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Soil, water, and air temperatures in furrow-irrigated rice

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ABSTRACT

The objectives of this study were to characterize how the soil water regimes and the ridge and furrow environments affect soil, water, and air temperatures during rice plant cycle and to compare these temperatures to those of a conventional water regime (flooded), and to the air temperature of a nearby grassy area. In the growing season 2021/2022, water and air temperatures were measured in three soil water regimes (water regime 1 - WR1: drained soil; water regime 2 - WR2: saturated soil; water regime 3 - WR3: waterlogged soil). In the growing season 2022/2023, water regime 4 - RH4 (flooded soil) was included. In each of these soil water regimes and in the ridge and furrow environments, the soil temperature at a depth of 5 cm and the air/water temperature at 5 cm above ground level were measured with Hobo® sensors and dataloggers. Hourly data were transformed into daily data and by subperiods of the cultivar BRS Pampa CL, considering four temperature variables: average, maximum, minimum and amplitude. The results allow us to conclude that soil, water, and air temperatures are influenced by soil water regimes, environments (ridge and furrow), and development subperiods of furrow-irrigated rice. Furthermore, the temperature amplitudes are smaller in the conventional irrigation system (flooded), and decrease from the beginning to the end of the cycle in all four soil water regimes studied.

Introduction

The State of Rio Grande do Sul (RS) is the largest producer of rice in Brazil, having contributed in the last three growing seasons (from 2020/21 to 2022/23) with about 70% of the national production, occupying an average area of 923 thousand hectares year^{-1}, with an average grain yield of 8.2 t ha^{-1} (IBGE, 2024). It is estimated that in the state there are about three million hectares of lowland soils (TB), which have drainage and irrigation infrastructure implemented for irrigated rice cultivation, and that around two million hectares of these soils have potential for soybean cultivation (Vedelago, 2014) or other dryland species in rotation or succession to rice.

The utilization of the furrow-ridge technology, which has shown good results for soybean and corn production in lowland soils in the RS (Parfitt et al., 2017; Campos et al., 2021), may also become an interesting option for furrow-irrigated rice cultivation, where the cereal can be part of a rotation scheme with soybean and corn (Concenço et al., 2020). The advantage for such scheme is that rice cultivation can follow soybean and/or corn cultivated in the furrow-ridge system, without the need for soil preparation. In this system, rice is dry-seeded over the same ridges as soybean or maize were cultivated in the previous summer season, and water for irrigation is provided by the furrow network.

However, for this method of cultivation to succeed, some challenges need to be overcome, the main one being avoiding losses in grain yield and quality resulting from rice cultivation in aerobic conditions (Stevens et al., 2020), as modern irrigated rice cultivars are developed for the flooded system. In addition to tolerance to water stress, the reaction to diseases, especially blast (*Magnaporthe oryzae* (formerly *Pyricularia oryzae*)), due to the absence of a surface layer of floodwater, is another critical aspect in the selection of cultivars for the furrow-irrigated system (Brooks et al., 2010).

The absence or low levels of a surface layer of floodwater can also interfere with the risk of cold injury, especially during the booting stage. It is for this reason that when cultivating conventional irrigated rice (flooded) in regions where there is a risk of cold weather (temperatures below 16 °C), it is recommended to raise the water level to approximately 15 to 20 cm during 15 to 20 days, aiming to increase the thermoregulatory effect of water, reducing the sterility of spikelets (Reunião..., 2022). Results obtained by Steinmetz et al. (2011) indicated that during the vegetative phase of the cultivar BRS Querência, the thermoregulatory effect of water, represented by the lowest temperature amplitude (Ta), was more significant at the 10 cm depth (Ta=5.4 °C) than at the 5 cm depth (Ta=10.9 °C).

According to the results of Della Lunga et al. (2020), soil temperature can also be affected in furrow-irrigated rice, with daily fluctuations being more pronounced in the upper part (Up-slope) of the field than in the middle (Mid-slope) and lower (Down-slope) ones. These authors also found that daily fluctuations of soil temperature were more pronounced in the initial than in the final phase of the cycle of the two cultivars used and that in the final phase of the cycle, soil temperature remained below the atmospheric air temperature.

The objectives of this study were: a) to characterize how the soil water regime, in three parts of the plot (upper - WR1: drained soil, intermediate – WR2: saturated soil and lower – WR3: waterlogged soil), and the ridge and furrow environments affect soil, water, and air temperatures during distinct subperiods of plant development of furrow-irrigated rice; b) to evaluate the relationship between the temperatures of the three soil water regimes and the two environments, and the temperatures of a conventional water regime (flooded soil), and the air temperature of a nearby grassy area.

Material and methods

The study was carried out in the area of the Lowlands Experimental Station (ETB) of Embrapa Temperate Agriculture, in the municipality of Capão do Leão, RS, Brazil (latitude of 31°49.029’ S; longitude of 52°28.014’ W and altitude of 13 m), during two growing seasons (2021/2022 and 2022/2023). The data were collected in a plot of approximately 300 m long of an experiment designed to generate multidisciplinary informations on the cultivation of furrow-irrigated rice, using one of the three available irrigation treatments, that is, irrigated every three days. According to the Köppen´s climate classification, the local climate is Cfa type, characterized as humid subtropical with hot summers and no defined dry season (Wrege et al., 2011). The soil in the experimental area is classified as a Planossolo (typic Albaqualf) (Santos et al., 2006).

In autumn 2021, a planialtimetric survey of the area and soil smoothing were carried out (systematization with varying slopes), establishing an average slope of 0.2% in the longitudinal direction of the plot. On this occasion, the soil in the experimental area was prepared using a conventional cultivation system, comprising plowing, harrowing, scarification (to a depth of 30 cm), and leveling of the surface. Concomitantly with soil preparation, correction fertilization was applied at a rate of 300 kg ha^{-1} of the 10-30-15 formulation, based on the results of the chemical analysis of the soil and considering the nutritional demand of the planned winter and summer crop succession for the first year of cultivation (Sociedade..., 2016). Next, infrastructure for ridges measuring 90 cm wide (center to center) and approximately 20 cm high was implemented using the SulcoSystem® ridge from KLR Implementos. Also during autumn, Persian clover (*Trifolium resupinatum* L.) was sown as winter cover in the area, at a seeding rate of 5 kg ha^{-1}. This forage was cultivated until early October, when it was desiccated.

Rice sowing in the 2021/2022 growing season (growing season 1 – GS1) was carried out on 10/28/2021, on Persian clover stubble, at a seeding rate of 100 kg ha^{-1}. Prior to sowing, basal fertilizer was applied to the surface at a rate of 20 kg ha^{-1} of N and 80 kg ha^{-1} of P_2O_5 and K_2O. In the 2022/2023 growing season (growing season 2 – GS2), rice was sown in an adjacent area where soybeans were grown in a furrow-ridge system during the previous growing season, followed by ryegrass during the autumn-winter period. Due to damage to the furrow-ridge infrastructure caused by soybean management and harvesting operations, it was necessary to carry out surface soil preparation with a harrow and planer, taking advantage of the opportunity to incorporate the existing vegetation cover and apply basal fertilizer for rice sowing (14 kg ha^{-1} of N and 64 kg ha^{-1} of P_2O_5 and K_2O). New ridges were then prepared, followed immediately by rice sowing. Given the dry and loose soil conditions, this operation resulted in a reduction in the average height of the ridges.

In both growing seasons, top-dressing nitrogen fertilization was divided into two applications: at the three to four leaf stages (V3/V4 – 70 kg ha^{-1} of N) and panicle initiation (R0 – 40 kg ha^{-1} of N), both applied as urea. Weed control included the application of herbicides in pre-and post-emergence of rice. This and other cultural practices followed the technical recommendations for rice cultivation in southern Brazil (Reunião..., 2018).

The irrigated rice cultivar BRS Pampa CL, considered as early-cycle, was used in both growing seasons. In GS1, irrigation was carried out every three days, applying an average depth of 23 mm, for 108 days. In GS2, irrigation was also carried out every three days with an average depth of 23 mm, but for a period of 109 days.

In GS1, the temperature data were obtained from three locations, within a plot approximately 300 m long: the upper third (upper portion or soil water regime 1 – WR1: drained soil), the center (central portion or soil water regime 2 – WR2: saturated soil) and the final part (lower portion or soil water regime 3 – WR3: waterlogged soil, without water depth control). In GS2, in addition to these three locations, water regime 4 - WR4 (flooded soil, with water depth control) was included. WR4 consisted of maintaining a water depth between 5 and 10 cm throughout the entire irrigation period, as recommended by research for this irrigation system (Reunião..., 2018). WR4 was included to serve as a reference for WR1, WR2 and WR3, and also because it is the traditional irrigation system used in the rice crop in southern Brazil.

In each of the three soil water regimes (WR1, WR2, and WR3) measurements of four temperature parameters were taken: two within the ridge (soil temperature at 5 cm depth and air/water temperature at 5 cm above ground level) and two within the furrow (soil temperature at 5 cm depth and air/water temperature at 5 cm above ground level). The term “air/water temperature” is used because, depending on the position in the field (water depth) and on the environment (ridge or furrow) it may be measuring either air or water temperature.

