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Rice development and water demand under drought stress imposed at distinct growth stages

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This study aimed to establish a comparison for theoretical water demand between rice plants grown under flooding and under different levels of water stress, imposed at distinct crop stages, in terms of plant morpho-physiology and phenology. The experiment was installed in a greenhouse, using complete randomized design and factorial scheme 3 × 4 + 1, with four replications. Factor "A" was defined as the growth stage when water stress was imposed on the treatments, these stages being (1) vegetative, (2) reproductive 1, and (3) reproductive 2; factor "B" was composed of four levels of water stress (0 to 200 kPa). The additional treatment consisted of a flooded check. Water was replenished back to saturation every time the threshold stress level was reached. There is damage to rice growth and development in water tensions greater than 30 kPa when applied between tillering start and anthesis. Main damage was observed as reduced rates of culm growth; leaf area tended to be maintained. Water luxury consumption by rice plants grown under flooding seems to be about 23% of the total demand, compared to the other irrigated treatments. The rice field should be irrigated back to saturation when soil water tension is between 10 kPa and 30 kPa. Overall, theoretical crop coefficient (K_c) for rice under sprinkler irrigation is about 20% lower than that observed for the flooded check.

Key words: Water consumption, planting system, *Oryza sativa*.

INTRODUCTION

Rice is a staple food for nearly half the world's population, being cultivated in 112 countries, with 90% of the world's production concentrated in Asia. In Brazil, about 3 million hectares are cultivated every year and rice is traditionally present in Brazilian meals, regardless of social class. The southern region of the country supplies approximately 65% of Brazilian rice (Gomes and Magalhães Jr., 2004). The demand for water in flooded rice cultivation is considerably higher than the water requirement of crops traditionally sprinkler irrigated, such as soybeans and corn. Physiologically, rice is a sub-aquatic plant adapted to a flooded environment (Correll and Correll, 1975), and may be grown without flooding if the water is managed properly. Early recommendations stipulated the need for

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up to 17,000 m^3 of water per hectare per cycle for flooded rice (Pérez, 1992), including both irrigation and rainfall. In the Brazilian state of Rio Grande do Sul, rice is predominantly grown under continuous flooding (Silva et al., 2015). To meet the water demand it is estimated that, with current technology, an average of 8,000 to 10,000 m^3 of water per hectare is necessary to supplement rainfall in an irrigation period of 80 to 100 days (SOSBAI, 2014). Almost 100% of this amount is supplied by pumping from rivers or ditches. This amount of water is very high when compared to other crops, and not every farmer is able to meet this estimated demand; there are losses in water capture, storage, pumping and transport. These losses are unique to each farm. In fact, real mean water demand for flooded rice may be much higher than that estimated by SOSBAI (2014).

Globally, several alternatives are being studied for improving water use efficiency in rice fields; among them, intermittent irrigation, furrow irrigation and center pivot (sprinkler irrigation) technologies have been emphasized. For these systems, reductions in both productivity and grain quality have often been reported; on the other hand, production costs also fall, which might improve net economic profitability. Research to date supports the evidence that each of the above-mentioned systems are better-suited to specific locations and management styles, and the proportion of water saved will depend greatly on local edaphoclimatic characteristics (Petrini et al., 2013; Londero, 2014). Sprinkler irrigation by pivots and linears has been, and continues to be, tested for rice cultivation, and there are claims for 50% water savings when rice grown under pivot irrigation is compared to continuous flooding (Parfitt et al., 2011). This seems to be the case mainly when the system is installed in uneven areas or in fields with significant slope, as well as where water is scarce. Supposing this economy is confirmed, farmers who grow rice under pivots would have a surplus of water which could be used either to increase rice acreage or to irrigate crops on additional fields.

In order to establish the real water savings by growing rice under sprinkler irrigation compared to flooded systems, there is need to characterize the water demanded for rice plants and the issues which could arise from water limitation in distinct stages of rice plant development. There is little information to date regarding crop coefficients to be used for managing irrigation of rice under pivots in high–yield conditions. These coefficients should be estimated under a controlled environment as a first step for estimating field crop coefficient values. Actual field-scale coefficients for rice under sprinkler irrigation would also have to consider the smaller run-off and percolation losses. These losses are most present in flooded fields, and the resulting water demanded for satisfying these losses should not be confused with crop demand. This study aimed to establish a comparison for theoretical water demand between rice plants grown under flooding and those grown under different levels of water stress, imposed at distinct stages of the crop growth cycle, in terms of plant morpho-physiology and phenology.

