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Irrigation strategies for upland rice cultivars in Brazil: Physiological responses and agronomic performance

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ABSTRACT

Irrigation strategies are essential for enhancing water productivity, thereby contributing to the sustainable water management in upland rice (*Oryza sativa* L.). This study aimed to quantify the effects of various irrigation strategies on the physiology, yield, and irrigation water productivity of three upland rice cultivars. Two shelter experiments (A and B) were conducted using two factors: irrigation managements and cultivars. In Experiment A, three irrigation levels were applied: 100 % (Control), 70 % and 40 % of the irrigation applied in the control. In Experiment B, irrigation was triggered at soil water potential thresholds of −20 and −40 kPa. The cultivars used in both experiments were BRS A501 CL, BRS Esmeralda, and BRS A502. In Experiment A, the Control treatment (100 %) demanded ~786 mm of water, which yielded 7.9 Mg ha^{-1}, corresponding to an irrigation water productivity of 0.88 kg m^{-3}. Irrigation levels of 70 % (579 mm) and 40 % (371 mm) caused yield reductions of 51–96 % and irrigation water productivity declines of 32–92 %. In Experiment B, the treatment of −20 kPa (683 mm) yielded 6.8 Mg ha^{-1} and 1.0 kg m^{-3} of irrigation water productivity. The irrigation threshold of −40 kPa (~590 mm applied) resulted in an average grain yield of 5.3 Mg ha^{-1} and irrigation water productivity of 0.89 kg m^{-3}. Overall, although drought-tolerant cultivars were used, water-saving treatments in Experiment A (70 and 40 %) were not suitable for upland rice. In contrast, the −40 kPa irrigation threshold in Experiment B reduced water use while maintaining irrigation water productivity, representing an effective strategy for water-limited environments. Future work should explore irrigation strategies based on Experiment B, targeting specific growth stages.

1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereals in the world, with over 27 % of total cereal consumption worldwide and a production of 709.9 million Mg (FAO, 2022). This cereal plays an important role in human nutrition, primarily across Asia, Latin America, and some African countries (Khan et al., 2021). Brazil is among the top ten global producers, with 11.5 million Mg produced and 1.1 million Mg (CONAB, 2021). In this country, cultivars were grouped for those adapted to fully flooded and upland conditions (Pinheiro et al., 2006). The flooded system dominates southern Brazil, accounting for 93 % of the country's total production, whereas upland rice, representing the remaining 7 %, is mainly grown in the central region (IBGE, 2022).

Over the last 40 years, the cropped area dedicated to upland rice in Brazil has decreased from 4.7 to 0.3 million ha (da Silva and Wander, 2023; Pinheiro et al., 2006). This reduction can be attributed to various factors, including water stress, which is a prevalent issue in this region (Heinemann et al., 2011; Ramirez-Villegas et al., 2018). The low productivity from 1975 to 2000, ranging from 0.6 to 2.6 Mg ha^{-1}, further supports this observation (You, 2012). However, although upland rice accounts for a small share of the total rice area in Brazil, it is essential for small-scale farmers (Heinemann et al., 2015).

During the 1990s, the Brazilian breeding program for upland rice primarily focused on selecting cultivars with high productivity, favoring regions that were not susceptible to climatic risks (Heinemann et al., 2019). Consequently, upland rice cultivars developed during this period

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displayed limited tolerance to water stress. However, after 2000, a new breeding program specifically targeted drought tolerance (Breseghello et al., 2021; Ramirez-Villegas et al., 2018). Recent research on these new cultivars has revealed consistent physiological and yield responses, particularly under moderate water stress at flowering and grain-filling stages (Quiloango-Chimarro et al., 2022).

Upland rice cultivation contributes to food security for agricultural and non-agricultural communities (Heinemann et al., 2019). This significance has grown significantly since 2024, as extreme climatic events, including severe flooding, have affected rice production in southern Brazil (Simoes-Sousa et al., 2025). New cropping systems have been introduced in central Brazil, integrating upland rice as a secondary crop after soybean cultivation (soybean-upland rice) under center pivot irrigation. Limited research exists on irrigation management in Brazilian upland rice systems, as the majority of studies focus on the advantages of only one irrigation management compared to rainfed conditions (Crusciol et al., 2013; Froes de Borja Reis et al., 2018; Stone et al., 1999). However, when upland rice is included in the soybean-upland rice sequence, cultivation occurs during the rainfed cessation period (Heinemann et al., 2021), requiring adequate water management strategies.