In WR4, the average of two replications of soil temperature at 5 cm depth and water temperature at 5 cm above ground level was used. The sensors that measured the air/water temperature were protected by shelters as described by Steinmetz et al. (2005). Previously calibrated Hobo® temperature sensors and four-channel dataloggers (Onset/Hobo Data Loggers, model UX120-006M) were used. Data were collected every minute, transformed into hourly and, subsequently, into daily and into subperiods of plant development. The variables considered were: mean (Tm), maximum (Tx), minimum (Tn) temperatures and thermal amplitude (Ta) or thermal range, which is the difference between Tx and Tn.

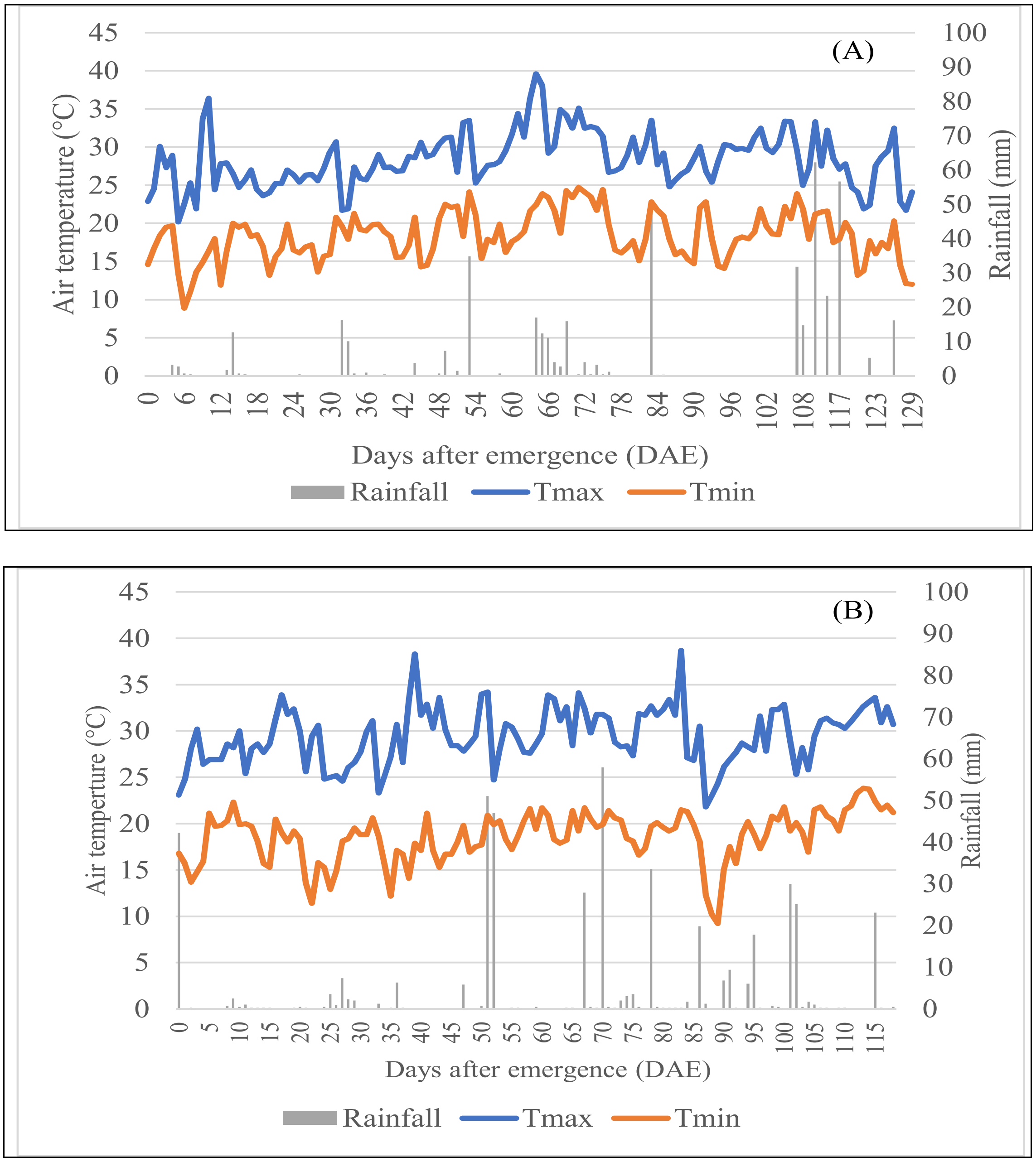
Statistical analysis was performed using SAS software v.9.04 (SAS Institute, 2022). Data normality was verified using proc. Univariate, the means and respective standard errors were calculated using proc. Means, and comparative tests of means were performed using proc. GLM. In all cases, the 95% significance criterion ($F<0.05$) was used to define the difference between treatments. Data from each growing season were analyzed separately.

Soil water tension (SWT) was measured using Watermark® sensors and a data acquisition system. Two sensors were installed in the furrow at a depth of 10 cm, and a set of five sensors were installed in the ridge in order to obtain the average SWT. Data were collected throughout the rice cycle, with measurements taken every 2-3 days. In GS1, phenology data were obtained from ten marked plants in the ridge and ten marked plants in the furrow at each of the three locations. In GS2, twenty plants were marked in the ridge and twenty plants in the furrow. Each of the marked plants was monitored throughout the cycle, with each stage characterized according to the scale of Counce et al. (2000). Two readings were taken per week, and the average dates for each stage were obtained from observations on ten or twenty plants (main stem). The R1 stage (panicle differentiation) was determined using the method described by Stansel (1975), which consists of collecting and opening six main stems longitudinally and considering the date of R1 when at least two plants (one third of the sampled plants) had the panicle in the differentiation stage, that is, with approximately 1 mm to 2 mm in length.

Based on the phenological data, four subperiods of plant development were considered in this study: E-R1 (from emergence to the panicle differentiation – vegetative); R1-R4 (from panicle differentiation to anthesis - reproductive 1); R4-R9 (from anthesis to the complete maturity of panicle´ grains – reproductive 2); E-R9 (from emergence to the complete maturity of panicle´ grains – cycle). These subperiods are important because they served as a reference for several rice crop management practices (Reunião..., 2022; Steinmetz et al., 2021a, b).

Meteorological data during the two GS were obtained using an automatic weather station (AWS), model “Davis Advantage Pro2”, installed approximately 100 m from the experimental field. In GS1, due to a sensor malfunction, air temperature data were replaced with those obtained from the Agroclimatological Station (EAPel) located in the headquarter area of the Lowlands Experimental Station

Figure 1. Maximum (Tmax) and minimum (Tmin) daily air temperature (°C) and daily rainfall (mm), in days after emergence (DAE), in the 2021/2022 (A) and 2022/2023 (B) growing seasons, recorded during the field experiments, in Capão do Leão, RS, Brazil.



(Embrapa/ETB, Capão do Leão, RS), around six km from the experiment. The main meteorological data recorded during the experiments are shown in Figure 1. The average maximum air temperatures were 28.4 °C and 29.5 °C and the average minimum air temperatures were 18.3 °C and 18.6 °C, respectively, for GS1 and GS2. Total rainfall during the crop cycle was 434.9 mm and 459.7 mm for GS1 and GS2, respectively.

Results and discussion

Influence of the soil water regimes on soil, water, and air temperatures

Daily evolution of maximum soil temperature on the ridges indicated higher values at the beginning of the cycle in WR1, WR2 and WR3, reaching 43.2 °C in DAE 19 of WR3, with a decreasing trend over time (Figure 2A, B, C). This response is likely associated with lower soil coverage by the crop canopy, allowing greater penetration of solar radiation and, consequently, greater soil heating. Similar results were reported by Della Lunga et al. (2020), but the highest temperature was 38°C. It is likely that their lower value, among other possible reasons, is because the sensor was placed at a depth of 7.5 cm, whereas in our study, the depth was 5.0 cm.

Maximum soil temperature in WR4 (flooded soil) showed lower values than those recorded in WR1, WR2, and WR3, with the differences being more pronounced at the end of the study (Figure 2A, B, C). This response is likely due to the thermoregulatory effect of the water layer in WR4, decreasing the penetration of solar radiation to heat the soil. This hypothesis is supported by data from Steinmetz et al. (2011), since the average maximum soil temperature during the vegetative phase of the cultivar BRS Querência was higher with a water layer of 5 cm (32.0 °C) than with a water layer of 10 cm (30.2 °C).

In GS2, the maximum air temperature, measured at the automatic weather station (Tx air AWS), indicated lower values than the maximum soil temperature in all soil water regimes up to around 40 days after emergence (DAE 40), close to them up to DAE 70, and higher after DAE 70. After DAE 40, the differences were more pronounced for WR4 than for WR1, WR2, and WR3 (Figure 2A, B, C).

The minimum soil temperature (Tn soil) in the ridge of WR1, WR2, and WR3 presented lower values than the Tn soil in WR4, with the differences being more pronounced in the initial phase of the experiment (Figure 3). The lowest Tn soil value found during GS2, i.e., 15.1 °C (DAE 14 in WR1) is lower than the 19.0 °C found by Della Lunga et al. (2020) during two growing seasons.