MATERIALS AND METHODS

The experiment was installed in a greenhouse at Embrapa Clima Temperado, Pelotas-RS, Brazil, during the traditional rice growing season. A complete randomized design was used with plots arranged in a factorial scheme, 3 × 4 + 1, with four replications. The rice variety was BRS-Querencia, with a medium duration growth cycle (Embrapa, 2005). Factor "A" was comprised of the growth stage when water stress was imposed on the treatments, being (1) vegetative (tillering start through panicle differentiation), (2) reproductive 1 (panicle differentiation through anthesis), and (3) reproductive 2 (anthesis through ripening start). Factor "B" was comprised of the four levels of water stress imposed on the plants. The additional treatment consisted of a constantly flooded treatment. Although the reproductive stage in rice starts at panicle initiation (SOSBAI, 2014), this stage is very difficult to identify; as a result, farmers generally use panicle differentiation as the start of the reproductive stage for nutrient management. As panicle initiation (PI) and panicle differentiation (PD) are spaced only about 4 days (Carli et al., 2016), we decided to use panicle differentiation in the present study. From emergence to the beginning of tillering, all plots were maintained with soil water tension under 10 kPa, including plots which would be flooded from tillering onward. Every time the treatment reached the threshold level of water deficit, it was irrigated back to saturation. Treatments which were not at the developmental stage when the stress was applied were maintained under 10 kPa. Treatments are listed in Table 1. Experimental units consisted of black plastic pots, each with capacity of 12 L, filled with 10 kg of previously corrected and fertilized soil. The soil used at the experiment was collected in agriculture-free natural areas near rice fields at Terras Baixas Experimental Station, Capão do Leão, RS, Brazil. Soil was fertilized with N-P-K and corrected for pH 6.0 with ground limestone. In rice fields, pH is usually not corrected because the water layer is enough to correct the pH after flooding is established, but as most plots of the trial were not going to be submitted to flooding, we decided to correct soil pH in order to guarantee equal soil pH conditions for all plots.

Water stress was monitored by using sets of Watermark electro-tensiometers (Irrometer Co.), with a single sensor installed in each experimental unit (pot), at depth of 10 cm (from soil surface to the center of the sensor), at the radial center of the pot. All sensors were connected by wire to a nearby Watermark data logger, which was programmed to record water tension in kPa at one hour intervals. Sensor readings were automatically corrected by the datalogger as a function of the mean temperature registered inside the plots, and for that, two Watermark temperature sensors were installed in each block of the experiment. Temperature data from these sensors were used by the datalogger to correct soil water tension readings of the corresponding plots. Temperature sensors were also installed at a depth of 10 cm. Soil water tension for all plots was read and recorded manually, twice a day (09:00 am and 04:00 pm), seven days a week. When it reached the threshold level, the water needed to adjust soil water tension back to saturation was added after reading. The amount of water to be added to each plot was determined by using a soil moisture retention curve, which relates water tension (kPa) with water content (%). The water tension curve was determined especially for the experiment, after the soil was corrected and fertilized, so no error in the curve would be attributed to differential soil density or structure. The water retention curve for the soil used in the experiment is supplied in Figure 1.

The daily maximum and minimum temperature and air humidity in

Table 1. Treatments studied at the greenhouse trial at Embrapa.

Treatment	Description / Details
Flooded	Flooded with 7cm of water at tillering start and kept flooded until ripening start. At ripening start water was not removed, but we just stopped re-filling back to 7cm of water layer. Water remained for some days before these plots were dry
water stress (kPa)	**"V" – under treatment between tillering start and panicle differentiation**
10	Irrigated back to the saturation every time water tension reached 10 kPa
30	Irrigated back to the saturation every time water tension reached 30 kPa
100	Irrigated back to the saturation every time water tension reached 100 kPa
200	Irrigated back to the saturation every time water tension reached 200 kPa
	"R1" – under treatment between panicle differentiation and anthesis
10	Irrigated back to the saturation every time water tension reached 10 kPa
30	Irrigated back to the saturation every time water tension reached 30 kPa
60	Irrigated back to the saturation every time water tension reached 60 kPa
130	Irrigated back to the saturation every time water tension reached 130 kPa
	"R2" – under treatment between anthesis and ripening start
10	Irrigated back to the saturation every time water tension reached 10 kPa
30	Irrigated back to the saturation every time water tension reached 30 kPa
60	Irrigated back to the saturation every time water tension reached 60 kPa
130	Irrigated back to the saturation every time water tension reached 130 kPa

In fact, treatments submitted to 10 kPa (V, R1 or R2) were under this water tension during all the cycle, because all treatments were kept under between saturation and 10 kPa, when out of the developmental stage they were supposed to be under treatment.

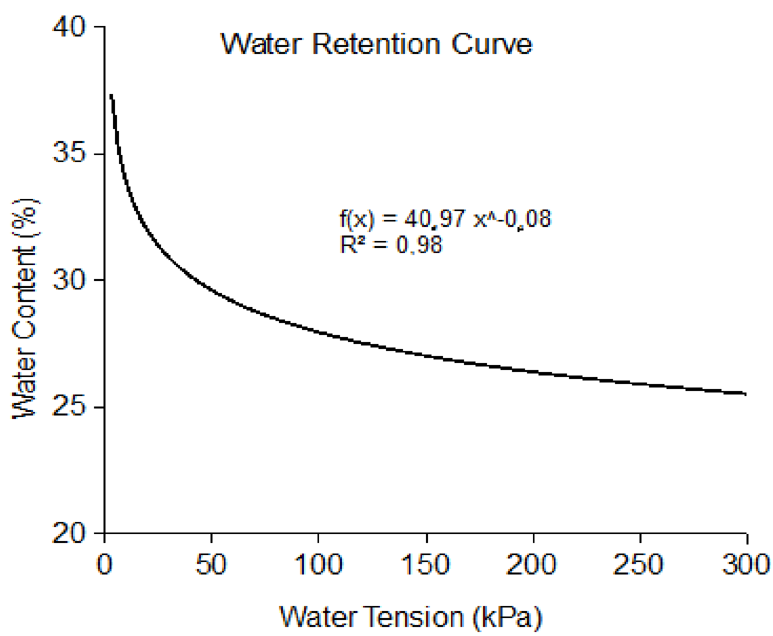

Figure 1. Water retention curve for the soil used at the experiment under controlled environment. Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