Effective irrigation strategies for upland rice (aerobic rice) are used to optimize yield and irrigation water productivity (Fukai and Mitchell, 2022; Mallareddy et al., 2023). For example, Kumar et al. (2017) examined irrigation at thresholds between −20 and −50 kPa across four cultivars, finding that thresholds of −30 and −40 kPa maximized grain yield and irrigation water productivity. Similarly, Mahajan et al. (2015) studied irrigation at −10 and −20 kPa in six cultivars, observing a 14 % increase in irrigation water productivity at −20 kPa. Additionally, irrigation levels during specific growth stages showed that grain yield could remain similar under water stress conditions during the vegetative or late grain-filling stages when compared with well-watered conditions (Alou et al., 2018; Vijayaraghavareddy et al., 2020). Therefore, testing some of these irrigation strategies is essential to ensure sustainable production in the new cropping systems that integrate upland rice in central Brazil.

As mentioned above, strategies to conserve water under aerobic conditions include irrigation at different soil potential thresholds and irrigation levels at various growth stages. However, rice is more susceptible to water stress than other cereals (Kato and Katsura, 2014). In addition, aerobic rice is not typically exposed to prolonged stress periods, and its physiological and morphological responses have been poorly studied (Luo et al., 2019). For example, it is unclear whether stomatal conductance is maintained during low soil water potential periods, which could contribute to higher irrigation water productivity and biomass production (Fukai and Mitchell, 2022). Additionally, rice cultivars may respond differently to water stress. For instance, tolerant cultivars exhibit a more extensive root system (Lanna et al., 2020), enhanced intrinsic water use efficiency (Quiloango-Chimarro et al., 2022), and the ability to regulate stomatal conductance to minimize water loss (Vijayaraghavareddy et al., 2020). Therefore, when selecting appropriate water-saving irrigation strategies, it is important to consider the physiology, yield, and irrigation water productivity of Brazilian upland rice cultivars, particularly in light of their drought tolerance.

This study compared the responses of three upland rice cultivars, developed after 2000, under two irrigation strategies: various irrigation levels (Experiment A) and irrigation at soil water potential thresholds (Experiment B). Given the limited information regarding irrigation management of upland rice in Brazil, the assessment of water-saving irrigation strategies is of critical importance. Therefore, we aimed to quantify the effects of these strategies on the physiology, yield, and irrigation water productivity of upland rice cultivars.

2. Materials and methods

2.1. Characterization of the experimental area, planting, and crop management

Two rain-out shelter experiments were conducted at the Department of Biosystems Engineering, University of São Paulo (USP/ESALQ), located in Piracicaba, São Paulo, Brazil (22°46'39" S, 47°17'45" W). The experiments were conducted from September 2020 to January 2021 and from October 2023 to February 2024. The rain-out shelter structures featured a ceiling height of 5.2 m, with a transparent diffuser film as the cover material. The shelter sides were enclosed with a black mesh that intercepted 30 % of the incident radiation. The experimental area consisted of 396 concrete containers, each with a volume of 0.33 m^3 (1.0 m length, 0.4 m width, and 0.8 m depth). These containers were filled with sandy-loam soil classified as Typic Haplustox (Oxisol) in the USDA Soil Taxonomy (USDA, 1999) and as Latossolo Vermelho-Amarelo in the Brazilian Soil Classification System (Santos et al., 2018). This soil type is typical of the Cerrado biome (central Brazil), where upland rice is widely cultivated, making these conditions representative of the major rainfed rice-growing areas in the country.

Daily solar radiation, minimum and maximum air temperatures, relative humidity, and wind speed were measured with an automatic weather station positioned inside the experimental area at a height of 2 m above ground. These parameters were recorded at 10-minute intervals by a CR1000 data logger (Campbell Scientific, Logan, Utah, USA), ensuring precise monitoring of microclimatic conditions within the shelter. Reference evapotranspiration (ET_o) was calculated using the Penman-Monteith equation (Allen et al., 1998).

For this study, seeds from three upland rice cultivars, as described in Table 1, were sown on September 1, 2020 (growing season 1) and on October 23, 2023 (growing season 2). The row spacing and seeding rate were set at 0.40 m and 180 seeds per meter, respectively. Thinning of the plants was conducted 13 days after the emergency to achieve a final density of 60 plants per meter of row length (60 plants per plot). Before fertilizer application, the chemical properties of the soil layer 0–0.40 m depth were as follows: pH of 5.8 (H_2O, 1:2.5), soil organic carbon content of 8.8 g kg^{-1} ($K_2Cr_2O_7$ volumetric and external heating method), exchangeable potassium of 1.3 mg kg^{-1} (extracted with Mehlich), and available phosphorus of 93 mg kg^{-1} (anion-exchange resin method). Based on this soil analysis, nutrient management was performed according to van Raij et al., (1997) recommendations. Mineral fertilizers were applied at rates of 80 kg N ha^{-1} , 25 kg P ha^{-1} , and 135 kg K ha^{-1} . Phosphate fertilizer was applied entirely in the sowing furrow, while nitrogen and potassium applications were split into three top-dressings at sowing, maximum tillering, and 50 % heading. Pesticides were applied as needed, and weeds were managed manually throughout the growing season.