On average, over the entire measurement period, the differences in Tn soil in WR1, WR2, and WR3 compared to WR4 were -1.1 °C, -1.1 °C, and -1.4 °C, respectively. Differences of around 1.0 °C also occurred in the study of Steinmetz et al. (2011), since the average minimum soil temperature during the vegetative phase of the cultivar

Figure 2. Daily maximum soil temperature in the ridge of the soil water regime 1 (WR1=drained soil: upper portion) (A), water regime 2 (WR2=saturated soil: central portion) (B), and water regime 3 (WR3=waterlogged soil, without depth control: lower portion) (C) compared to water regime 4 (WR4=flooded soil, with depth control: conventional system) and to air temperature measured in an automatic weather station (AWS) in the growing season 2022/2023, in Capão do Leão, RS, Brazil.

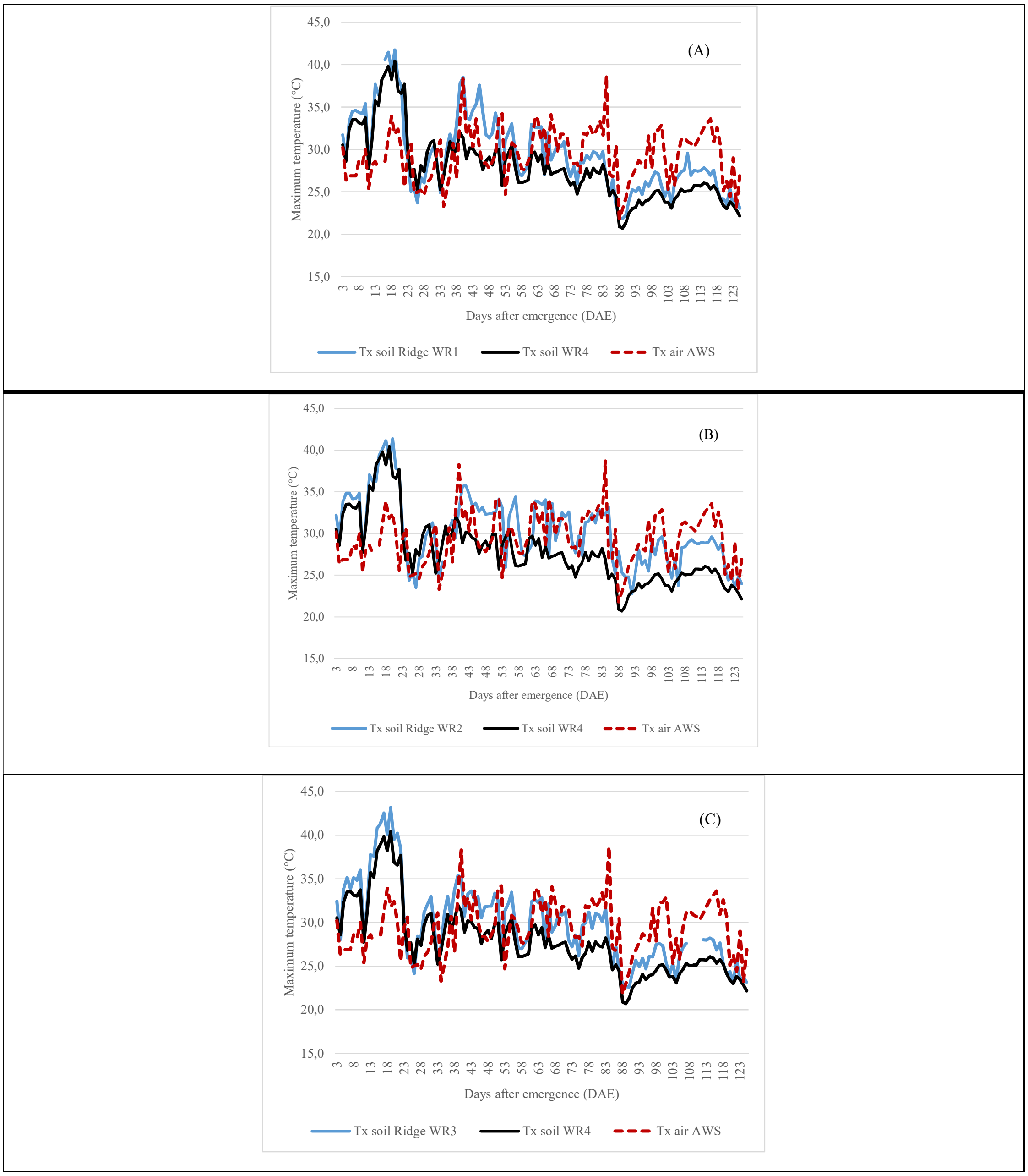
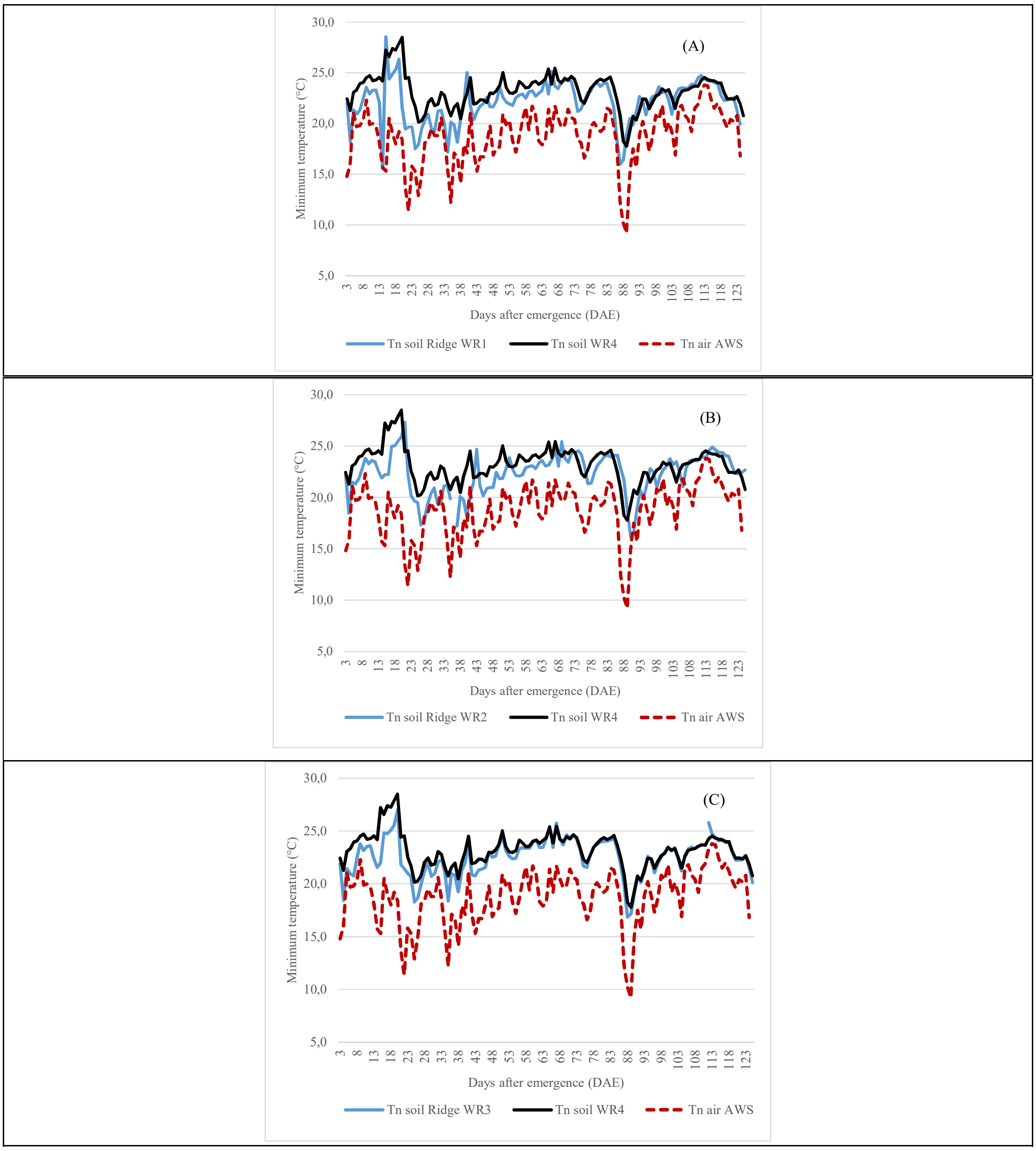


Figure 3. Daily minimum soil temperature in the ridge of the soil water regime 1 (WR1=drained soil: upper portion) (A), water regime 2 (WR2=saturated soil: central portion) (B), and water regime 3 (WR3=waterlogged soil, without depth control: lower portion) (C) compared to water regime 4 (WR4=flooded soil, with depth control: conventional system) and to air temperature measured in an automatic weather station (AWS) in the growing season 2022/2023, in Capão do Leão, RS, Brazil.



BRS Querência was 22.9 °C with a 10 cm water layer and 21.9 °C with a 5 cm water layer. This response is probably associated with the thermoregulatory effect of water, allowing greater loss of radiation to the atmosphere during the night in areas with lower soil humidity or lower surface water layer over the soil.

The minimum air temperature measured at the weather station (Tn air AWS) was lower than Tn soil in the four water regimes throughout the measurement period (Figure 3A, B, C), with the lowest values recorded at DAE 89 (9.2 °C), DAE 22 (11.4 °C), and DAE 35 (12.2 °C), respectively. This response may also be associated with the greater cooling of the air during the night period of the grassy surface where the AWS was installed in relation to Tn soil in the four water regimes.