the greenhouse during the trial are shown in Figure 2a and b, respectively. The evapotranspiration (ET_0) was calculated as an auxiliary method to the tensiometers to help estimate when the plots would reach the threshold water stress level. ET_O was calculated using the Hargreaves equation (Figure 2c), based on daily maximum and minimum temperatures (Figure 2a). At the end of the experiment, the volume of water demanded by each treatment (from rice planting to harvest) was obtained and compared to the additional treatment (flooded) as a percentage.

The impact of the distinct water restriction levels on rice was studied by production of dry mass of culms and leaves as well as total shoot dry mass (excluding the panicle). Based on these data, a

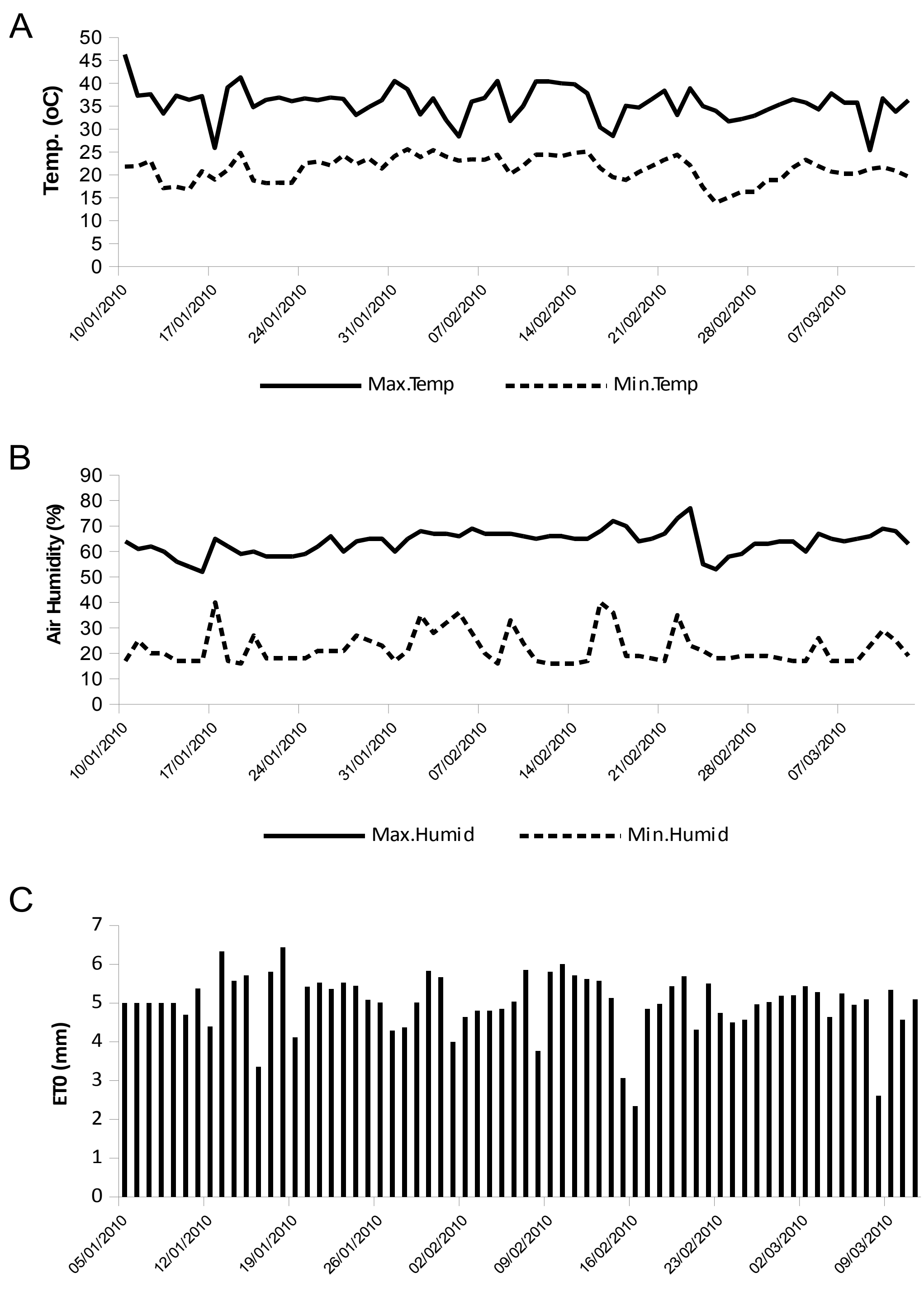

Figure 2. (A) Daily maximum and minimum temperatures collected inside the greenhouse for ETo estimation; (B) maximum and minimum air humidity into the greenhouse throughout the experimental period; (C) Eto estimation by the Hargreaves formula based on maximum and minimum daily temperatures. Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

brief plant growth analysis was done by calculating the Specific Leaf Area (SLA), Leaf Weight Ratio (LWR) and Leaf Area Ratio (LAR), according to Gardner et al. (1985) and Parmar and Chanda (2002), using their instantaneous formulas. The number of days from emergence to anthesis (for treatments grouped "V" or "R1") in the rice growth cycle were also determined, as function of water tension. For "R2", stress was imposed at anthesis.

