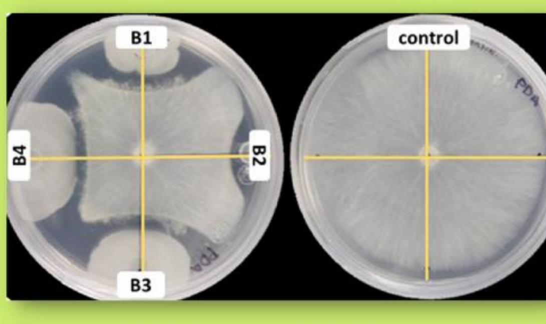
Investigaciones Biológicas, Agrícolas y Ambientales de México

Leandris Argentel Martínez
Ofelda Peñuelas Rubio
Organizadores



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Prólogo

Investigaciones Biológicas, Agrícolas y Ambientales de México es un libro electrónico científico, basado en estudios experimentales desarrollados por un colectivo de prestigiosos investigadores de México y de otros países que, en colaboración, aportan respuestas a problemáticas existentes en dichas ramas del saber. Estos trabajos aparecen divididos en capítulos donde se ofrece información actualizada sobre los avances más recientes en dichas áreas, con un estilo de artículo científico y con referencias bibliográficas de gran nivel de actualización científica.

El proceso de revisión de los capítulos fue desarrollado, bajo la modalidad a doble ciegas, por varios investigadores que participan en el comité editorial de PANTANAL EDITORA. Se agradece a los autores de los respectivos capítulos por la dedicación al atender las sugerencias y comentarios realizados por los revisores, optimizando el tiempo de los procesos de revisión y aceptación.

Los autores

Sumário

Capítulo 9

Are there atmospheric conditions for water loss at night in wheat canopies in the Yaqui Valley, Sonora, Mexico?

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ABSTRACT

Global warming and drought are the result of climate change, which can negatively affect wheat grain yield, potentially increasing food insecurity and poverty. It has been reported that for every 1 °C increase in global mean temperature, grain production can decrease by 6% across all continents. The temperature increase at night is 1.4 times greater than daytime temperatures. The objective of this research is to determine if the conditions exist for the loss of water during the night in the wheat crop in the Yaqui Valley, Sonora, under experimental conditions of climate change. During the 2019-2020 cycle, wheat plots were experimentally exposed at 2 °C above reference plots under nocturnal environmental conditions. The period of observation and data recording included four phenological stages in the development of the crop. We adapted a water stress index of wheat that considers temperature and atmospheric humidity to test for potential conditions of water loss at night. Determining the water stress index, it was possible to observe an important difference between the heat and control plots, since in heat plots during the stages of heading, anthesis and beginning of grain filling, 14.28% of the time showed conditions for the loss of water at night, and up to 28.57% of the time in the stage of physiological maturity, while in the control plots there were no conditions for nocturnal water loss. We conclude that the increase in nighttime temperatures due to climate change could have important consequences for the loss of water during the night in the wheat crop.

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INTRODUCTION

Global warming and drought are related to climate change, and both can negatively affect the yield of wheat grain, potentially increasing food insecurity and poverty (Ortiz et al., 2008). For example, it has been reported that for each 1 °C increase in global mean temperature, wheat grain yields may decline by 6% across continents (Asseng et al., 2014). Therefore, improving drought and heat tolerance in plants is considered a promising approach for sustainable food production in water-scarce areas. Under climate change scenarios, the most affected and predictable variable is temperature (García et al., 2016). An increase in temperature can produce a warming effect that can bring yield declines in primary crops and can mostly be attributed to increases in nighttime temperatures, which can increase at a rate that is 1.4 times the daytime temperatures (Russell & van Sanford, 2020; Peng et al., 2004; Ma et al., 2019). This is important because historical data have shown that cereal grain yield is strongly correlated with minimum temperatures (Lobell & Ortiz-Monasterio, 2007), which are often reached at night. Such an increase in nighttime temperatures shortens the grain filling period and can result in larger reductions in grain yield compared to those estimated by the effect of daytime temperatures (Akter & Rafiqul Islam, 2017). However, it is considered that accelerated nighttime warming will be associated with increases in the nighttime vapor pressure deficit (VPD), but variations in VPD under nighttime conditions are still uncertain (Groh et al., 2019).