2.2. Experimental design and treatments

A randomized split-plot design with two factors (irrigation management and upland rice cultivars) was implemented in two separate experiments, denominated A and B, each with four replications. Experiment A included three irrigation levels: 100 % irrigation (to keep soil moisture at appropriate levels), 70 % irrigation, and 40 % irrigation relative to the 100 % treatment. The 100 % irrigation level was selected to prevent water stress, based on previous studies showing that rice maintains yield when soil matric potential is kept between −20 and −30 kPa (Froes de Borja Reis et al., 2018). The 70 and 40 % irrigation treatments were selected considering the drought tolerance of the new cultivars and the potential for a second crop, where reduced precipitation limits the water available for irrigation in Central Brazil (Antolin et al., 2025). These treatments were applied across three upland rice cultivars (BRS A501 CL, BRS Esmeralda, and BRS A502), with the exception of BRS A502, which was not included in the 2020–2021

Table 1
Description of upland rice cultivars used in this experiment.

Cultivar	Drought tolerance	Yield potential (Mg ha^{-1})	Year of release	Description
BRS A501 CL	Susceptible	8.2	2018	This cultivar is recommended for no-till systems and for areas with glyphosate-resistant weed problems (Rangel et al., 2020).
BRS Esmeralda	Intermediate	9.2	2012	Cultivar with wide adaptation and stability. It is moderately resistant to panicle blight, brown spot, and grain spot (Castro et al., 2014).
BRS A502	Intermediate	9.6	2020	This cultivar is ideal for irrigated areas and can be effectively integrated into crop rotation and succession practices (Furtini et al., 2022).

growing season. Experiment B evaluated two irrigation managements defined by soil water tension thresholds: irrigation triggered at −20 and −40 kPa in the layer 0–0.20 m. Additionally, Experiment B incorporated destructive sampling plots to measure growth traits at key phenological stages, including panicle initiation, heading, and anthesis.

During the first 20 days, all plants were irrigated based on daily evapotranspiration ($K_c = 0.40$) (Arf et al., 2003). Subsequently, the upland rice cultivars were subjected to the irrigation management detailed hereafter. Irrigation water was provided through a drip irrigation system. A drip line of 1 m length was installed in each plot with six emitters, each with a flow rate of 0.6 L h^{-1} and spaced at 0.15 m, resulting in a total flow rate of 3.6 L h^{-1} per container (plot). All plots were controlled individually through micro-registers installed on a control panel.

2.3. Irrigation management

For Experiment A, tensiometers were installed in the plots corresponding to the 100 % irrigation treatment for each cultivar, totaling 12 batteries. In each plot, three tensiometers were placed at depths of 0.10, 0.25, and 0.35 m, providing soil matric potential measurements for three soil layers: 0–0.20 m, 0.20–0.30 m, and 0.30–0.40 m (Supplementary Material, Fig. S1). Measurements were taken daily using a portable digital punction tensimeter. Irrigation for the 100 % irrigation level was calculated by replenishing the soil moisture in the top two layers (0–0.30 m) to field capacity (Table 2), with the third layer (0.30–0.40 m) serving as a drainage control. Irrigation was applied whenever the soil water potential in the top layer (0–0.20 m) reached approximately −30 kPa (Supplementary Material, Fig. S2). For the 70 and 40 % treatments, water depths were adjusted to represent fractions of the irrigation volume applied to the 100 % treatment for each cultivar.

For Experiment B, tensiometers were installed in all plots maintained until harvest, totaling 24 batteries. Each battery included three tensiometers placed at depths of 0.10, 0.30, and 0.50 m, providing soil matric potential measurements for three soil layers: 0–0.20 m, 0.20–0.40 m, and 0.40–0.60 m (Supplementary Material, Fig. S1). Soil matric potential was monitored daily and irrigation was performed to replenish the soil water content to field capacity (Table 2) for the top two layers (0–0.40 m). As mentioned above, irrigation was carried out following two criteria: a) when the average soil matric potential at 0.20 m depth reached approximately −20 kPa, and b) when the average soil matric potential at 0.20 m depth reached approximately −40 kPa.

