ETgage Company Loveland, Colorado, USA), located 20 m from the experimental site.

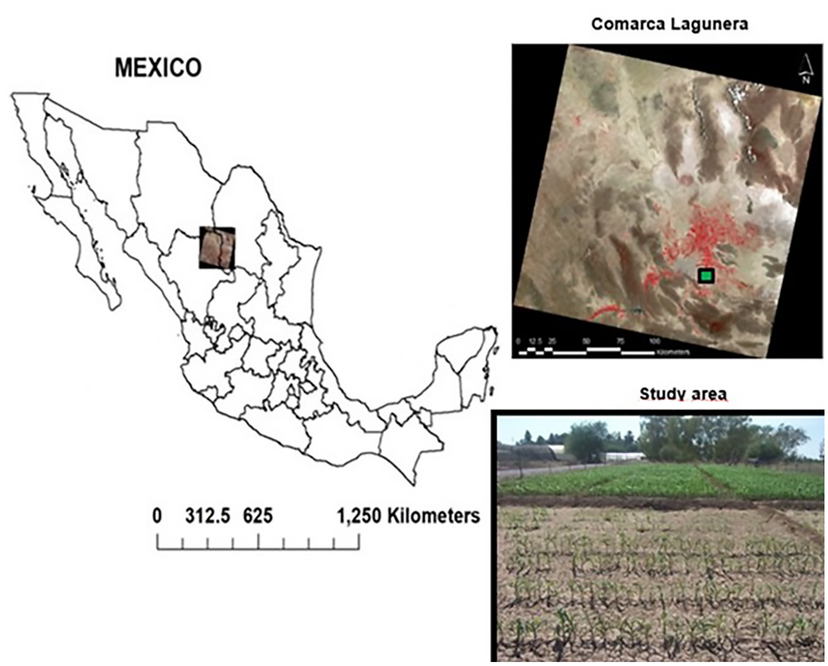

Figure 1. Study area, Comarca Lagunera, México.

The irrigation tape used was RO-DRIP 8000 (Rivulis Irrigation Inc., San Diego, CA, USA) with a wall thickness of 0.2 mm, inner diameter of 16 mm, with emitters 0.2 m apart, and a flow rate of 0.5 L h^{-1} per emitter. The tape was buried 0.3 m below the soil surface, with a distance of 0.76 m between them. The operating pressure of the irrigation system was 8 PSI with irrigation frequencies of three days. The irrigation time ranged from 1 to 4 hours during the growing season (e.g., 1 hour when plant height was 0.2 m and 4 hours when plant height was 2.0 m). For surface irrigation treatment, one irrigation was done at planting (~10 cm depth of water) and four post-plant irrigations (~15 cm) at 20-day intervals.

Data Collection

Final plant height was measured with a tape measure from the soil surface to the last leaf of the crop, five readings were taken per treatment and replicate, then averaged for each crop growing season.

Harvesting was carried out at 95 DAP in drip irrigation and at 100 DAP in surface irrigation when the grain reached one-third milk line advance. Green forage production was estimated by weighing the biomass of each useful plot of each treatment (6.08 m^2), then a 500 g sample was taken and dried in a forced air oven at 65 °C temperature for 72 h to determine percentage of dry material (DM). The green forage yield (GF) and percentage of DM were used to estimate the dry forage yield (DF).

Water use efficiency was determined by dividing the weight of DF (kg ha^{-1}) by the total volume of water applied (m^3) in each treatment for five growing seasons.

Treatment means differences between growing seasons and irrigation treatments were separated using Tukey's least significance difference (LSD) test at $P \leq 0.05$ using SAS 9.3 statistical software (SAS Institute. 2011).

The maximum temperatures were downloaded from the weather station located at the National Institute of Forestry, Agriculture and Livestock Research (INIFAP), Matamoros, Coahuila.