The soil water regimes and the subperiods of plant development influenced the soil temperature in any of the four variables used, that is, the average temperatures (Tm), maximum (Tx), minimum (Tn), or the difference between the maximum and minimum temperatures (Ta). Taking the Tx soil in the vegetative subperiod (E-R1) as an example, it can be seen that in the ridge the extreme values varied from 29.7 °C (WR1) to 28.4 °C (WR2), but there was no significant difference between them. On the other hand, in the furrow, the extreme values ranged from 28.9 °C (WR2) to 26.9 °C (WR3), with a significant difference between them. Likewise, there was a significant difference between the Tx in the ridge (29.7 °C) and in the furrow (28.5 °C) in WR1 and also between the Tx in the ridge (28.9 °C) and in the furrow (26.9 °C) in WR3. The average values of the ridge (29.0 °C) and furrow (28.1 °C) environments also showed a significant difference between them (Table 1).

In the E-R1 subperiod, the extreme Tn values recorded in the ridge ranged from 21.1 °C (WR1) to 19.9 °C (WR3), with a significant difference between them. On the other hand, in the furrow, the Tn extreme values ranged from 21.9 °C (WR2) to 21.4 °C (WR3), with no significant difference between them (Table 1). The comparison between the environments indicated no significant difference between the Tn of WR2 (20.3 °C) and WR3 (19.9 °C) in the ridge and the Tn of WR2 (21.9 °C) and WR3 (21.4 °C) in the furrow. However, the average Tn values in the ridge (20.5 °C) and in the furrow (21.7 °C) showed a significant difference between them (Table 1). The results obtained by Della Lunga et al. (2020), with furrow-irrigated rice, also showed that maximum and minimum soil temperatures were influenced by both the soil water regime and the crop development phase. In corn, Song et al. (2013) also found that soil temperature varied according to the plant development subperiods and with the ridge and conventional planting systems.

In GS2 (Table 2), the average Tx value in the E-R1 subperiod in the furrow (29.9 °C) is closer to that recorded in WR4 (flooded) (30.9 °C) than that obtained in the ridge (32.4 °C). This behavior is similar for Tn, as the average value in the furrow (22.7 °C) is closer to that recorded in WR4 (23.3 °C) than the average value in the ridge (21.8 °C). This behavior is likely due to the thermoregulatory effect of water, especially in WR4, causing Tx not to be as high and Tn as low when compared to water regimes without water depth control, as suggested by the results obtained by Della Lunga et al. (2020) and Steinmetz et al. (2011).

Soil water regimes and plant development subperiods also influenced the soil temperature amplitude (Ta), considering that in GS1 the extreme values ranged from 9.0 °C (WR3-ridge) to 5.5 °C (WR3-furrow) for the E-R1 subperiod, from 4.9 °C (WR2-ridge) to 1.8 °C (WR3-furrow) for the R1-R4 subperiod, and from 4.8 °C (WR1-ridge) to 1.1 °C (WR3-furrow) for the R4-R9 subperiod (Table 1 and Fig. 4A). A similar pattern occurred in GS2, with the lowest values occurring in WR3-furrow and in WR4, as indicated by the results in Table 2 and Figure 4B. For WR4, the results

Table 1. Soil temperature during three subperiods and during the cycle of rice cultivar BRS Pampa CL as a function of the soil water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, without depth control: lower portion) and the environment (Ridge and Furrow), and air temperature (Tair) measured in an automatic weather station (AWS) in the 2021/2022 growing season, in Capão do Leão, RS, Brazil.

Sub-Period	Soil Temperature	Environment										Air temperature (AWS)
		Ridge				Furrow				Average values		
		Water regime										
		WR1	WR2	WR3	CV	WR1	WR2	WR3	CV	Ridge	Furrow	
		(°C)			(%)	(°C)			(%)	(°C)		(°C)
E-R1	Average	24.9 (0.31) a	# 23.8 (0.30) b	23.6 (0.30) b	9.6	24.6 (0.25) a	24.8 (0.25) a	23.8 (0.42) b	7.6	24.1 (0.18)	24.4 (0.14)	20.1
E-R1	Maximum	# 29.7 (0.50) a	28.4 (0.50) a	# 28.9 (0.55) a	13.6	28.5 (0.36) a	28.9 (0.39) a	26.9 (0.48) b	10.1	29.0 (0.30)	28.1 (0.22) *	25.3
E-R1	Minimum	21.1 (0.28) a	# 20.3 (0.27) ab	# 19.9 (0.31) b	10.8	21.7 (0.25) a	21.9 (0.25) a	21.4 (0.46) a	8.8	20.5 (0.17)	21.7 (0.14) *	15.2
E-R1	Amplitude	# 8.7 (0.47) a	8.1 (0.48) a	# 9.0 (0.60) a	21.9	6.7 (0.30) ab	7.0 (0.36) a	5.5 (0.30) b	20.0	8.6 (0.30)	6.5 (0.21) *	10.1
R1-R4	Average	25.1 (0.42) a	# 24.8 (0.38) a	25.0 (0.37) a	8.5	25.9 (0.39) a	26.3 (0.34) a	24.4 (0.31) b	7.4	25.0 (0.22)	25.5 (0.22)	22.8
R1-R4	Maximum	27.7 (0.48) a	27.7 (0.47) a	# 27.2 (0.45) a	9.2	28.5 (0.48) a	29.0 (0.44) a	25.4 (0.30) b	8.2	27.6 (0.27)	27.6 (0.29)	27.7
R1-R4	Minimum	23.2 (0.46) a	# 22.7 (0.43) a	23.3 (0.41) a	10.2	24.0 (0.41) a	24.4 (0.37) a	23.6 (0.33) a	8.5	23.0 (0.25)	24.0 (0.22) *	18.2
R1-R4	Amplitude	4.5 (0.30)	4.9 (0.35)	# 4.0 (0.32)	19.1	4.5 (0.32) a	4.5 (0.37) a	1.8 (0.14) b	19.7	4.5 (0.19)	3.6 (0.21) *	9.5
R4-R9	Average	23.9 (0.19) a	# 22.7 (0.18) b	22.6 (0.19) b	4.1	24.3 (0.16) a	24.0 (0.15) a	22.4 (0.15) b	3.3	23.0 (0.13)	23.5 (0.13) *	25.1
R4-R9	Maximum	26.6 (0.26) a	# 25.2 (0.19) b	# 24.0 (0.18) c	4.1	26.7 (0.24) a	26.0 (0.17) b	23.0 (0.13) c	3.6	25.2 (0.17)	25.1 (0.21)	30.5
R4-R9	Minimum	21.8 (0.29) a	# 20.8 (0.27) b	21.3 (0.24) ab	6.3	22.5 (0.25) a	22.5 (0.26) a	21.9 (0.18) a	5.0	21.3 (0.16)	22.3 (0.13) *	20.5
R4-R9	Amplitude	4.8 (0.39) a	# 4.4 (0.29) a	# 2.7 (0.19) b	18.5	4.2 (0.38) a	3.5 (0.28) a	1.1 (0.11) b	20.0	3.9 (0.20)	2.8 (0.21) *	10.0
E-R9	Average	24.7 (0.21) a	# 23.8 (0.20) b	23.7 (0.20) b	8.9	24.9 (0.18) a	25.0 (0.17) a	23.6 (0.15) b	7.4	24.1 (0.12)	24.5 (0.10) *	22.0
E-R9	Maximum	28.6 (0.33) a	27.5 (0.31) b	# 27.3 (0.36) b	12.6	28.1 (0.24) a	28.2 (0.26) a	25.6 (0.24) b	9.7	27.8 (0.19)	27.3 (0.16)	27.2
E-R9	Minimum	# 21.8 (0.22) a	# 21.0 (0.21) a	# 21.1 (0.24) a	11.0	22.5 (0.20) a	22.7 (0.19) a	22.1 (0.18) a	9.1	21.3 (0.13)	22.4 (0.11) *	17.3
E-R9	Amplitude	# 6.8 (0.33) a	# 6.4 (0.31) a	# 6.2 (0.42) a	26.9	5.6 (0.23) a	5.5 (0.26) a	3.5 (0.28) b	26.1	6.5 (0.20)	4.9 (0.16) *	9.9

Obs.: 1) E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive 2); E-R9 = period comprising the entire crop cycle (Cycle). 2) Values in parentheses indicate the standard error of the mean. 3) For the same line and environments (ridge and furrow), means followed by the same letter do not differ significantly (comparison between water regimes by environments; Tukey test. p>0.05). 4) The “#” indicates a significant difference between environments within the same water regime, and the “*” indicates that the mean values differ significantly between environments (F test. p<0.05).

Table 2. Soil temperature during three subperiods and during the cycle of rice cultivar BRS Pampa CL as a function of the soil water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, without depth control: lower portion; WR4=flooded soil, with depth control) and the environment (Ridge and Furrow), and air temperature (Tair) measured in an automatic weather station (AWS) in the 2022/2023 growing season, in Capão do Leão, RS, Brazil.