The crop coefficient (Kc) is a property of plants used in predicting water demand by evapotranspiration (Gardner et al., 1985), and as consequence the water demand. This value was also determined weekly for all treatments. The values of Kc were compared to the flooded treatment as a percentage. Data were analyzed into the "R" statistical environment (R Core Team, 2016). Before any analysis, data sets were verified for normality and variance homogeneity by the tests of Shapiro-Wilk and Bartlett, respectively, being transformed by $\sqrt{(x+1)}$ when needed. These were then submitted for analysis of variance by the F-test at 5% probability. Data were explored according to significances of the interactions, being presented in graphical form. Data graphically presented are original; transformed data were used only for the parametric tests.

RESULTS AND DISCUSSION

The dry mass of rice plants (Figure 3A) was affected when the water stress was applied at the "V" (tillering start through panicle differentiation) or at the "R1" (panicle differentiation through ripening start) growth stages. At these treatments leaf dry mass was equivalent to that of the flooded check (approximately 4 g plant^{-1}), but culm dry mass was reduced compared to plants under flooding (12 g plant^{-1} under flooding and approximately 8 g plant^{-1} for "V" and "R1" treatments) (Figure 3A).

These values are reasonable, according to the literature, where the shoot of a single rice plant under field conditions averages about 9 g plant^{-1} (Paranhos et al., 1995), or about 1200 g m^{-2} (Mauad et al., 2011). Under controlled environment, however, plants reached about 18 g plant^{-1} (Figure 3a) due to the lower intraspecific competition (lower plant density) and lower levels of other stresses besides those imposed by treatments (Radosevich et al., 2007).

For treatments grouped under "R2" (water stress between anthesis and ripening start), there was no difference in dry mass compared to the flooded check (Figure 3A). Plants in this group, however, weighed more than the ones reported at "V" and "R1"; this is expected because rice plants do not stop growing at panicle differentiation but at heading (panicle emission) (Moldenhauer et al., 2013), which occurs some days before anthesis (flowering). The Specific Leaf Area (SLA) varied greatly among treatments (Figure 3B), averaging 0.06 m^2 g^{-1} for most treatments. This is comparable to Nagai and Makino (2009), who reported about 0.03 m^2 g^{-1} for Japanese rice varieties. Water tensions of 100 and 200 kPa applied at the "V" stage resulted in SLA of about 0.2 m^2 g^{-1}, most probably as consequence of the severe effect of drought on the growth of rice culms when rice is at the vegetative stage (Figure 3B). Rice did not actually increase leaf area under severe drought stress, but reduced culm growth, while trying to maintain minimum increase in the leaf area, which resulted in disproportionate SLA. Lonbani and Arzani (2011) reported that triticale and wheat mostly tended to keep or increase their leaf area when under moderate levels of water stress; a similar behavior could be present in rice. The leaf weight (LWR) and area (LAR) ratios (Figure 3B) also seem reasonable, according to Nagai and Makino (2009), who found values of about 0.30 and 0.010, respectively, for Japanese rice varieties. In this study, values averaged 0.28 and 0.007, respectively for LWR and LAR. In general terms, SLA and LAR increased when severe water stress was imposed at the "V" stage (Figure 3B) while LWR was little affected.

According to the damage to rice growth as shown in Figure 3, the rice reproductive cycle was lengthened when water stress was imposed at "V" or "R1" stages (Figure 4), with no obvious effect when stress was imposed in "R2" since rice plants had already stopped growth before treatment imposition. Drought effect was most effective in lengthening rice cycle when imposed at the "V" stage, where 46 days were needed to reach anthesis at 10 kPa compared to 55 days and 64 days, respectively, for tensions of 100 and 200 kPa (Figure 4). When drought was imposed in "R1", days to anthesis were 50 and 54, respectively, for 60 and 130 kPa (Figure 4). When water stress was imposed in "V" or "R1", there was no difference in days to anthesis among the flooded check and treatments with water tensions up to 60 kPa (Figure 4). This conclusion is based on the confidence interval (data not shown), according to the observed data for dry mass (Figure 3A) and growth analysis (Figure 3B). The main effect of water stress on any reproductive stage is believed to be a reduction in grain yield as a consequence of the reduction in fertile panicles and filled grain percentage (Sarvestani et al., 2008), which was not the focus of the present study.

Some consequences may arise from the delay in rice cycle and anthesis timing in the presence of stress. As an example, in high latitude areas where rice is planted, a delay in crop cycle may subject the field to environmental stresses such as cool weather in anthesis, lack of rains at the proper time and problems in harvest scheduling, similar to those observed for delayed planting (Gomes and Magalhães Jr., 2004). In addition, delays in rice growth stages could result in issues with remobilization and distribution characteristics of photoassimilates between plant organs, as well as reduced photosynthesis rates at the critical stage of grain filling (Liu et al., 2015).The water used by evapotranspiration (Figure 5) declined as water stress increased. While 839 mm (equal to 8,390 m^3 ha^{-1}) were consumed throughout the cycle for the flooded check treatment, only 655, 618 and 644 mm were demanded when rice was grown under 10 kPa of water tension (Figure 5A), which represents an average of 23% theoretical potential water savings by simply changing from flooding to sprinkler irrigation in rice (Figure 5B).