Plant transpiration is mainly determined by the evaporative demand, leaf-to-air VPD, and water movement resistance in the plant hydraulic continuum to the surrounding atmosphere (Devi & Reddy, 2020). As is known, up to 90% of water absorbed by the plant from the soil is lost by transpiration (Pei et al., 1998; Jasechko et al., 2013; Filipović, 2021). Plants can sense water availability around the roots and respond to the reduced water availability by sending chemical signals to close stomata and over the night (Rawson & Clarke, 1988). Therefore, it is a challenge to separate the impact of temperature on VPD and the effect of temperature directly on plants because saturated vapor pressure is temperature sensitive (Sinclair et al., 2017).

The vapor pressure deficit is an accurate indicator of the real evaporative capacity of air (López-López et al., 2009), and it is calculated as the difference between the vapor pressure in ambient air and the pressure of water vapor held in saturated air (Seager et al., 2015):

$$VPD = e_s - e_a \qquad (1)$$

where e_s is the saturation water vapor pressure at a given air temperature and e_a is the current water vapor pressure. When the air is not saturated, the actual vapor pressure will be lower than the saturation vapor pressure. The saturated water vapor pressure e_s, in kPa, is the maximum amount of water vapor that the air can contain at a given temperature and is calculated with the following equation (Weiss, 1977):

$$e_s = 0.6108\ exp\left[\frac{17.27\ T}{T+237.3}\right] \qquad (2)$$

The current water vapor pressure e_a can be obtained using relative humidity (RH; %):

$$e_a = e_s \left[\frac{RH}{100}\right] \qquad (3)$$

Schoppach et al. (2017) have shown that wheat, under increasing VPD, displayed a VPD breakpoint in transpiration rate (TR) such that TR is limited at VPD above 2 kPa. Recent evidence confirmed that in modern wheat, the nighttime transpiration rate (TRn) depends on nighttime VPD, and under soil water deficit, TRn could represent an increasing fraction of crop daily water loss (Claverie et al., 2018). This means that nocturnal transpiration plays an important role in modulating the daytime transpiration response to increasing evaporative demand, enabling drought tolerance in wheat (Tamang et al., 2019). Therefore, a better understanding of the effect of VPD on nighttime plant water relations is important. This may be done by incorporating VPD in the estimation in a crop water stress index.

The crop water stress index (CWSI) is a metric related to plant water content in wheat crops (Jackson et al., 1981) derived from canopy-air temperature differences versus VPD (Idso et al., 1982). Therefore, it is a nondestructive method of plant response to water stress (Jackson et al., 1981; Idso et al., 1981). Since CWSI calculations are based on three environmental variables that influence water used by plants, VPD, canopy temperature, and air temperature, when transpiration decreases, the canopy temperature increases and can reach 4 to 6 °C higher than the air temperature, in which case the value of the CSWI will tend to unity (Lopez-Lopez et al., 2011). When there is no water stress, the plant transpires freely; when plant water loss occurs, the canopy temperature fluctuates from 1 to 4 °C below the air temperature, and the CWSI value tends to zero. Considering this, the CWSI is effective in indicating if conditions for plant water losses exist.

Considering that wheat production in the Yaqui Valley is of regional as well as national importance in Mexico because it represents approximately 50% of the national value of the grain (SIAP, 2020), knowledge advancement on the vulnerabilities of this crop to climate change is important for the design of adaptation strategies in the near future. The objective of this work is to analyze canopy and environmental conditions during a wheat cropping cycle to determine if conditions for water losses can occur at night in wheat canopies at the Yaqui Valley and if experimental nighttime warming conditions (± 2 °C) modify such conditions. We hypothesize that nighttime environmental conditions at the Yaqui Valley do not allow water losses by wheat canopies, but experimentally increased nighttime temperatures (± 2 °C) set conditions for water losses to occur at night. Our tool to reach this goal was a crop water stress index and an experimental temperature manipulation in the Yaqui Valley.