Sub-period	Soil temperature	Environment									Average values		Air temperature (AWS)
		Ridge				Furrow							
		Water regime											
		WR1	WR2	WR3	CV	WR1	WR2	WR3	CV	WR4	Ridge	Furrow	
		(°C)			(%)	(°C)			(%)	(°C)	(°C)		(°C)
E-R1	Average	25.9 (0.36)	25.8 (0.34)	26.3 (0.33)	10.1	25.8 (0.30)	25.9 (0.27)	25.8 (0.27)	8.3	26.1	26.0 0.20)	25.8 (0.16)	23.2
E-R1	Maximum	# 32.1 (0.58)	# 32.1 (0.56)	# 32.8 (0.60)	13.5	30.2 (0.43)	30.0 (0.42)	29.4 (0.41)	10.6	30.9	32.4 (0.33)	29.9 (0.24) *	28.9
E-R1	Minimum	21.6 (0.30)	# 21.7 (0.28)	# 22.0 (0.24)	9.5	22.4 (0.32)	22.7 (0.23)	23.0 (0.22)	8.6	23.3	21.8 (0.16)	22.7 (0.15) *	17.9
E-R1	Amplitude	# 10.3 (0.54)	# 10.5 (0.46)	# 10.8 (0.53)	18.7	7.7 (0.42	7.2 (0.33)	6.4 (0.33)	18.8	7.6	10.5 (0.29)	7.1 (0.21) *	11.0
R1-R4	Average	24.8 (0.42)	25.5 (0.41)	# 25.9 (0.21)	7.8	25.3 (0.37)	25.4 (0.36)	25.4 (0.16)	6.7	24.7	25.4 (0.21)	25.4 (0.18)	24.1
R1-R4	Maximum	28.0 (0.57) b	# 30.1 (0.60) a	# 29.4(0.42) ab	10.1	27.8 (0.48)	27.8 (0.47)	26.9 (0.23)	8.1	26.5	29.2 (0.32)	27.5 (0.24) *	30.2
R1-R4	Minimum	22.5 (0.42)	22.7 (0.41)	23.6 (0.22)	8.7	23.3 (0.36)	23.6 (0.35)	24.1 (0.16)	7.0	23.3	22.9 (0.21)	23.7 (0.18) *	18.6
R1-R4	Amplitude	# 5.6 (0.38) b	# 7.3 (0.47) a	# 5.7 (0.40) b	18.3	4.5 (0.29) a	4.2 (0.30) a	2.8 (0.18) b	17.0	3.2	6.2 (0.25)	3.8 (0.17) *	11.6
R4-R9	Average	24.4 (0.21) ab	24.8 (0.23) a	23.5 (0.39) b	5.7	24.5 (0.19) a	24.4 (0.22) a	23.1 (0.32) b	5.0	23.6	24.2 (0.17)	24.0 (0.16)	24.5
R4-R9	Maximum	26.5 (0.26) b	# 27.8 (0.32) a	# 25.6 (0.37) b	5.9	26.1 (0.25) a	25.7 (0.23) a	23.9 (0.30) b	5.1	24.5	26.7 (0.21)	25.3 (0.18) *	30.1
R4-R9	Minimum	22.9 (0.25)	23.0 (0.26)	21.9 (0.46)	7.1	23.3 (0.21) a	23.4 (0.23) a	22.4 (0.36) b	5.8	22.9	22.6 (0.19)	23.1 (0.16)	20.3
R4-R9	Amplitude	# 3.4 (0.17) b	# 4.8 (0.30) a	# 3.7 (0.28) b	14.8	2.6 (0.15) a	2.3 (0.13) a	1.6 (0.12) b	13.5	1.6	4.0 (0.16)	2.2 (0.09) *	9.8
E-R9	Average	25.3 (0.23)	25.5 (0.22)	25.6 (0.22)	10.1	25.4 (0.19)	25.4 (0.18)	25.1 (0.19)	8.3	25.2	25.5 (0.11)	25.3 (0.11)	23.7
E-R9	Maximum	29.8 (0.41)	30.6 (0.37)	30.4 (0.44)	13.5	28.6 (0.30)	28.4 (030)	27.6 (0.31)	10.6	28.2	30.2 (0.18)	28.2 (0.18) *	29.5
E-R9	Minimum	22.1 (0.20)	22.3 (0.19)	22.4 (0.18)	9.5	22.9 (0.20)	23.1 (0.16)	23.2 (0.15)	8.6	23.2	22.3 (0.11)	23.0 (0.10) *	18.6
E-R9	Amplitude	7.5 (0.40)	8.3 (0.35)	7.9 (0.42)	18.7	5.7 (0.30)	5.3 (0.27)	4.4 (0.27)	18.8	5.0	7.9 (0.23)	5.1 (0.17) *	10.9

Obs.: 1) E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive 2); E-R9 = period comprising the entire crop cycle (Cycle). 2) Values in parentheses indicate the standard error of the mean. 3) For the same line and environments (ridge and furrow), means followed by the same letter do not differ significantly (comparison between water regimes by environments; Tukey test. $p>0.05$). 4) The "#" indicates a significant difference between environments within the same water regime, and the "*" indicates that the mean values differ significantly between environments (F test. $p<0.05$).

are in agreement with those obtained by Della Lunga et al. (2020) and by Steinmetz et al. (2011).

The air temperature measured at the automatic weather station (AWS) increased from the beginning to the end of the experiment in both growing seasons (Tables 1 and 2) and showed distinct patterns when compared to the soil temperature. For the maximum temperature (Tx), during the E-R1 subperiod in GS1, for example, the air temperature at AWS (Tx AWS) was 3.7 °C and 2.8 °C lower than the average Tx of the ridge and furrow, respectively. The opposite situation occurred in the R4-R9 subperiod, as Tx AWS was 5.3 °C and 5.4 °C higher than the average Tx of the ridge and furrow, respectively (Table 1). Similar patterns were observed in GS2 (Table 2). The likely reason for this behavior is that the low leaf coverage at the beginning of the crop cycle (subperiod E-R1) allowed greater soil heating than air heating in the area completely covered by short vegetation where the AWS was installed. On the other hand, during the final period of the crop cycle (subperiod R4-R9), the complete soil coverage by the rice canopy decreases the penetration of solar rays, causing Tx soil to be lower than Tx AWS.

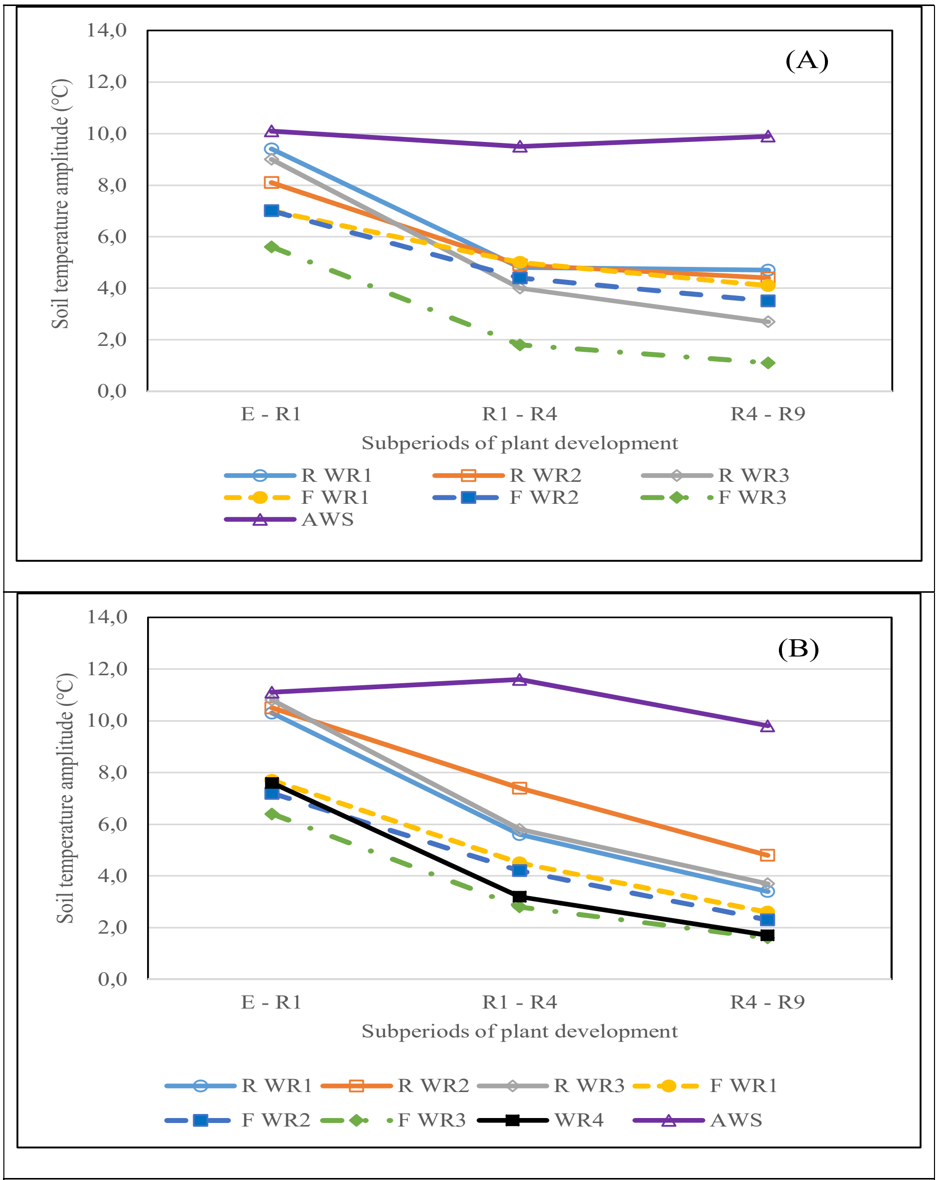
The influence of soil water regimes indicates a different pattern when comparing the amplitude of air temperature measured at the automatic weather station (Ta AWS) with the amplitude of soil temperature (Ta soil), since Ta AWS values were higher and more uniform throughout the experiment, as indicated by the data in Tables 1 and 2 and Figure 4A, B. The most contrasting data are those of GS2, where Ta AWS values were 11.0 °C, 11.6 °C, and 9.8 °C, while those of Ta soil in WR4 were 7.6 °C, 3.2 °C, and 1.6 °C, respectively, in the vegetative, reproductive 1, and reproductive 2 subperiods (Table 2 and Figure 4B). The reasons for this pattern are the same as those indicated previously.