The current soil volumetric water content (θ, cm^3 cm^{-3}) was estimated from the measured soil water potential values using the van Genuchten (1980) model (Eq. 1):

$$\theta\,(\Psi_m) = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + (\alpha \times \Psi_m)^n)^m} \tag{1}$$

where $\theta\,(\psi_m)$ is the current soil volumetric water content (cm^3 cm^{-3}), θ_r is the soil residual volumetric water content (cm^3 cm^{-3}), θ_s is the volumetric water content of the saturated soil (cm^3 cm^{-3}), m and n are the regression parameters of equation (dimensionless), α is the parameter with dimension equal to the inverse of the tension (cm^{-1}) and ψ_m is the function of the matric potential (kPa). The fitting parameters of the van Genuchten equation (Table 2) were obtained using the RETC computer program (van Genuchten et al., 1991). For this purpose, undisturbed soil samples were collected using 50 cm^3 cylindrical cores at three depths, 0.10, 0.30, and 0.50 m, corresponding to the 0–0.20 m, 0.20–0.40 m, and 0.40–0.60 m soil layers. Four plots were randomly sampled (one per block), resulting in a total of 12 samples collected. In the laboratory, soil water contents for these layers were determined using tension tables at −1, −2, −4, and −6 kPa, and pressure plates with membranes for matric potentials of −10, −30, −50, −100, −500, −1000, and −1500 kPa (Dane, 2002).

Using the current soil moisture (θ) estimated with Eq. (1) and the hydraulic properties of each soil layer (Table 2), the irrigation depths required to restore soil moisture to field capacity (θ_{fc}) were calculated for each soil layer (Eq. 2):

$$I = \sum_i (\theta_{fc,i} - \theta_i) Z_i \tag{2}$$

where I is the depth in mm needed to raise soil moisture to field capacity, $\theta_{fc,i}$ is the soil volumetric water content at field capacity (−4.85 kPa matric potential) for a layer i in cm^3 cm^{-3}, θ_i is the soil volumetric water content observed before irrigation for layer i in cm^3 cm^{-3}, and Z_i is the thickness of layer i in mm. Eq. 2 was applied for each cultivar, considering the specific irrigation management criteria described above for Experiments A and B.

2.4. Physiological measurements

Leaf gas exchange rates, including photosynthetic rate (μmol m^{-2} s^{-1}), stomatal conductance (mol m^{-2} s^{-1}), and transpiration rate (mmol m^{-2} s^{-1}), were determined on panicle initiation, anthesis, and grain filling stages. In the first season (2020–2021), measurements were conducted on October 20, November 18, and December 17, 2020. In the second season (2023–2024), measurements were taken on December 27, 2023, January 14, 2024, and January 30, 2024. The measurement was

Table 2
Empiric parameters (α, m e n), soil residual and saturation water content (θ_r, θ_s) of the van Genuchten model (1980), moisture at field capacity (θfc), moisture at the wilting point (θwp), and available water capacity (AWC).

Layers (m)	Θ_s (cm^3 cm^{-3})	Θ_r (cm^3 cm^{-3})	α (cm^{-1})	m	n	θfc (cm^3 cm^{-3})	θwp (cm^3 cm^{-3})	AWC (mm)
0–0.20	0.421	0.098	1.346	0.179	2.717	0.227	0.106	24.2
0.20–0.40	0.412	0.085	1.570	0.164	2.503	0.226	0.098	25.6
0.40–0.60	0.374	0.122	1.129	0.275	1.562	0.241	0.132	21.8

performed on the last fully developed leaves of rice between 9:00 and 11:00 am with a portable photosynthetic system LiCor-6400 XT (LiCOR-Inc., Nebraska, USA), at 1400 μmol m^{-2} s^{-1} photon flux density and 400 ppm CO_2 concentration in the leaf chamber. In addition, the chlorophyll index (unitless) was measured using a handheld chlorophyll meter (Falker, Porto Alegre, Brazil) that uses photodiode emitters at three wavelengths: two emit within the red band, close to the peaks of each chlorophyll type (λ = 635 and 660 nm), and another in the near-infrared (λ = 880 nm). The chlorophyll index for each plot was determined by averaging five measurements taken from the youngest fully expanded leaves on the same dates as the gas exchange assessments.