MATERIALS AND METHODS

Experimental design

Measurements were made during the wheat cropping cycle of 2019–2020 at Block 710 of the CENEB in the Yaqui Valley, within the experimental fields of the Patronato para la Investigación y Experimentación Agrícola del Estado de Sonora A.C. near Ciudad Obregon, Sonora, México (27°24'N 109°56'W), 38 m above sea level, with a typical calciorthid soil and low organic matter composition of 0.76% and a slightly alkaline pH of 7.7 (Sayre et al., 1997), under drip irrigation conditions.

In January 2020, four 7.1 by 7.1 meter metal structures were installed; two of them with an array of heaters similar to the ones described in Kimball et al. (2008), to increase 2 °C from reference local canopy temperatures during the nighttime (Figure 1).

Figure 1. The panoramic image of the field experiment, Yaqui Valley season 2019–2020, comprised four plots, two of which were equipped with heaters and two controls, all connected to a power source that provided heat in the handling plots.

The experiment was sown under flat beds with no limitation of water or nutrients; pests were controlled when needed. Each plot comprised 12 selected wheat genotypes that were randomized on each replication. However, this study is focused on the plot-mean performance of the plot, and genotypic variability is not included as an objective of interest. The observation period and data recording comprised the phenological stages that are considered the key stages in the development of the crop. The periods for this study were determined as follows: From March 4th, where the average of the genotypes used had reached heading (HD) and anthesis (At) and ended with the grainfilling reached on March 31st, we divided the stage of beginning of grainfilling into two parts: beginning of grainfilling (BGF) and grainfilling (GF) because this stage is longer than the previous ones. To standardize, 7 days were defined for each study period (Table 1), and nomenclature was according to the decimal code for cereal growth stages (Zadoks et al., 1974). The means presented in the results correspond to the average data for the first seven days since the beginning of each stage; the starting point of data analysis was set when the wheat reached heading on March 4th and ended with grainfilling on March 31st. The data obtained from the two reps of the heat plots were averaged to obtain a single heat plot datapoint and the same for the control plot, which we will name the heat plot and control plot hereafter.

Table 1. Dates in March 2020 for the different phenological stages of wheat

	Heading	Anthesis	Beginning of grainfilling	Grainfilling
	4th – 10th	11th – 17th	18th – 24th	25th – 31st

Note. Seven days were considered in each stage, these periods were given the name of the stages according to Zadoks et al., (1974).

The heaters were FTE-1000s (1000 W, 240 V, 245 mm long by 60 mm wide) manufactured by Mor Electric Heating Assoc., Inc. (Comstock Park, MI), which were suspended from a squared metal structure 1.2 m above the canopy crop at all times (Figure 2).

Figure 2. a) Field installation of b) infrared radiometers, as a reference in terms of controlling the manipulated temperature, in addition to recording the temperature of the canopy, c) a sensor that records the air temperature and relative humidity, and d) all sensors connected to a data logger (CR1000, Campbell Scientific, Logan, Utah, USA), programmed to record readings every 15 minutes. Maintenance and data management were carried out weekly.

Heathers were turned on from 18:00 to 6:00 hrs local time, 76 days after sowing. Canopy temperatures in the plots were detected using infrared thermometers (IRT; model IRR, Apogee

Instruments, Logan, Utah, USA). The heaters were controlled with a datalogger (CR1000, Campbell Scientific, Logan, Utah, USA), as devised by Kimball (2005). Canopy temperatures were recorded in fifteen-minute averages. The control system followed the same logic previously described in Garatuza-Payan et al. (2018). The meteorological data were obtained from data recorded by climatic implements that were installed on the plot. Measurements were made using sensors for temperature and relative humidity (Vaisala HMP45), radiation (LI200S Pyranometer, Campbell Scientific), wind speed and direction (05103-WS, Young Company, Michigan, USA), and soil humidity (CS-616 Campbell Scientific). For the calculations performed to obtain the water stress index, only the readings obtained from the infrared radiometers, relative humidity and temperature sensors were used.