These savings are theoretical since the plots used at the trial are impermeable and free from water losses by runoff or percolation; thus, under field conditions, water savings by growing rice under sprinkler irrigation, compared to the traditional flooded system, would likely be more than the recorded 23%. In addition, it could be said that the "luxury" water consumption by rice when

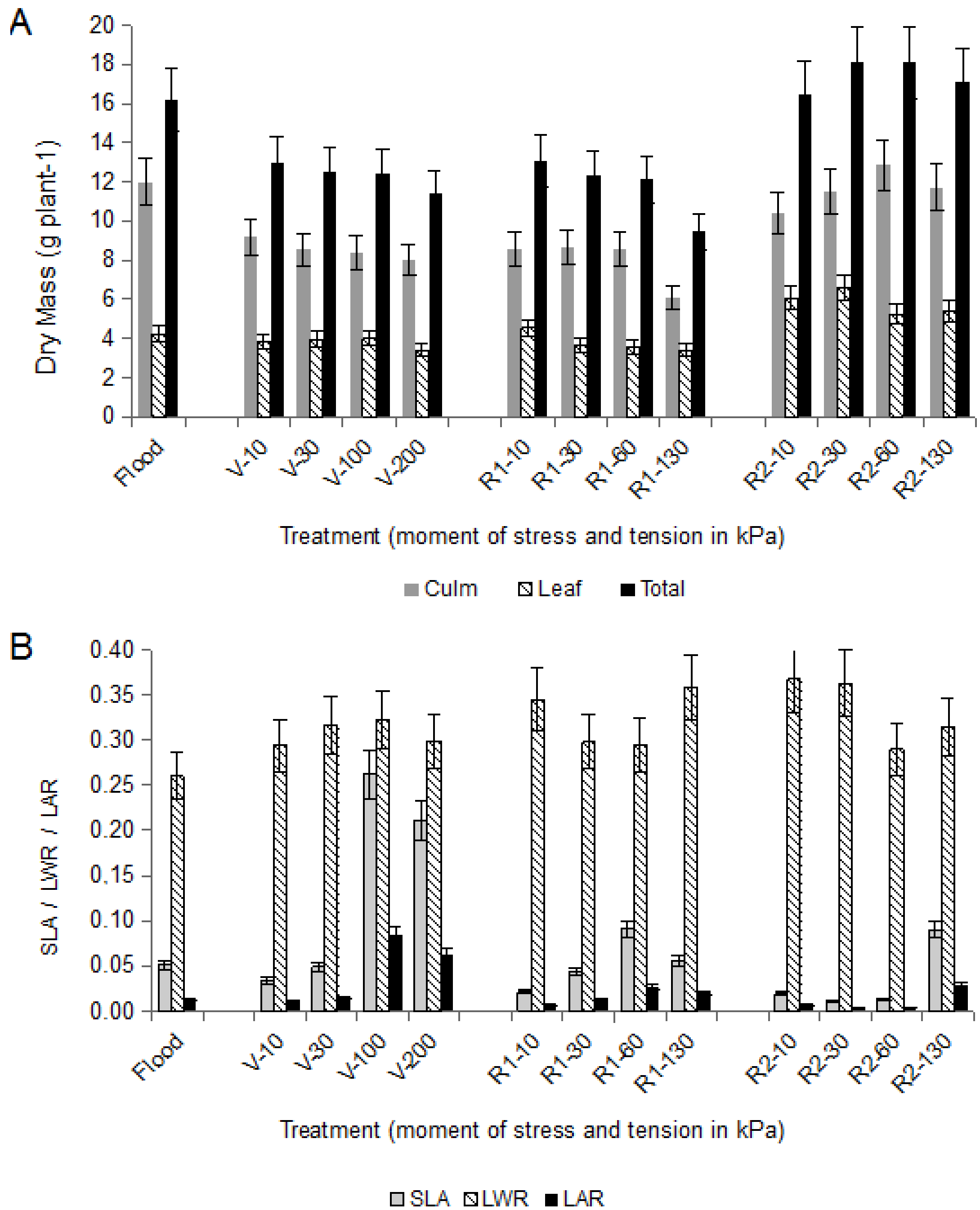

Figure 3. (A) Dry mass of culms, leaf and total (shoot), and (B) growth parameters for rice plants of the variety BRS-Querencia grown under increasing water stress levels applied at distinct developmental stages. V = vegetative stage (from tillering start to panicle differentiation); R1 = reproductive 1 (from panicle differentiation to anthesis); R2 = reproductive 2 (from anthesis to ripening start). Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

grown under flooding (compared to sprinkler irrigation systems) equals about 23%. Bacon (2009) reported that rice is the "king of the plants" regarding luxury water consumption; the author remarks that this crop demands about half the available water resources. This shows what a great worldwide impact on water savings could be achieved by improving rice water use efficiency. For the "V" stage, there was no significant reduction in water consumption from V-10 kPa to V-30 kPa, but the demand fell for treatments under 100 and 200 kPa (Figure 5). For stress imposed in "R1", tensions up to 130 kPa did not reflect in lower water demand throughout the cycle