RESULTS AND DISCUSSION

Maximum Temperature

Figure 2 shows the maximum daily temperature recorded during five growing seasons. The red dotted line indicates the maximum threshold temperature (35 °C), at which maize stops growing and developing (Lobell *et al*., 2013). During the study, the behavior of the maximum temperature was different between growing seasons. Figure 3 shows the number of days with a maximum temperature above 35 °C during the crop growing season. The highest number (63) days with maximum temperature above the indicated threshold was recorded during the spring of 2022, while the lowest (2) was recorded during the summer of the same year. It is observed that the spring season had the highest number of days with maximum temperatures above 35 °C during the growing seasons, with 45 days in the spring 2020 and 63 days in the spring 2022. Some research indicates that maize yield is reduced by up to 74% when plants are subjected to temperatures above 35 °C for more than eight days during the reproductive stage (Rincón-Tuexi *et al*., 2006). Also, Hu and Buyanovsky (2003), reported that high temperatures were associated with low grain corn yields in a fieldwork carried out in Missouri, USA.

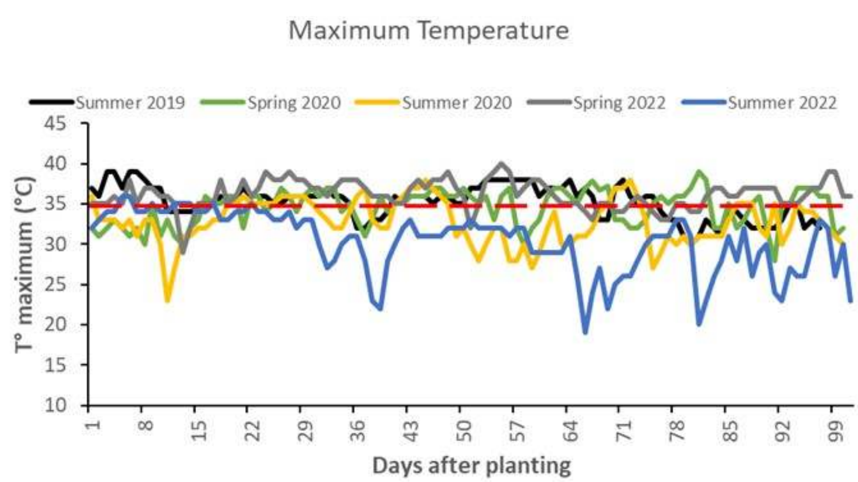

Figure 2. Maximum temperature behavior during five growing seasons of forage corn in the Comarca Lagunera.

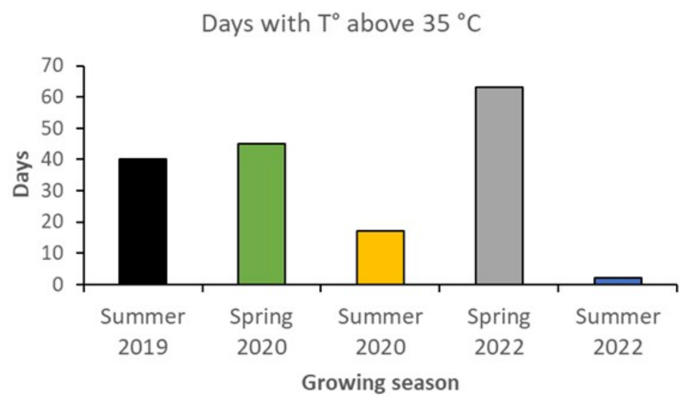

Figure 3. Days with maximum temperature above 35 °C during five growing seasons of forage maize in the Comarca Lagunera.

Plant Height

Plant height was statistically different among the five growing seasons and among irrigation treatments (Figure 4). On average, the highest height (2.41 m) occurred in the summer 2022 and the lowest (1.79 m) in spring 2020 and there was a statistically significant difference between them ($P \leq 0.05$). Likewise, in the summer 2022 growing season, there were fewer days with maximum temperature above 35 °C, than in the spring 2020 (Figure 3). In all growing seasons, the highest heights were achieved with drip irrigation at 100% ET, except in the summer 2022, while the lowest heights were achieved with surface and drip irrigation at 60% ET. These results were similar to those reported by Amini *et al*. (2023) in a forage maize crop irrigated with drip irrigation in central Iran. In the same context, in Western India, Dharaiya *et al*. (2022) obtained the highest heights with the 100% ET treatment and the lowest with the 60% ET treatment. Similarly, Nilahyane, Islam, Mesbah, and Garcia (2018) achieved the highest heights with the 100% ET treatment, followed by 80% and 60% ET in Wyoming, USA; no doubt, that maize plant height decreases with decreasing the amount of water. On the other hand, in drip irrigation treatments, the greater heights were due to an adequate amount of nitrogen (N) being supplied through fertigation, as N activates cell division resulting in the elongation of maize plant stalk internodes (Nilahyane *et al*., 2018).