The soil water regimes and the subperiods of plant development also influenced the air and/or water temperature (Tair/water) in any of the four variables used. Taking the Tx in the E-R1 subperiod in GS2 as an example, it can be seen that in the ridge the extreme values ranged from 32.4 °C (WR1 and WR3) to 31.9 °C (WR2) (Table 4). On the other hand, in the furrow, the extreme values ranged from 34.6 °C (WR2) to 32.3 °C (WR1), with a significant difference between them. Likewise, there was a significant difference between the Tx in the ridge (31.9 °C) and in the furrow (34.6 °C) in WR2. The average values of the ridge (32.2 °C) and furrow (33.5 °C) environments also showed a significant difference between them (Table 4).

The data in Table 3 (GS1) indicate that the extreme values of the air and/or water temperature amplitude (Ta air/water) ranged from 16.4 °C (WR1-furrow) to 11.9 °C (WR3-furrow) for the E-R1 subperiod, from 12.2 °C (WR2-ridge) to 7.9 °C (WR3-furrow) for the R1-R4 subperiod, and from 13.1 °C (WR1-furrow) to 3.9 °C (WR3-ridge) for the R4-R9 subperiod. Similar results were obtained in GS2 (Table 4) and are in agreement with those obtained by Steinmetz et al. (2011).

In GS2, the extreme values of the air and/or water temperature range ranged from 14.8 °C (WR2-furrow) to 13.6 °C (WR3-furrow) for the E-R1 subperiod, from

Figure 4. Soil temperature amplitude during three subperiods of rice cultivar BRS Pampa CL as a function of the water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, without depth control: lower portion; WR4=flooded soil, with depth control: conventional system) and the environment (Ridge and Furrow), and air temperature amplitude measured in an automatic weather station (AWS) in the growing season 2021/2022 (A) and 2022/2023 (B), in Capão do Leão, RS, Brazil.



Obs.: E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive).

12.3 °C (WR2-ridge) to 6.7 °C (WR3-furrow) for the R1-R4 subperiod, and from 9.7 °C (WR2-ridge) to 3.2 °C (WR2-furrow) for the R4-R9 subperiod (Table 4). Assuming that the degree of soil coverage by the rice canopy was similar in WR2, WR3, and WR4, the lowest Ta values in WR4 may have been caused by the thermoregulatory effect of water and, for the vegetative subperiod, are in agreement with the results obtained by Steinmetz et al. (2011).

The analysis of the influence of water regimes indicates a different pattern when comparing the amplitude of air temperature measured at the automatic weather station (Ta AWS) with the amplitude of air/water temperature (Ta air/water). The most contrasting data are those from the E-R1 subperiod of GS1, in which Ta AWS was 10.1 °C while the highest values of Ta air/water were 16.4 °C for WR1-furrow and 16.2 °C for WR2-ridge (Table 3). The likely explanation for this behavior is that the air/water temperature, both in the ridge and in the furrow, was influenced by the penetration of solar radiation into the canopy, causing maximum temperatures during the day to be higher than those at the AWS and nighttime cooling to be less intense and, consequently, minimum temperatures to be higher than those recorded at the AWS. The smaller differences in Ta AWS with the soil water regimes in GS2 (Table 4) may be associated with the lower soil water tension (SWT) values that occurred in GS2 in relation to GS1, as indicated by the data in Table 5.

The difference of only 1.7 °C between Ta AWS (10.9 °C) and Ta air/water of WR4 (flooded) (9.2 °C) during the entire cycle (E–R9) in GS2 (Table 4) is compatible with the average deviation of – 0.5 °C between Ta AWS (12.9 °C) and Ta air/water (13.4 °C) during the cycle of a commercial irrigated rice crop in the municipality of Dom Pedrito, in the state of Rio Grande do Sul (Steinmetz et al., 2006).

Influence of the ridge and furrow environments on soil, water, and air temperatures

Using the maximum soil temperature in GS2 as an example to evaluate the influence of the furrow and ridge environments, it can be seen that at the beginning of crop development (E-R1 subperiod), the average of the three WR was 32.4 °C in the ridge (Tx soil ridge), and 29.9 °C in the furrow (Tx soil furrow), with a significant difference between both. In the final phase of crop development (R4-R9 subperiod), the average of the three WR was 26.7 °C in the ridge and 25.3 °C in the furrow, also with a significant difference between the two environments. As a reference, in these two subperiods, the Tx soil in WR4 (flooded) were 30.9 °C and 24.5 °C, respectively (Table 2). These results suggest that the higher Tx values in the E-R1

Table 3. Air/water temperature during three subperiods and during the cycle of rice cultivar BRS Pampa CL as a function of the soil water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, without depth control: lower portion) and the environment (Ridge and Furrow), and air temperature (Tair) measured in an automatic weather station (AWS) in the 2021/2022 growing season, in Capão do Leão, RS, Brazil.

Sub-period	Air/water temperature	Environment								Average values		Air temperature (AWS) (°C)
		Ridge				Furrow						
		Water regime										
		WR1	WR2	WR3	CV	WR1	WR2	WR3	CV	Ridge	Furrow	
		(°C)			(%)	(°C)			(%)	(°C)		
E-R1	Average	24.3 (0.30) a	23.7 (0.32) ab	23.2 (0.33) b	10.2	23.7 (0.32) a	23.9 (0.33) a	23.6 (0.27) a	10.0	23.7 (0.18)	23.7 (0.18)	20.1
E-R1	Maximum	# 33.1 (0.61) ab	33.3 (0.70) a	31.1 (0.60) b	15.0	33.5 (0.70) a	32.6 (0.63) ab	30.7 (0.59) b	15.3	32.5 (0.37)	32.3 (0.38)	25.3
E-R1	Minimum	# 18.7 (0.39) a	17.1 (0.39) b	# 17.3 (0.44) b	17.5	17.1 (0.37) b	17.9 (0.42) ab	18.8 (0.43) a	17.3	17.7 (0.24)	17.9 (0.24)	15.2
E-R1	Amplitude	14.5 (0.76) a	16.2 (0.81) a	13.8 (0.72) a	20.1	16.4 (0.76) a	14.6 (0.76) a	11.9 (0.84) b	21.5	14.8 (0.44)	14.4 (0.47)	10.1
R1-R4	Average	25.7 (0.47) a	25.3 (0.47) a	25.1 (0.43) a	9.8	24.7 (0.49) a	25.9 (0.47) a	27.0 (0.99) a	14.7	25.4 (0.26)	25.8 (0.14)	22.8
R1-R4	Maximum	31.9 (0.69) a	33.3 (0.86) a	29.3 (0.55) b	12.3	32.0 (0.80) a	32.6 (0.74) a	30.8 (1.42) a	17.8	31.5 (0.44)	31.8 (0.42)	27.7
R1-R4	Minimum	# 22.5 (0.54) a	21.1 (0.55) a	22.4 (0.49) a	13.2	20.7 (0.58) b	22.2 (0.57) ab	22.9 (0.74) a	15.9	22.0 (0.31)	21.9 (0.25)	18.2
R1-R4	Amplitude	9.4 (0.63) b	12.2 (0.84) a	6.9 (0.43) c	18.8	11.3 (0.76) a	10.4 (0.71) a	7.9 (1.39) b	26.8	9.5 (0.44)	9.9 (0.57)	9.5
R4-R9	Average	24.2 (0.22) a	23.6 (0.25) ab	# 23.0 (0.22) b	5.0	23.9 (0.27) b	23.7 (0.24) b	28.5 (1.23) a	15.5	23.5 (0.14)	25.4 (0.52) *	25.1
R4-R9	Maximum	# 30.2 (0.62) a	# 31.2 (0.54) a	# 25.1 (0.22) b	8.3	32.2 (0.70) ab	29.3 (0.43) b	33.0 (1.33) a	14.9	28.8 (0.42)	31.5 (0.56) *	30.5
R4-R9	Minimum	# 21.0 (0.47) a	# 19.2 (0.43) b	21.2 (0.31) a	9.9	19.2 (0.50) b	20.5 (0.45) b	23.4 (1.05) a	17.8	20.4 (0.25)	21.1 (0.47)	20.5
R4-R9	Amplitude	# 9.3 (0.95) b	# 12.1 (0.77) a	# 3.9 (0.28) c	21.7	13.1 (0.95) a	8.9 (0.68) b	9.6 (0.63) b	19.8	8.4 (0.57)	10.3 (0.47) *	10.0
E-R9	Average	24.6 (0.22) a	24.1 (0.22) ab	# 23.7 (0.22) b	9.7	24.0 (0.23) b	24.3 (0.23) b	25.7 (0.46) a	13.9	24.1 (0.13)	24.7 (0.19) *	22.0
E-R9	Maximum	32.2 (0.41) a	32.8 (0.44) a	# 29.1 (0.40) b	14.2	32.8 (0.45) a	31.8 (0.41) a	31.3 (0.58) a	16.1	31.4 (0.26)	32.0 (0.28)	27.2
E-R9	Minimum	# 20.1 (0.31) a	# 18.6 (0.31) b	# 19.6 (0.34) ab	17.5	18.5 (0.31) b	19.6 (0.32) b	21.0 (0.43) a	19.4	19.4 (0.19)	19.7 (0.21)	17.3
E-R9	Amplitude	# 12.1 (0.53) b	# 14.2 (0.53) a	9.6 (0.55) c	24.4	14.4 (0.53) a	12.2 (0.51) b	10.3 (0.59) c	24.1	12.0 (0.33)	12.3 (0.33)	9.9