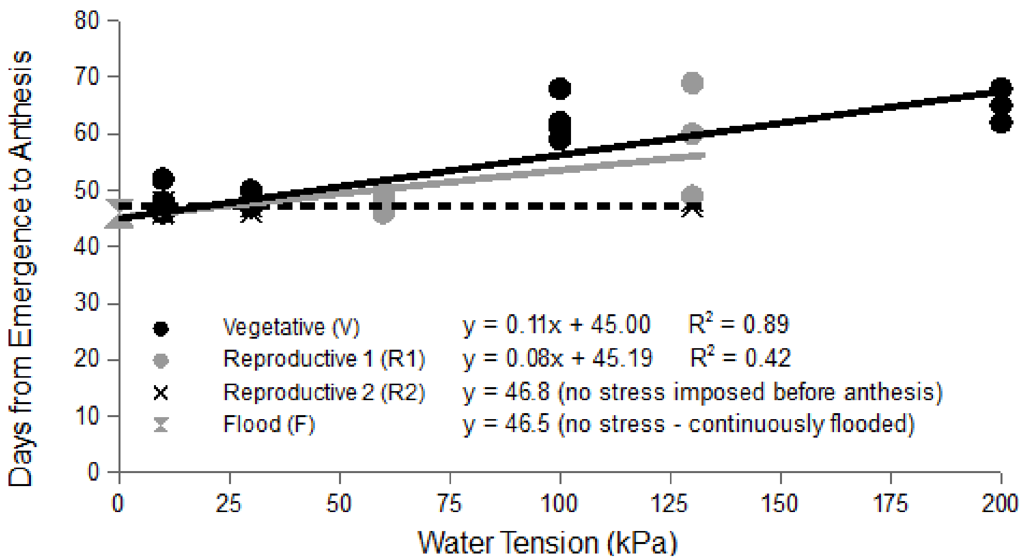

Figure 4. Days from rice emergence to anthesis for variety BRS-Querencia grown under increasing water stress levels applied at distinct developmental stages. V = from tillering start to panicle differentiation; R1 = from panicle differentiation to anthesis; R2 = from anthesis to ripening start. Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

compared to R1-10 kPa. However, injury to rice was observed for R1-60 and R1-130 kPa (Figures 3 and 4). For treatments applied in "R2", there was no significant reduction in water demand for any treatment compared to R2-10 kPa.

According to the data presented in Figures 3 and 4, water tension up to 30 kPa did not cause significant damage to rice growth. Considering this threshold level for water tension, and considering also that water stress at "R1" could result in reduced number of grains per panicle (Sarvestani et al., 2008), when aiming for maximum yield, it seems to be prudent to irrigate rice every time the soil water tension is between 10 and 30 kPa. The 30 kPa value seems to be the limit for avoiding water-related problems in rice growth. In fact, Silva et al. (2015) concluded that there was no damage to rice growth or grain yield when soil water tension was kept below 20 kPa; they reported problems with water tensions of 40 kPa. Our results support the idea that soil water tensions up to 25 or 30 kPa would not damage rice under sprinkler irrigation, but there was no significant water saving when treatments were irrigated back to saturation from 30 kPa (compared to 10 kPa, as seen in Figure 5B). As a practical application, a farmer, considering irrigation capacity, labor and hardware available, could choose to irrigate every time soil water tension reaches 25 - 30 kPa. Irrigating back to saturation at 10 kPa does not result in water savings compared to irrigation applied at 30 kPa, and could demand additional labor or equipment resources with higher flow rates to meet demand.

The resulting crop coefficients (Kc) for each treatment, estimated on a weekly basis, are shown in Figure 6, presented both in original form as well as a percentage of the K_C observed for the flooded treatment. In general terms, the higher values of Kc were observed for the flooded treatment, whose values often stayed between 3.0 and 3.3 (Figure 6). In order to compare Kc between treatments, differences of more than two standard deviations (2SD) were established as the threshold level for differentiation, according to Cumming et al. (2007) and Peternelli and Mello (2011).

Considering the above-determined criterion for differentiation, there was no significant difference in Kc between flooding and 10 or 30 kPa, when these treatments were imposed at the vegetative ("V") or at the reproductive 1 ("R1") stages (Figure 6). In these situations, the lower Kc for the higher two water tensions in each stage resulted in serious damage for rice morpho-physiology (Figure 3) and phenology (Figure 4). The lower values of Kc observed for 60 and 130 kPa applied to "R2", would probably result in little to no crop grain yield (Sarvestani et al., 2008).In general terms, the comparison between sprinkler-irrigated and flooded treatments showed that for the stress level of 10 kPa applied to "V", "R1" or "R2", the Kc for irrigated treatments averaged about 80% of that observed for the flooded check in the same week (Figure 6). The water tension of 30 kPa presented similar behavior to the observed for 10 kPa, but irrigating at 30 kPa could be an issue if labor is limited, so it is wise to irrigate rice back to saturation earlier. This reduction of 20% in Kc correlates to the 23% average reduction in water demand when the tension of 10 kPa was compared to flooding (Figure 3B). There is evidence that average water consumption by a farmer's flooded rice in Southern Brazil, estimated by SOSBAI