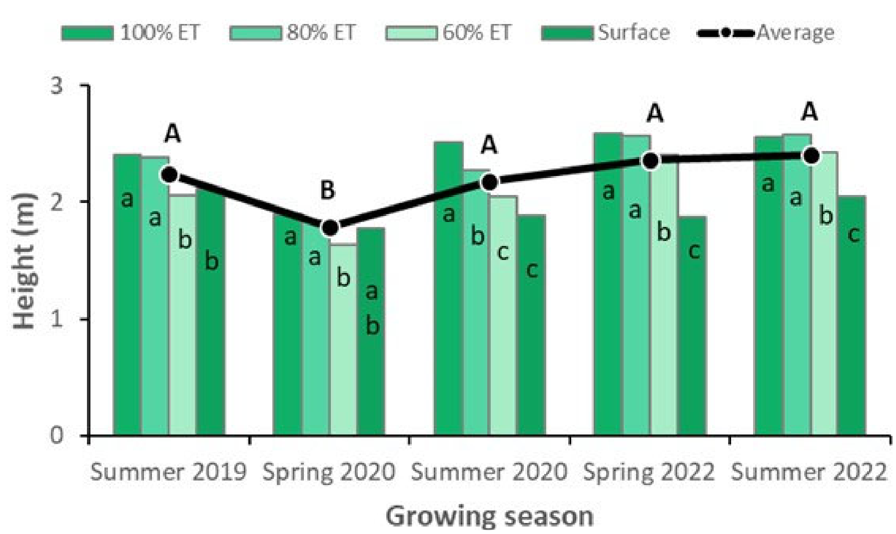

Figure 4. Plant height of forage corn in five growing seasons, with three percentages of ET and surface irrigation in the Comarca Lagunera. Means with different letters are significantly different ($P \leq 0.05$).

Dry Forage (DF)

The DF was different between growing seasons and between irrigation treatments (Figure 5). The best average DF yield was achieved in summer 2022 (19 Mg ha^{-1}) and the lowest in spring 2020 (15 Mg ha^{-1}) with a difference of 21% concerning the highest yield. In most of the growing seasons, the 100% ET treatment presented higher yields, while the lowest yields were obtained with 60% ET treatment and in surface irrigation. Corn is a crop sensitive to water stress, more than other grasses (wheat and sorghum) (Ojeda, Sifuentes, and Unland, 2006). As expected, with a drip irrigation system, water is frequent and biomass production does not stop during the crop growing season; the opposite occurs with surface irrigation, where the irrigation interval is longer affecting, biomass accumulation and consequently lower yields. This result coincides with that reported by Chauhdary *et al*. (2017) who found higher yields when applying 100% ET in drip irrigation in forage maize. Amini *et al*. (2023) concluded that low yields are obtained with surface irrigation.

Also, Nilahyane *et al*. (2018) reported higher yields with the 100% ET treatment and the lowest with 60% ET. According to Wilhelm and Wortmann (2004) in a 16-year study, they concluded that the highest corn yields occurred in the cooler years, which agrees with the results found in this research. In addition, Rincón-Tuexi *et al*. (2006) found a significant difference in biomass in the two growing seasons, with the lowest values in the season with the highest environmental temperature. However, in an experiment with six maize cultivars in the Toluca Valley, Mexico, Morales and Diaz (2020) indicated that maize yield was not affected by temperature (25 °C) but it was affected by rainfall. Similarly, Rivera, Palomo, Anaya, Reyes, and Martínez (2013) indicated that the summer growing season was associated with low yields in forage maize. Similarly, Granados-Niño *et al*. (2022) concluded that the spring season with surface irrigation in maize achieved higher dry forage yields than the summer season in the Comarca Lagunera during three growing seasons.