Crop Water Stress Index

The Crop Water Stress Index (CWSI) was originally used as a nondestructive method of plant response to water stress during the daytime (Jackson et al., 1981; Idso et al., 1981), but we believe that it can also be an indicator of possible conditions for water loss from crop canopies at night. The CWSI is a metric related to plant water content in wheat crops (Jackson et al., 1981) derived from canopy-air temperature differences versus VPD for quantifying crop water stress (Idso et al.,1982). The CWSI can be calculated using the formula described by Nielsen (1990):

$$CWSI = \frac{[(Tc - Ta) - D_2]}{(D_1 - D_2)} \qquad (4)$$

where Tc = canopy temperature (°C); Ta = air temperature (°C); D_1 is the upper limit resulting from the maximum difference between Tc and Ta (Idso et al., 1981); and D_2 is the lower limit expressed in the form:

$$D_2 = a + b\,(VPD) \qquad (5)$$

A linear regression determines *a* and *b*, the intercept and slope, respectively. The result of this will be multiplied by VPD. Alderfasi & Nielsen (2001), in their study on scheduling irrigation in wheat with CWSI, concluded that the CWSI should provide a useful tool for the evaluation of crop water status, especially of winter wheat, and concluded that it could be useful for irrigation scheduling. Jackson (1982) suggested that irrigation should be applied when the CWSI for wheat is in the range 0.3-0.5.]

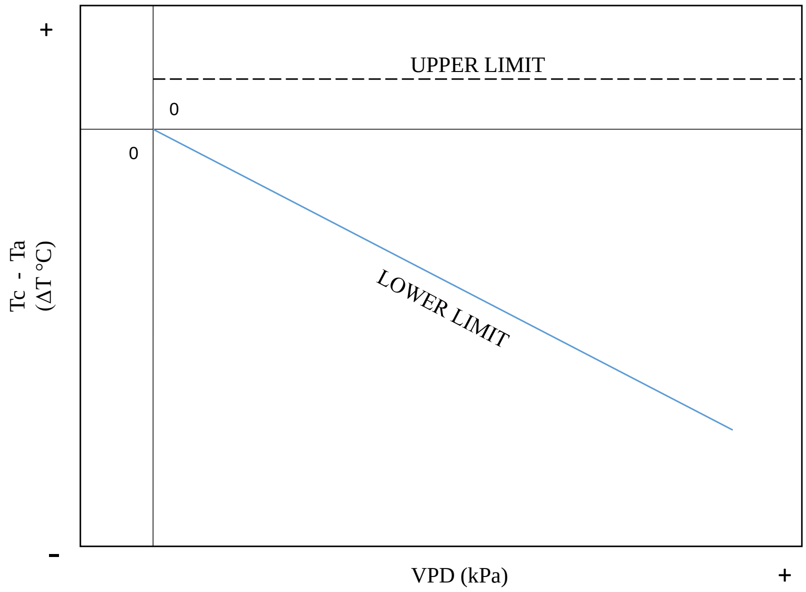

Figure 3. The general form of the relationship between the canopy-air temperature differential (ΔT = Tc – Ta) and air vapor pressure deficit (VPD) for a stand of vegetation sufficiently with water to transpire at the potential rate, i.e., the points above the lower limit line, present conditions for the loss of water from the crop, considering the general form of the relationship between ΔT and VPD (Idso et al.,1982).

To better understand the general form of the relationship between the canopy-air temperature differential and VPD, if a graph is generated with nonstressed daytime data obtained from ΔT and VPD for all phenological stages (blue line in Figure 3), we can then plot the nocturnal values to show when conditions for water loss occur in the crop. If the lower limit (D_2) is drawn from the value of a, (i.e., where it intersects with the axis of ΔT), which means that when canopy temperatures increase and consequently ΔT, VPD points will be located above the lower limit and below the upper limit, suggesting conditions for water loss from wheat canopies during the night period. It should be considered that the upper limit is calculated for each phenological stage, and this is the maximum value of ΔT (Figure 3).

Statistical analysis

All analyses and tests, including the linear regressions to determine the CWSI, were performed using the SPSS 23.0 statistical package (SPSS, Chicago, IL, USA). Data were tested against the Shapiro–Wilk test (Shapiro & Wilk, 1965).