Obs.: 1) E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive 2); E-R9 = period comprising the entire crop cycle (Cycle). 2) Values in parentheses indicate the standard error of the mean. 3) For the same line and environments (ridge and furrow), means followed by the same letter do not differ significantly (comparison between water regimes by environments; Tukey test. $p>0.05$). 4) The “#” indicates a significant difference between environments within the same water regime, and the “*” indicates that the mean values differ significantly between environments (F test. $p<0.05$).

Table 4. Air/water temperature during three subperiods and during the cycle of rice cultivar BRS Pampa CL as a function of the soil water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, without depth control: lower portion; WR4=flooded soil, with depth control) and the environment (Ridge and Furrow), and air temperature (Tair) measured in an automatic weather station (AWS) in the 2022/2023 growing season, in Capão do Leão, RS Brazil.

Sub-period	Air/water temperature	Environment									Average values		Air temperature (AWS)
		Ridge				Furrow							
		Water regime											
		WR1	WR2	WR3	CV	WR1	WR2	WR3	CV	WR4	Ridge	Furrow	
		(°C)			(°C)	(°C)			(°C)	(°C)	(°C)		(°C)
E-R1	Average	24.6 (0.44)	# 23.9 (0.33)	# 24.2 (0.28)	11.0	23.9 (0.32) b	26.2 (0.39) a	25.6 (0.24) a	9.8	24.7	24.2 (0.21)	25.2 (0.20) *	23.2
E-R1	Maximum	32.4 (0.43)	# 31.9 (0.53)	32.4 (0.48)	11.2	32.3 (0.53) b	34.6 (0.49) a	33.7 (0.53) ab	11.7	32.9	32.2 (0.28)	33.5 (0.31) *	28.9
E-R1	Minimum	18.1 (0.36)	# 17.4 (0.43)	# 18.2 (0.32)	15.8	17.7 (0.31) b	19.8 (0.58) a	20.1 (0.3) a	16.6	20.1	17.9 (0.22)	19.2 (0.25) *	17.9
E-R1	Amplitude	14.2 (0.58)	14.5 (0.57)	14.2 (0.6)	15.3	14.2 (0.63)	14.8 (0.72)	13.6 (0.69)	19.1	12,8	14.3 (0.33)	14.2 (0.39)	11.0
R1-R4	Average	23.7 (0.48)	# 24.8 (0.47)	# 24.7 (0.31)	9.6	24.0 (0.46) c	27.8 (0.56) a	25.7 (0.23) b	9.2	24.8	24.4 (0.25)	25.8 (0.30) *	24.1
R1-R4	Maximum	30.6 (0.75)	32.4 (0.76)	31.3 (0.68)	12.7	30.7 (0.79) ab	32.2 (0.73) a	29.8 (0.51) b	12.1	29.1	31.4 (0.42)	30.9 (0.41)	30.2
R1-R4	Minimum	19.2 (0.54)	# 20.1 (0.52)	# 20.8 (0.33)	12.9	20.0 (0.51) c	25.3 (0.61) a	23.2 (0.23) b	11.3	22.2	20.1 (0.28)	22.8 (0.36) *	18.6
R1-R4	Amplitude	11.4 (0.62)	# 12.3 (0.67)	# 10.4 (0.63)	16.0	10.7 (0.65) a	6.8 (0.45) b	6.7 (0.49) b	18.3	6.9	11.4 (0.37)	8.1 (0.37) *	11.6
R4-R9	Average	24.2 (0.28) a	# 25.0 (0.28) a	22.9 (0.51) b	7.4	23.5 (0.22) b	25.8 (0.14) a	23.4 (0.43) b	5.6	24.0	24.1 (0.23)	24.3 (0.20)	24.5
R4-R9	Maximum	# 30.2 (0.52) a	# 31.3 (0.50) a	# 27.6 (0.5) b	8.4	27.9 (0.46) a	27.7 (0.21) a	25.4 (0.39) b	6.7	26.5	29.8 (0.34)	27.1 (0.24) *	30.1
R4-R9	Minimum	21.0 (0.37) ab	# 21.6 (0.35) a	# 19.9 (0.7) b	11.3	21.0 (0.26) b	24.5 (0.17) a	21.9 (0.53) b	7.3	22.4	20.9 (0.28)	22.5 (0.26) *	20.3
R4-R9	Amplitude	# 9.3 (0.45) a	# 9.7 (0.41) a	# 7.7 (0.56) b	12.9	6.7 (0.35) a	3.2 (0.18) b	3.6 (0.28) b	14.0	4.1	9.0 (0.28)	4.5 (0.24) *	9.8
E-R9	Average	24.3 (0.27)	# 24.4 (0.22)	# 24.1 (0.2)	10.1	23.8 (0.21) c	26.5 (0.26) a	25.2 (0.19) b	9.3	24.6	24.2 (0.13)	25.2 (0.14) *	23.7
E-R9	Maximum	31.4 (0.33)	31.9 (0.35)	31.1 (0.37)	11.7	30.9 (0.39) b	32.4 (0.41) a	30.9 (0.45) b	14.0	30.4	31.5 (0.20)	31.4 (0.24)	29.5
E-R9	Minimum	19.1 (0.27)	# 19.1 (0.32)	# 19.3 (0.26)	15.6	19.1 (0.25) b	22.3 (0.42) a	21.3 (0.24) a	15.9	21.2	19.1 (0.16)	20.9 (0.20) *	18.6
E-R9	Amplitude	12.3 (0.4)	# 12.8 (0.40)	# 11.8 (0.44)	17.5	11.6 (0.47) a	10.1 (0.61) b	9.6 (0.56) b	28.3	9.2	12.3 (0.24)	10.5 (0.32) *	10.9

Obs.: 1) E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive 2); E-R9 = period comprising the entire crop cycle (Cycle). 2) Values in parentheses indicate the standard error of the mean. 3) For the same line and environments (ridge and furrow), means followed by the same letter do not differ significantly (comparison between water regimes by environments; Tukey test. p>0.05). 4) The "#" indicates a significant difference between environments within the same water regime, and the "*" indicates that the mean values differ significantly between environments (F test. p<0.05).

Table 5. Soil water tension, in ridge and furrow, in WR1=drained soil (upper portion), in WR2=saturated soil (central portion) and in WR3=waterlogged soil, without depth control (lower portion of the field), in growing seasons 2021/2022 and 2022/2023, in Capão do Leão, RS, Brazil.

Water regime (WR)/ Environment	Soil water tension (kPa)		Average Cropping seasons
	Cropping season 2021/2022	Cropping season 2022/2023	
WR1 Ridge	41,1	18,2	29,7
WR1 Furrow	17,2	7,6	12,4
Average WR1	29,2	12,9	21
WR2 Ridge	32,4	6,8	19,4
WR2 Furrow	21,7	4,1	12,9
Average WR2	27	5,5	16,2
WR3 Ridge	15,8	3,5	9,7
WR3 Furrow	10,3	2,4	6,4
Average WR3	13,1	3	8
Average WR	23,1	7,1	15,1
Average Ridge	29,8	9,5	19,7
Average Furrow	16,4	4,7	10,6