Canopy temperature of upland rice was measured using a FLIR T640 thermal camera model Duo_{TM} Pro R (Teledyne FLIR, Wilsonville, USA) with emissivity (ε) set at 0.94. The thermal images were obtained at a distance of 2 m from the top of the canopy at around 11:00–12:00 a.m. on the same dates as gas exchange evaluations. The average canopy temperature of each plot was obtained using FLIR Thermal Studio® with the tool line measurement (Supplementary Material, Fig. S3). Subsequently, the crop water stress index was calculated as follows (Eq. 3):

$$\text{Crop water stress index} = \frac{(T_c - T_{air}) - T_{wet}}{T_{dry} - T_{wet}} \quad (3)$$

where T_{air} is air temperature (°C), T_c is canopy temperature (°C), T_{wet} is the non-water-stressed baseline (temperature of leaves with open stomata), and T_{dry} is the water-stressed baseline (temperature of leaves with closed stomata). Baselines were calculated following the methodology proposed by Costa et al. (2020), where T_{wet} and T_{dry} corresponded to the minimum and maximum difference observed between T_c and T_{air}, respectively.

2.5. Crop growth and yield traits

For experiment B, growth parameters such as leaf area index, shoot and root biomass, and root dry mass were assessed at panicle initiation, heading, anthesis, and maturity, except for heading and panicle initiation for root dry mass. Plants were sampled from the central part of the row (0.5 m length), totaling 30 plants (0.2 m^2) per plot. First, leaf area was determined with a leaf area meter LI-3000 C (LiCOR-Inc, Lincoln, Nebraska, USA). The leaf area index was calculated by dividing the measured leaf area by the sampling area. After that, all the shoot biomass was dried at 60 °C in an oven with forced air circulation for 72 h to determine shoot dry mass.

For root sampling, a soil cube (0.20 m length, 0.20 m width, and 0.30 m depth) in the middle of the sowing line was dug up using a sampling core. According to Xu et al. (2018), this cube contains approximately 95 % of the total rice root biomass. Each soil-root column was placed into a 0.25 mm sieve and slowly rinsed with running water until the root system was completely separated from the soil. Subsequently, roots were dried at 60 °C in an oven with forced air circulation for 72 h to determine root dry mass.

At physiological maturity, plants from the central part of the row (0.5 m) were harvested and separated into vegetative and reproductive components. Panicle number per m^2 and spikelets number per panicle were recorded. Then, each panicle was hand-threshed, and the unfilled spikelets were separated from the filled spikelets with a blower to determine spikelet fertility. The spikelet fertility was the whole grains to the total number of spikelets multiplied by 100. Finally, 1000-grain weight and yield were determined (adjusted to 14 % moisture). In addition, irrigation water productivity was calculated as the ratio between the marketable yield produced by the crop along the growing season and the irrigation water applied over the same period (Fernández et al., 2020), as follows (Eq. 4):

$$\text{Irrigation water productivity} = \frac{\text{Yield}}{\text{Irrigation water applied} \times 10} \quad (4)$$

where irrigation water productivity is expressed in kg m^{-3}, yield in kg ha^{-1}, irrigation water applied in mm, and 10 is the conversion factor between units.

2.6. Statistical analysis

All the statistical analyses were performed with R Studio (R Project for Statistical Computing, version 4.1.2). Each growing season and each phenological stage were analyzed separately (ANOVA) using the package ‘agricolae’ (de Mendiburu and Yaseen, 2020). Shapiro-Wilk and Levene tests were used to estimate normality and homogeneity of variance. The effects of irrigation management and cultivar were evaluated using the F-test at the 0.05 and 0.01 probability levels. The means of variables with a significant F-test value were compared using the Tukey-Kramer test, which uses the honest significant difference to indicate if a significant difference is present.

3. Results

3.1. Weather conditions and irrigation water applied

During growing season 1, the minimum daily temperature ranged from 12.2 to 21.5 °C, with an average of 18.1 °C for the period. The maximum temperature varied between 23.6 and 44.2 °C, with an average of 35.5 °C throughout the season (Fig. 1**A**). During growing season 2, the minimum daily temperature ranged from 14.1 to 24.2 °C, with an average of 20.3 °C for the period. The maximum temperature varied between 23.3 and 43.8 °C, with an average of 36.5 °C throughout the season (Fig. 1**C**). Mean solar radiation in the first growing season was 10.5 MJ m^{-2} day^{-1} (Fig. 1**A**), while in season 2 was 13.4 MJ m^{-2} day^{-1} (Fig. 1**C**). Average reference evapotranspiration was 3.9 mm day^{-1} in growing season 1 (Fig. 1**B**), while in growing season 2 was 4.8 mm day^{-1} (Fig. 1**D**).