RESULTS AND DISCUSSION

The heat control system to manipulate nighttime temperatures seems to be effective, since an effective mean temperature rise of 1.77 ± 0.09 was achieved in our manipulation across wheat phenological stages (Table 2).

Table 2. Mean nighttime canopy temperatures by phenological stage in wheat exposed to increased nighttime temperature in the Yaqui Valley.

Trait	HD	At	BGF	GF
Heat	15.10 ± 3.20	16.05 ± 2.87	12.83 ± 2.38	14.08 ± 1.51
Control	13.33 ± 3.41	14.40 ±3.31	10.97 ± 2.49	12.28 ± 1.56

Heading (HD), Anthesis (At), Beginning of grainfilling (BGF), Grainfilling (GF). Data are expressed as the mean across the indicated period ± one standard deviation.

Differences in the nighttime temperature manipulation were reflected in the vapor pressure deficit since marked differences were evident between control and temperature manipulated plots across the study period (Figure 4).

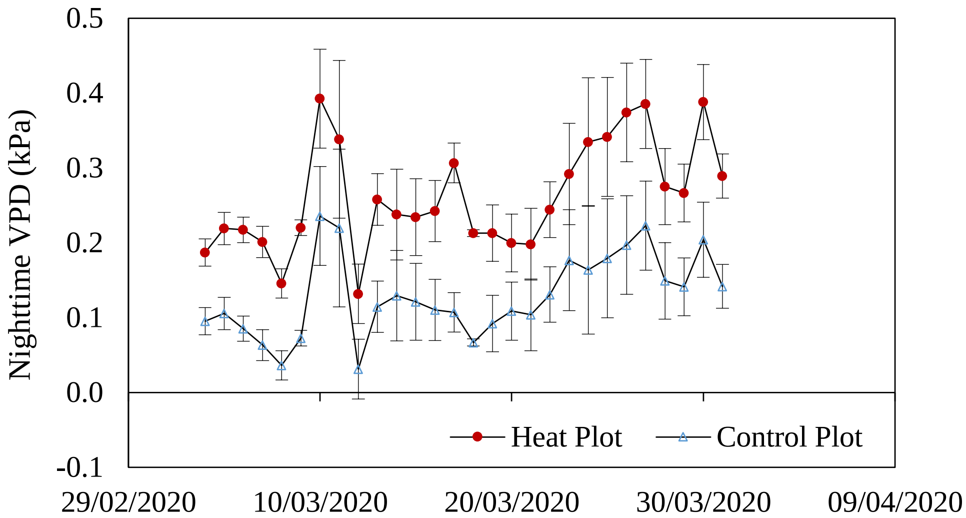

Figure 4. Mean nighttime vapor pressure deficit (VPD) recorded at heat and control experimental plots from February to April during the crop season 2019–2020 in the Yaqui Valley.

Crop water stress index (CWSI) estimation

The variables used to calculate the CWSI for the heat plots appear in Table 3. All calculations were made for each phenological stage during the cropping season. To obtain the upper limit (D_1), the maximum value obtained from Tc-Ta (ΔT) was taken in the seven-day period for each phenological stage; to obtain the lower limit (D2), a linear regression of ΔT with respect to VPD was performed to determine the coefficients a and b, which were used in the equation (5). Once D_1 and D_2 were obtained, the equation (4) was applied to determine the CWSI, which in this study only refers to periods of plentiful water availability to the crop.

Table 3. Crop water stress index (CWSI) estimation for nighttime heat/experimental conditions in wheat crop at the Yaqui Valley.

	T_c	T_a	VPD	Δt	D_1	D_2	CWSI
HD	15.10 ± 3.20	15.79 ± 2.84	0.23 ± 0.08	-0.68 ± 0.41	-0.14	-0.41 ± 0.07	-1.05 ± 1.71
At	16.05 ± 2.87	16.73 ± 2.55	0.25 ± 0.06	-0.69 ± 0.33	-0.20	-0.43 ± 0.06	-1.09 ± 1.51
BGF	12.83 ± 2.38	13.47 ± 2.23	0.24 ± 0.05	-0.64 ± 0.37	-0.21	-0.43 ± 0.05	-1.27 ± 2.06
GF	14.08 ± 1.51	14.58 ± 1.45	0.33 ± 0.05	-0.51 ± 0.12	-0.29	-0.51 ± 0.05	-0.12 ± 0.75

For 12 hours night period heat; Canopy temperature (T_c), air temperature (T_a), vapor pressure deficit (VPD), Regression parameters of ΔT (difference between T_c and T_a) respect VPD (Intercept a = -0.2096 °C, and Slope b= -0.8966 kPa), upper limit (D_1), lower limit (D_2), and Crop water stress index (CWSI). Data are expressed as the mean ± standard deviation. Heading (HD), Anthesis (At), Beginning of grainfilling (BGF), Grainfilling (GF).