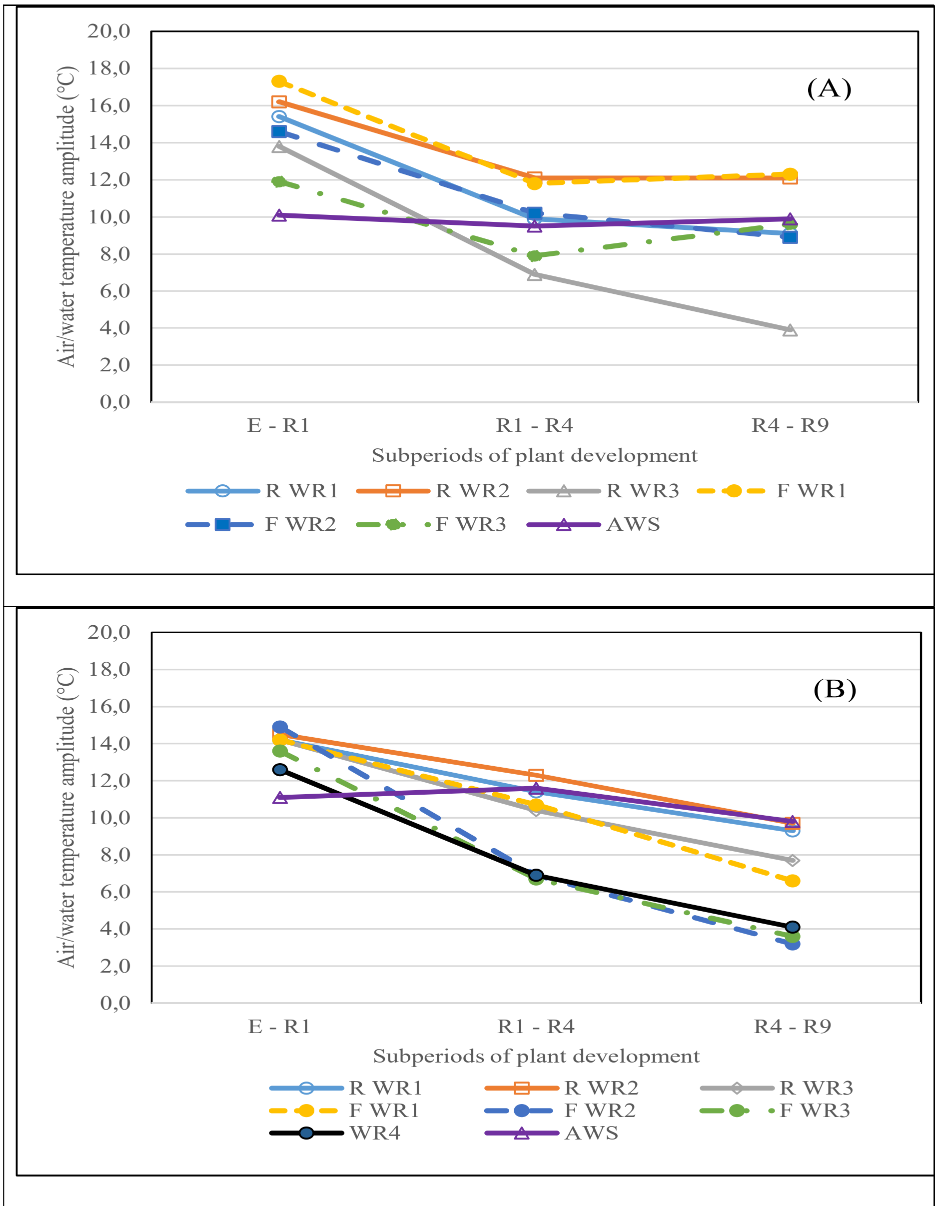
Obs.: Quanto maior o valor, mais seco está o solo.

subperiod were caused by the lower soil coverage by the crop canopy, allowing greater penetration of solar rays and, consequently, greater soil heating, as indicated by the results obtained by Della Lunga et al. (2020). The lower values observed in the furrow may be associated with the higher moisture content or even the existence of a water layer in the lower parts of the plot. Similar behavior was observed with the corn crop, although the temperature differences between the ridge and the furrow were more accentuated by the fact that plastic mulching was used on the ridge (Li, et al., 2017).

The minimum soil temperature, also in GS2, indicated an opposed behavior to that observed with the maximum soil temperature, since in the E-R1 subperiod the average of the three WR was 21.8 °C in the ridge and 22.7 °C in the furrow, with a significant difference between them. In the R4-R9 subperiod the average of the three WR was 22.6 °C in the ridge and 23.1 °C in the furrow (Table 2). Similar results were obtained in GS1 (Table 1). These results are also in agreement with those obtained by Li et al. (2017) despite the previously indicated particularity of this study.

The thermal amplitude of soil temperature (Ta soil), as it represents the difference between the maximum and minimum temperatures, is one of the variables that best characterizes the influence of the ridge and furrow environments. Using Ta soil in GS2, as an example, it can be seen that in the E-R1 subperiod the average of the three WR was 10.5 °C in the ridge and 7.1 °C in the furrow, with a significant difference between them. In the R4-R9 subperiod, this average was 4.0 °C in the ridge and 2.2 °C in the furrow, also with a significant difference between them. As a reference, in these two subperiods, the Ta soil in WR4 (flooded) were 7.6 °C and 1.6 °C, respectively (Table 2). These results characterize well the influence of the degree of soil coverage due to crop development as well as the thermoregulatory effect of water, for the reasons

Figure 5. Air/water temperature amplitude during three subperiods of rice cultivar BRS Pampa CL as a function of the soil water regime (WR1=drained soil: upper portion; WR2=saturated soil: central portion; WR3=waterlogged soil, wihout depth control: lower portion; WR4=flooded soil, with depth control: conventional system) and the environment (Ridge and Furrow), and air temperature amplitude measured in an automatic weather station (AWS) in the growing season 2021/2022 (A) and 2022/2023 (B), in Capão do Leão, RS, Brazil.



Obs.: E-R1 = subperiod between emergence and stage R1 (Vegetative); R1-R4 = subperiod between stages R1 and R4 (Reproductive 1); R4-R9 = subperiod between stages R4 and R9 (Reproductive).

already discussed for the previous variables.

The thermal amplitude of soil temperature (Ta soil) in the furrow indicated lower values than those in the ridge in both growing seasons (Figure 4 and Table 1), with the differences being more pronounced in the GS 2 (Figure 4B and Table 2), whose values were similar to those observed in WR 4 (flooded) (Figures 4A and B). This behavior is due to the fact that, in the furrow, the soil remains wetter, including periods with water layer in WR3.

The thermal amplitude of air temperature measured at the AWS (Ta AWS) indicated higher values than the thermal amplitude of soil temperature (Ta soil), both in the ridge and in the furrow, with the differences being less pronounced in the E-R1 subperiod (Figure 4 and Table 1) and in the ridge compared to the furrow. It is likely that, in this subperiod, the lower soil coverage by rice plants generated soil heating and cooling conditions closer to those of the short vegetation surface where the AWS was installed. On the other hand, the thermoregulatory effect of irrigation water caused lower Ta values in the furrow, especially in GS2 (Figure 4B and Table 2). The combination of the thermoregulatory effect of water and the initial phase of plant development on the thermal amplitude of soil temperature was also observed by Steinmetz et al. (2011) and by Della Lunga et al. (2020).

The amplitude of the air temperature measured at the AWS (Ta AWS), when compared with the amplitude of the air/water temperature, presented lower values than those observed both in the ridge and in the furrow in the vegetative subperiod and intermediate values in the reproductive superiods 1 and 2 (Figure 5 A and B). The greatest differences were observed in the E-R1 subperiod of GS1, reaching 10.1 °C, 14.8 °C and 14.4 °C, respectively, for Ta AWS, Ta ridge, and Ta furrow (Figure 5A and Table 3). The higher Ta values both in the ridge and in the furrow indicate that this variable was more influenced by the variation of the Tx and Tn values in these two environments than in the environment (grassy vegetation cover) where the AWS was installed.

Conclusions

Soil, water, and air temperatures are influenced by the soil water regime in the three parts of the plot (upper, intermediate and lower), by the environments (ridge and furrow), and by the subperiods of furrow-irrigated rice plant, with the greatest temperature amplitudes occurring in the upper part of the plot, and in the vegetative subperiod of plant development;

Temperature amplitudes are smaller in the conventional water regime (flooded soil) compared to the other three and decreases from the beginning to the end of the cycle, and are lower than the air temperature amplitudes of a nearby grassy area, especially those related to soil temperature.

Authors´contribution

S. STEINMETZ designed and conducted the experiments, analysed the data and wrote the manuscript. J. M. B. PARFITT and A. D. de CAMPOS obtained and analysed the soil water tension data. W. B. SCIVITTARO collaborated in the review of the manuscript. G. THEISEN performed the statistical analysis and collaborated in the review of the manuscript. L. de S. DIAS helped to obtain the phenological data.

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Temperaturas do solo, da água e do ar em arroz irrigado por sulco

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RESUMO

Os objetivos deste estudo foram caracterizar como o regime hídrico do solo e os ambientes camalhão e sulco afetam as temperaturas do solo, da água e do ar durante o ciclo da planta de arroz e como se relacionam com as temperaturas de um regime hídrico convencional (inundação do solo), e com a temperatura do ar de uma área gramada próxima do experimento. Na safra 2021/2022 os dados de temperatura foram obtidos em três regimes hídricos do solo (regime hídrico 1 – RH1: solo drenado; regime hídrico 2 – RH2: solo saturado; regime hídrico 3 – RH3: solo alagado). Na safra 2022/2023, foi incluído o regime hídrico do solo 4 - RH4 (solo inundado). Em cada um desses regimes hídricos do solo e dos ambientes camalhão e sulco, foi medida a temperatura do solo a 5 cm de profundidade e do ar/água a 5 cm acima do nível do solo com sensores e sistemas de aquisição de dados Hobo®. Os dados horários foram transformados em diários e por subperíodos do ciclo da cultivar BRS Pampa CL, considerando-se quatro variáveis de temperatura: média, máxima, mínima e amplitude. Os resultados permitem concluir que as temperaturas do solo, da água e do ar são influenciadas pelos regimes hídricos do solo, pelos ambientes (camalhão e sulco), pelos subperíodos de desenvolvimento do arroz irrigado por sulcos, e que as amplitudes de temperatura são menores no sistema convencional de irrigação (inundação do solo) e diminuem do início para o fim do ciclo nos quatro regimes hídricos do solo estudados.

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