In experiment A, the total amount of irrigation water applied in the treatments varied between 389 and 876 mm in growing season 1 and between 351 and 748 mm in growing season 2 (Table 3). On average, the three cultivars received 856, 627, and 397 mm of irrigation water in the 100 %, 70 %, and 40 % treatments during season 1, and 739, 546, and 354 mm in season 2, respectively. Regarding cultivars, BRS A501 CL received the highest amount of irrigation water applied at both growing seasons. The number of irrigation events averaged 60 in growing season 1 and 52 in growing season 2.

In experiment B, the total amount of irrigation depth applied varied between 584 and 736 mm (Table 3). Under the treatment of −20 kPa, the irrigation depth applied averaged 683 mm, whereas under −40 kPa, it averaged 590 mm. The cultivars BRS A501 CL, BRS Esmeralda, and BRS A502 reduced by 8, 11, and 21 % when compared to both irrigation treatments. The number of irrigation events averaged 43 and 35 for treatments at −20 and −40 kPa, respectively. It is worth mentioning that among cultivars, BRS A502 showed higher water consumption under −20 kPa and lower water consumption under −40 kPa.

3.2. Experiment A: irrigation levels

3.2.1. Effect of irrigation treatments and cultivars on physiological traits

During the panicle initiation stage, in the two growing seasons, photosynthetic rate showed differences for irrigation management, following a trend 100 % > 70 % > 40 %, which was more evident in the season 2023–2024 (Figs. 2**A**, 2**D**; Table S1). Only in the second growing season, significant differences for cultivar were observed, being higher in BRS A502 and BRS Esmeralda than in BRS A501 CL. Stomatal conductance exhibited significant differences for the individual effects of management and cultivar in the two growing seasons (Figs. 2**B**, 2**E**; Table S1). The 40 % irrigation treatment showed the highest reduction in stomatal conductance, with an average of 53 % compared to