Water Depth

The total water depth was different in all growing seasons (Figure 6). The highest average (71 cm) occurred in spring 2022, this was due to the high temperatures recorded during the growing season, in which the highest number of days with temperatures above 35 °C occurred (Figures 2, 3). In the other growing season, the water depth was similar among them ($P > 0.05$).

In all growing seasons, surface irrigation was the system that used the highest water depth and the 60% ET treatment was the one that used the lowest. It is important to emphasize that the total water depth includes the precipitation recorded during the growing season.

In this research, four water depths were applied in each growing season, which were different ($P \leq 0.05$), due to the fact that climate determines the water use or evapotranspiration rate of crops. As in this work, Nilahyane *et al*. (2018) and Tari (2022) applied three and four different water depths with a drip irrigation system in two growing seasons of forage maize. Similarly, Montemayor-Trejo *et al*. (2012) supplied different water depths with surface (62 cm), drip (45 cm), and center pivot (52 cm) systems in forage corn established in the Comarca Lagunera.

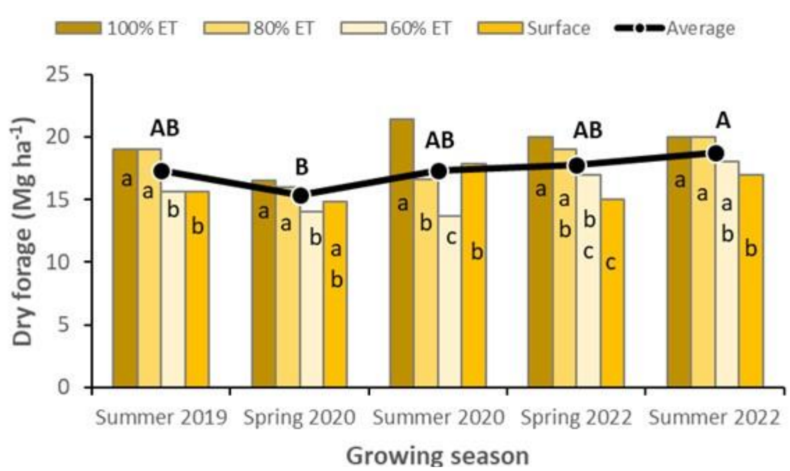

Figure 5. Dry forage production of forage corn in five growing seasons, with three percentages of ET and surface irrigation in the Lagunera region. Means with different letters are significantly different ($P \leq 0.05$).

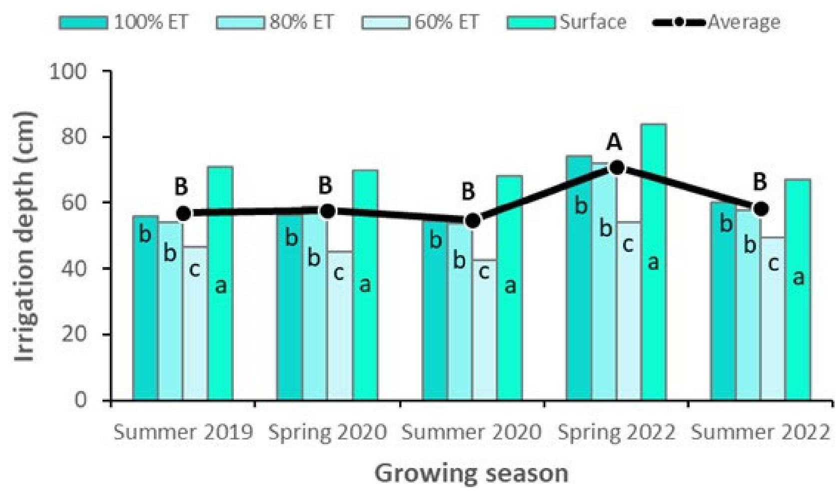

Figure 6. Total forage corn irrigated yield sheet in five growing seasons, with three percentages of ET, drip irrigation, and surface irrigation. Means with different letters are significantly different ($P \leq 0.05$).