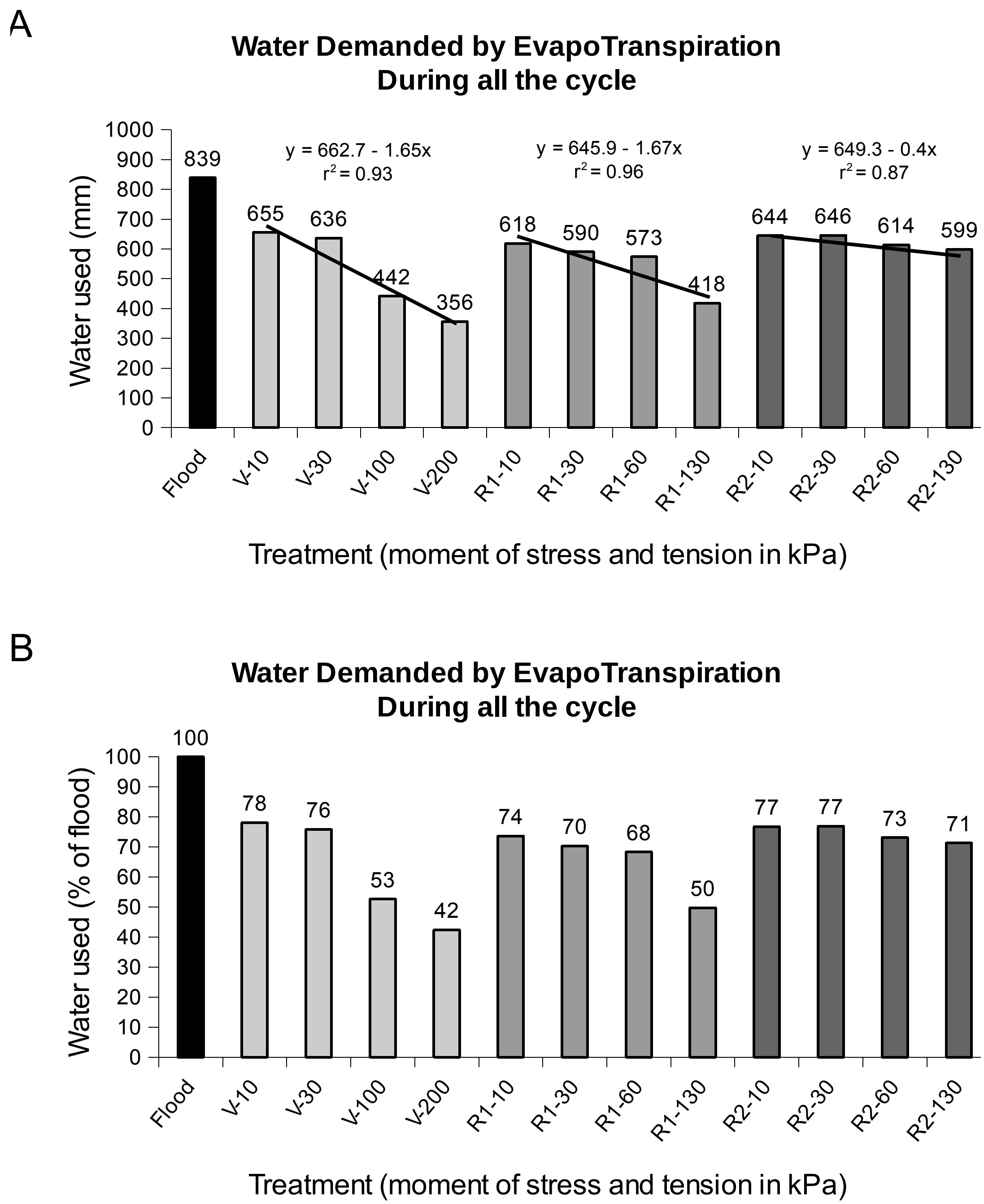

Figure 5. Water demanded by evapotranspiration in mm (A) and percent of the observed for the flooded check (B) for rice plants of the variety BRS-Querencia grown under increasing water stress levels applied at distinct developmental stages. V = vegetative stage (from tillering start to panicle differentiation); R1 = reproductive 1 (from panicle differentiation to anthesis); R2 = reproductive 2 (from anthesis to ripening start). Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

(2014) as being between 8,000 and 10,000 m^3 ha^{-1}, may be a little underestimated for real field conditions. There is need to measure real consumption, measuring pumping and evapotranspiration. Our results also supply evidence that the claimed 50% water savings by growing rice under sprinkler irrigation compared to continuous flooding (Parfitt et al., 2011) is feasible and may be achievable under field conditions. Further studies will aim to determine field-scale water losses by runoff and percolation in field trials, as a way to understand the nature of the additional 27% savings when rice is grown under sprinkler irrigation. This represents the difference