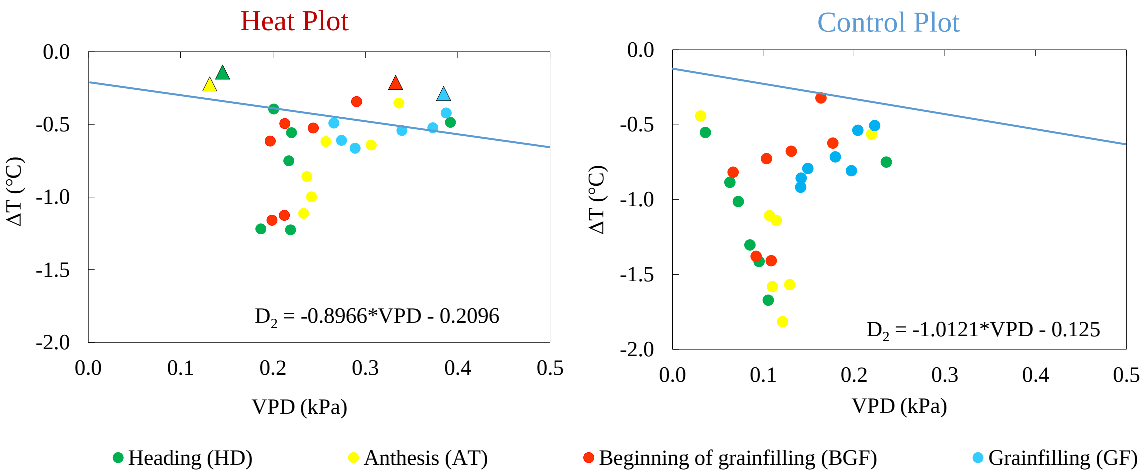

Figure 6. The regression line expresses the relationship of ΔT with respect to VPD during daytime conditions, using the key phenological stages of the crop (colored circles). Symbols are the nighttime data during the 7-day duration of different phenological stages (indicated by different colors). Points above the lower limit (D2) suggest conditions for water loss by the crop at night; this water loss occurs only at points below the upper limit (D1; shown as triangles for each phenological stage). The figure on the left shows the behavior in the heat plots, while the figure on the right side shows the control.

Similarly, in Table 4, the components of the CSWI for the control conditions are shown. In this study, CWSI was calculated to determine the upper and lower limits, given the importance that these have in determining the possible loss of water, it can be considered that these limits coincides with the behavior of ΔT respect to the VDP in its general form described by Idso et al., (1982).

Table 4. Crop water stress index (CWSI) estimation for nighttime control/ambient conditions in wheat crop.

	T_c	T_a	VPD	Δt	D_1	D_2	CWSI
HD	13.14 ± 3.45	14.23 ± 3.10	0.10 ± 0.06	-1.08 ± 0.40	-0.60	-1.02 ± 0.01	-0.14 ± 0.93
At	14.20 ± 3.38	15.38 ± 2.87	0.12 ± 0.06	-1.17 ± 0.52	-0.40	-1.03 ± 0.01	-0.23 ± 0.84
BGF	10.79 ± 2.48	11.64 ± 2.37	0.12 ± 0.04	-0.85 ± 0.40	-0.30	-1.03 ± 0.00	0.24 ± 0.55
GF	12.14 ± 1.59	12.88 ± 1.49	0.18 ± 0.03	-0.73 ± 0.16	-0.50	-1.03 ± 0.00	0.56 ± 0.30

For 12 hours night period Control; Canopy temperature (T_c), air temperature (T_a), vapor pressure deficit (VPD), Regression parameters of Δt respect VPD (Intercept a = -0.125 °C, and Slope b= -1.0121 kPa), upper limit (D_1), lower limit (D_2), and Crop Water Stress Index (CWSI). Data are expressed as the mean ± standard deviation. Heading (HD), Anthesis (At), Beginning of grainfilling (BGF), Grainfilling (GF).