Water Use Efficiency (WUE)

WUE is the result of dividing the dry forage yield by the total volume of water applied during the growing season. WUE was statistically different between growing seasons and irrigation treatments ($P \leq 0.05$). Figure 7 indicates that the WUE value was higher in summer than observed in spring. Overall, summer presented better WUE values, as WUE was higher by 18.5% concerning the spring growing season. This variation in WUE between growing seasons was due to higher temperatures in spring. It should be noted that in the summer 2019 growing season, although there were 40 days with temperatures higher than 35 °C, the WUE did not have such a marked decline as in the spring growing season, since in summer 2019, 25% of these temperatures occurred in the initial stage of the crop (Figure 2). Certainly, the crop response varies according to the phenological stage in which such temperatures occur, as well as the corn variety or hybrid (Lizaso *et al*., 2018). In the spring 2022 growing season, the highest number of days with temperatures above 35 °C was recorded, which led to the application of a higher water depth and droop in WUE.

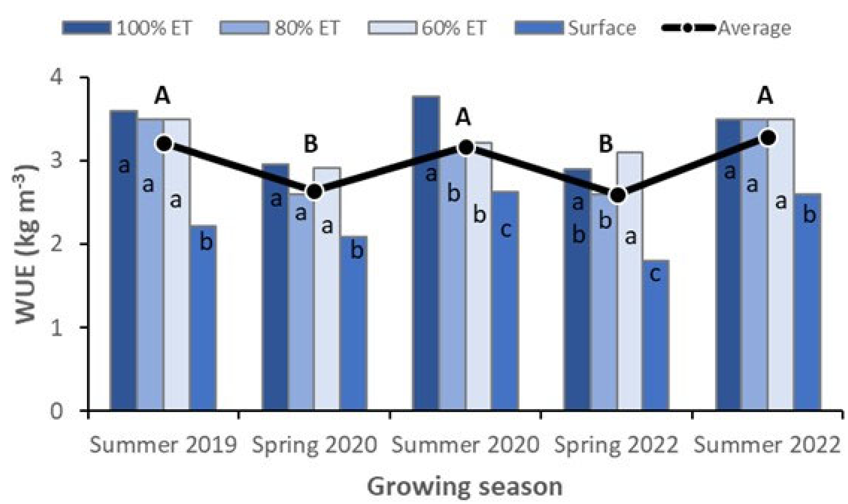

Figure 7. Water use efficiency of forage corn in five growing seasons, with three percentages of ET, drip irrigation, and surface irrigation in the Comarca Lagunera. Means with different letters are significantly different ($P \leq 0.05$).

Regarding irrigation treatments, surface irrigation had the lowest WUE values (2.2 kg m^{-3}); while the 100% ET treatment had the highest values (3.3 kg m^{-3}), except for the spring 2022 growing season. Similar results were reported by Bozkurt *et al*. (2006) who concluded that high WUE does not always correspond to the lowest water depth. Higher WUE results were reported by Howell *et al*. (2008) who obtained values of 3.63 and 3.64 kg m^{-3}. In Nebraska, USA, Suyker and Verma (2009) were able to obtain 5.2 kg m^{-3} of corn under irrigation for five years. On the other hand, Tari (2022) comments that the best water use efficiencies occur when climatic conditions are favorable for the crop. WUE in the 100% ET treatment was 9, 18, and 33% higher concerning the 60%, 80% ET, and surface irrigation treatments, respectively. WUE is an indicator that varies among regions and is affected by stocking densities, cultural practices, irrigation systems, and climate. Its value should be improved, because water competitiveness between agriculture and other sectors that also demand the water resource increases considerably (Reyes-González *et al*., 2019).

Relationships Between Dry Forage, Water Use Efficiency, and Temperature.

Figure 8 shows the negative linear relationship between DF, WUE, and temperature during the study period. DF and WUE tended to decrease with temperature rises. DF yield decreased by 11% with increasing temperature from 30 to 38 °C, because the ideal temperatures for the crop ranges from 24 to 30 °C (Bannayan, Hoogenoom, and Crout 2004). In arid and semi-arid climates such as the Comarca Lagunera, temperature is a limiting factor in forage corn production. Similar to what was obtained in this work, Maitah *et al*. (2021), found a negative correlation between maize yield and temperature. Also, Simon *et al*. (2023) reported an inverse relationship ($R^2 = 0.34$) between temperature and yield. Li *et al*. (2020) observed a reduction in yield with increasing temperature from 25 to 45 °C in work carried out in Nebraska, USA. Nevertheless, Baffour-Ata, Tabi, Sangber, Etu, and Asamoah (2023) in a study for Eastern Ghana, concluded that increasing mean annual temperature (28°C) also increases yield, their observations covered from 2012 to 2021.