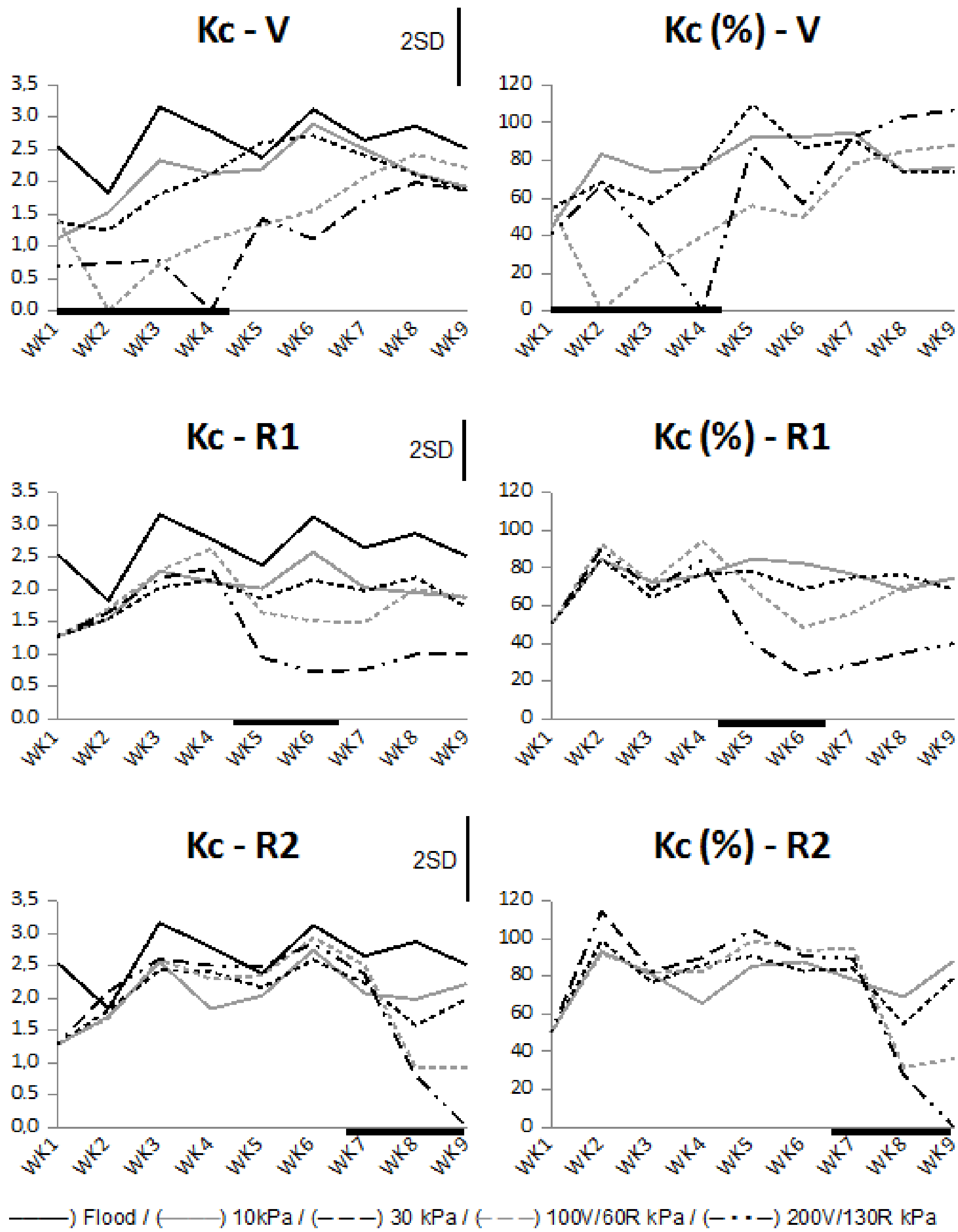

Figure 6. Weekly crop coefficients (Kc's) in absolute values (left) and percentage of the Kc observed for flooded treatment in the same period (right) for the greenhouse trial with the variety BRS-Querencia, estimated by dividing the amount of water added to each plot in the week by the ETo calculated for the same period. Thick line section (——) at the X-axis represents the period when the stress levels were applied to the group of treatments. V = vegetative stage (from tillering start to panicle differentiation); R1 = reproductive 1 (from panicle differentiation to anthesis); R2 = reproductive 2 (from anthesis to ripening start). Embrapa Clima Temperado, Pelotas-RS, Brazil, 2016.

between our results and those reported by Parfitt et al. (2011).

Conclusions

1. There is damage to rice plant growth and development in soil water tensions beyond 30 kPa from tillering start to anthesis. Main damage was observed as reduced rates of culm growth; leaf area tended to be maintained;
2. For the period between anthesis and ripening, no damage to rice growth was observed since rice plants had already naturally stopped growth. Serious damages for yields, however, are frequently reported in the

literature;
3. Water luxury consumption by rice plants grown under flooding seems to be about 23% of the total demand, compared to the other irrigated treatments;
4. When using sprinkler irrigation, rice should be irrigated back to saturation when soil water tension is between 10 and 30 kPa;
5. Overall, theoretical crop coefficients for rice under sprinkler irrigation are about 20% lower than that observed for the flooded check;

Conflict of Interests

The authors have not declared any conflict of interests.

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