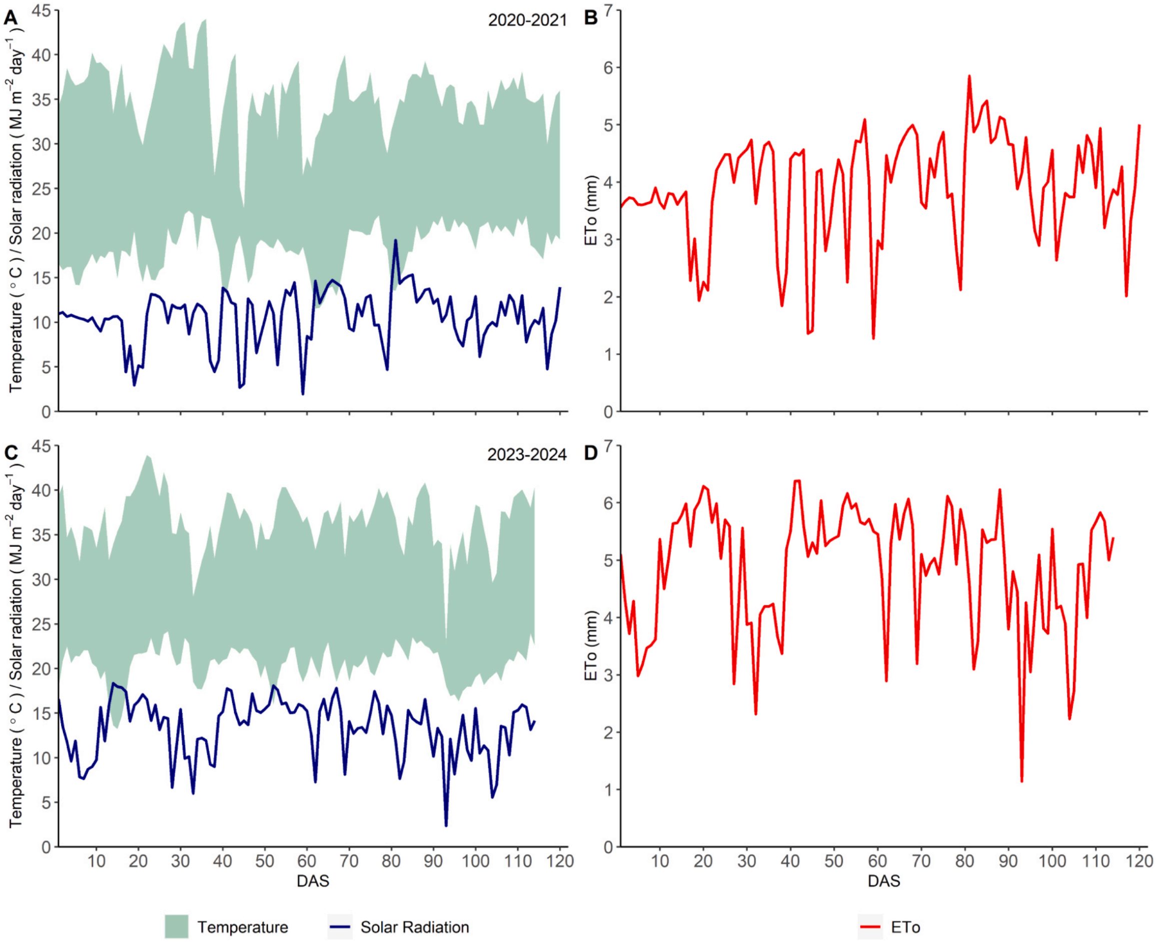

Fig. 1. Range of maximum and minimum air temperature (green), solar radiation (blue), and reference evapotranspiration (red) in 2020–2021 (A, B) and 2023–2024 (C and D).

treatment 100 %. Related to cultivars, BRS Esmeralda showed the highest values at panicle initiation with an average value of 0.4 mol m^{-2} s^{-1}. Transpiration was significant for cultivar in the first growing season (Fig. 2**C;** Table S1), following a trend BRS Esmeralda>BRS A502 >BRS A501 CL. For the second growing season, transpiration was significant for the interaction management × cultivar (Fig. 2**F;** Table S1). Notably, in this season, under 100 % irrigation, transpiration was similar for all cultivars, whereas under 70 % and 40 %, BRS A501 CL showed the lowest values. At the anthesis stage, in both growing seasons, photosynthetic rate, transpiration, and stomatal conductance showed differences only in response to irrigation (Fig. 2), following the trend 100 % > 70 % > 40 %. However, in the 2020 –2021 season, the 100 % irrigation treatment did not show differences with the 70 % treatment. The 40 % irrigation treatment, compared to the 100 % treatment, reduced photosynthetic rate, stomatal conductance, and transpiration by an average of 55, 75, and 66 %, respectively. At the grain-filling stage, in both growing seasons, photosynthetic rate, transpiration, and stomatal conductance differed only in response to irrigation (Fig. 2**;** Table S1), with the 40 % treatment differing from the 100 % treatment. Compared to the 100 % treatment, the 40 % treatment resulted in reductions of 27, 63, and 65 % in photosynthetic rate, stomatal conductance, and transpiration, respectively. Notably, the reductions in photosynthetic rate and stomatal conductance were less pronounced in this stage than at anthesis, showing that the anthesis stage is more sensitive to water stress than the grain-filling stage.

Irrigation influenced the crop water stress index at the three stages (panicle initiation, anthesis, and grain-filling) during both growing seasons (Table 4). Additionally, in the 2023–2024 season, a significant interaction effect of management × cultivar was observed at the anthesis and grain-filling stages. Similar trends were observed in both growing seasons, with the 100 % irrigation treatment achieving the lowest crop water stress index values, ranging from 0.15 to 0.32, and showing no significant differences from the 70 % treatment at the three evaluated stages. In contrast, the 40 % treatment resulted in the highest crop water stress index values, ranging from 0.52 to 0.73. In the 2023–2024 season, at anthesis, BRS A501 CL and BRS Esmeralda under the 70 % treatment exhibited crop water stress index values comparable to those of the 100 % treatment across all cultivars. During the grain-filling stage, the cultivar BRS Esmeralda exhibited the highest CWSI value (0.74) under the 40 % irrigation level, compared with BRS A501 CL and BRS A502.

The cultivar significantly influenced the chlorophyll index across both growing seasons (Table 4). Consistently, BRS Esmeralda exhibited the highest chlorophyll index values among the cultivars in all the stages (panicle initiation, anthesis, and grain-filling). Irrigation also played a key role, particularly at the anthesis stage. In both seasons, a 40 % irrigation level at this stage decreased the chlorophyll index by an average of 6.2 % when compared to the 100 % treatment.

3.2.2. Effect of irrigation treatments and cultivars on yield and irrigation water productivity

Irrigation significantly influenced shoot dry mass, grain yield, and its components across both growing seasons (Table 5). In 2020–2021, the management × cultivar interaction was significant for shoot dry mass, while in 2023–2024, it was significant for grain yield. During the 2020–2021 growing season, BRS A501CL recorded the greatest shoot

Table 3
Irrigation water applied and the number of irrigation events of upland rice cultivars subjected to various irrigation levels and different soil water potential thresholds.