WUE is also affected by increasing temperature, since higher temperatures increase crop water demand, because of low water use efficiency. Concerning WUE, Wang *et al*. (2023) reported negative relationships ($R^2 = 0.40$) between maize leaf water content and temperature. In the present work, WUE decreased by 19% with increasing temperature from 30 to 38 °C. Besides, WUE decreased by 2.4% for each degree celsius that the temperature rose.

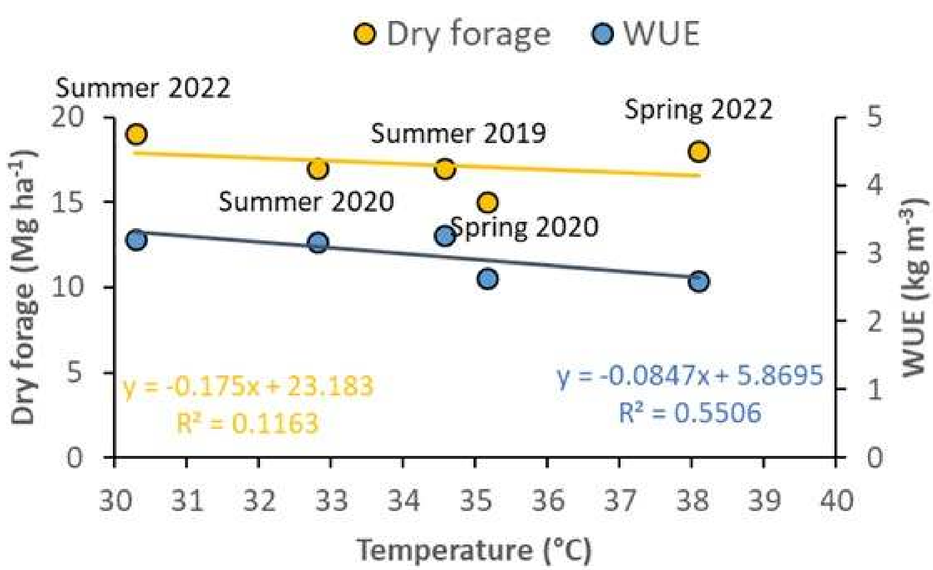

Figure 8. Relationship between dry forage, water use efficiency, and temperature in forage corn in five growing seasons with three ET percentages drip irrigation and surface irrigation in the Comarca Lagunera.

CONCLUSIONS

During the study, high ambient temperatures (> 35 °C) occurred in greater numbers in the spring than summer growing seasons, in which in turn a clear negative effect on water use efficiency was observed. Plant height and dry forage yield were better in the summer 2022, in this growing season the weather was favorable and there were fewer days with temperatures above 35 °C. Although, the highest water depth was applied in spring 2022, which had more days with temperatures above 35 °C, resulting in lower water use efficiency. Overall, summers presented better yield values, which were higher by 21% compared to spring growing seasons. In the Comarca Lagunera, water use efficiency decreased by 19% when the temperature increased from 30 to 38 °C between growing seasons; water use efficiency also dropped by 2.4% for each degree celsius that temperature rose onwards 30 degree celsius.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

Data sets used or analysed during the current study are available from the corresponding author upon reasonable request.

COMPETING OF INTERESTS

The authors declare that they have no competing interests.

FINANCING

Not applicable.

AUTHORS' CONTRIBUTIONS

Conceptualization: A.R.G., and O.R.A. Methodology: A.R.G., J.I.S.D., and D.G.R.S. Research: A.R.G., J.I.S.D., and O.R.A. Writing: preparation of the original draft, A.R.G., J.I.S.D., and D.G.R.S. Writing, review and editing; J.J.E.A., and P.P.R.

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Not applicable.

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