In Figure 6, we represent the upper limit with a triangle with the color of its corresponding stage. Based on this figure, it is possible to determine the percentage of time in each phenological stage in which conditions for water loss at night occur in heat plots with respect to its control. Noticeable no apparent conditions for water loss at night seemed to occur in the control plots (Table 5).

Table 5. Percentage of time in each phenological stage were conditions for water lost occur at nighttime.

Phenological stages	Heat Plot	Control Plot
HD	14.28	0
At	14.28	0
BFG	14.28	0
GF	28.57	0

Percentages obtained from the points with possible conditions for water loss in Figure 6. Heading (HD), Anthesis (At), Beginning of grainfilling (BGF), Grainfilling (GF).

A higher VPD in heat plots, compared to the control plots, shows that atmospheric water demand changes when the temperature of the wheat canopy increases 2 °C (Figure 4).

The increase in temperatures under climate change scenarios suggests a warming effect that can bring yield declines in wheat crops; these effects can, in particular, be attributed to increases in nighttime temperatures. This is important because historical data have shown that cereal grain yields are strongly correlated with minimum temperatures, which are often reached at night. This susceptibility, suggest that heating conditions in an experimental treatment, can provide insights into the mechanisms and responses that influence the loss of water during the night by wheat crops in the Yaqui Valley.

One of the most important results observed in this study comes from the use of the water stress index for plants (CWSI) in our experimental treatment. That is, under normal control conditions, it seems that current conditions for water lost at night do not exist. However, because our nighttime ΔT observations in the heat plots plotted below the lower limit defined during the daytime VPD vs. ΔT relationship, our analysis suggests that conditions for water lost at night are plausible by the crop under climate change scenarios; for instance, 28.57% of the time of the phenological stage of grain filling showed conditions for water lost at night, and 14.28% of the time crossed the previous stages of heading, anthesis and the beginning of grain filling.

In previous studies, the CWSI has been used as an indicator of water requirements by crops, and these studies have been carried out in daytime periods (Alderfasi & Nielsen, 2001; López-López et al., 2009; Alghory & Yazar, 2019). To our knowledge, this is the first work where the CWSI is used to explore nighttime conditions that can point to potential water losses in wheat crops. Advancing on the construction of the general form of a relationship of VPD with ΔT would allow exploring the capacity and sensitivity of the wheat crop to environmental drivers that result in a potential loss of water by the crop during the night, which would give insights about the potential responses of wheat to conditions of climatic change in the Yaqui Valley. Furthermore, this study highlights the importance of VPD behavior as one of the environmental drivers for the observation of water loss at night.

The phenomenon of water loss from the canopy at night may play a role in modulating drought tolerance in the crop, as reported by Tamang et al., (2019), in what they consider a phenomenon called circadian resonance where the canopy could prepare for a gas exchange at the beginning of the next day and improve water use efficiency (Schoppach et al., 2014). On the other hand, water loss could have possible physiological advantages, such as the continuation of the supply of O_2 to the xylem or the maintenance of carbohydrate exports for the needs of dark respiration (Snyder et al., 2003; Marks & Lechowicz, 2007). However, Sadok and Jagadish, 2020 suggest that there is sparse knowledge about the overall consequences of water losses at night and their environmental control since plant water relations are commonly studied during the day, even if nocturnal conditions for water use and demand could alter physiological properties.

CONCLUSION

With this research work, it can be concluded that the nighttime environmental conditions at the Yaqui Valley do not generally allow water losses by wheat canopies, but experimental nighttime warming conditions (± 2 °C) set conditions for water losses to occur at night in wheat canopies. Relaying a crop water stress index and determining the relationship of water potential with canopy and air temperature differentials during nighttime under experimental warming conditions shed light on the potential effects of global warming.

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