Experiment	Treatment	Cultivar	Irrigation (mm)	Number of irrigation events
2020–2021				
Experiment A	100 %	BRS A501 CL	876	60
	100 %	BRS ESMERALDA	836	59
	70 %	BRS A501 CL	641	60
	70 %	BRS ESMERALDA	613	59
	40 %	BRS A501 CL	405	60
	40 %	BRS ESMERALDA	389	59
2023–2024				
Experiment A	100 %	BRS A501 CL	748	53
	100 %	BRS ESMERALDA	736	52
	100 %	BRS A502	733	52
	70 %	BRS A501 CL	553	53
	70 %	BRS ESMERALDA	545	52
	70 %	BRS A502	542	52
	40 %	BRS A501 CL	357	53
	40 %	BRS ESMERALDA	352	52
	40 %	BRS A502	351	52
Experiment B	−20 kPa	BRS A501 CL	635	42
	−20 kPa	BRS ESMERALDA	678	43
	−20 kPa	BRS A502	736	44
	−40 kPa	BRS A501 CL	587	35
	−40 kPa	BRS ESMERALDA	601	35
	−40 kPa	BRS A502	584	35

dry mass under 100 % and 70 % irrigation levels, whereas BRS Esmeralda exhibited 13 and 17 % lower values, respectively. Overall, the greatest variations in shoot biomass were observed under the 40 % treatment, with a 60 % reduction compared to the 100 % treatment.

Considering both growing seasons, reducing irrigation from 100 % to 70 % led to an average yield reduction of 51 %, while a reduction to 40 % resulted in near-total yield failure (96 %). In 2023–2024, under full irrigation (100 %), the grain yield achieved by BRS A501 CL and BRS A502 outperformed BRS Esmeralda. In contrast, under 70 and 40 % irrigation levels, the three cultivars achieved similar grain yield values.

Yield components were the most impacted by the 40 % irrigation treatment in both seasons (Table 5). Under this condition, panicles per m^2, spikelets per panicle, spikelet fertility, and 1000-grain weight decreased by an average of 39, 59, 70, and 27 %, respectively, relative to the 100 % irrigation level. Additionally, among the yield components, spikelet fertility was the most affected by the 70 % irrigation treatment, with an average reduction of 23 %. Regarding the effect of cultivar, BRS A501 CL and BRS A502 consistently outperformed BRS Esmeralda across both seasons in panicles per m^2, with increases of 33 and 42 %, respectively.

Irrigation levels influenced irrigation water productivity in both growing seasons (Fig. 3). In addition, management × cultivar interaction was significant in the growing season 2023–2024 (Fig. 3**B**). Overall, irrigation water productivity followed the trend 100 % > 70 % > 40 %, with reductions of 32 and 92 % under the 70 and 40 % irrigation treatments, respectively, compared to 100 % treatment. In the 2020–2021 season, no significant differences were observed among cultivars (Fig. 3**A**). However, in 2023–2024, under the 70 % irrigation treatment, BRS A501 CL showed a 40 % decrease in irrigation water productivity compared to BRS Esmeralda and BRS A502.

3.3. Experiment B: Irrigation at different thresholds

3.3.1. Soil water potential dynamics

The soil matric potential at the 0–0.20 m depth averaged −11.8 kPa under the −20 kPa treatment and −18.5 kPa under the −40 kPa treatment (Fig. 4). The minimum values recorded for the −20 and −40 kPa treatments were −28.9 and −47.4 kPa, respectively. At the 0.20–0.40 m soil layer, all cultivars maintained similar average matric potential values to those observed at 0–0.20 m, regardless of the irrigation threshold. For the 0.40–0.60 m soil layer, under the −20 kPa treatment, BRS A501 CL exhibited the lowest matric potential (−69 kPa), particularly between 64 and 95 days after sowing (DAS), compared to BRS Esmeralda and BRS A502, which averaged −49.3 kPa. Under the −40 kPa treatment, BRS Esmeralda recorded the lowest matric potential (−72.5 kPa) compared to BRS A501 CL and BRS A502, which averaged −54.2 kPa.

3.3.2. Effect of irrigation treatments and cultivars on physiological traits

At the panicle initiation stage, photosynthetic rate, transpiration, and stomatal conductance varied significantly in response to irrigation (Fig. 5; Table S2). The −40 kPa treatment resulted in the lowest values for all three parameters, with reductions of 18, 45, and 30 %, respectively. At the anthesis stage, photosynthetic rate, transpiration, and stomatal conductance were influenced by both irrigation and cultivar, and a significant interaction between management × cultivar for stomatal conductance. The negative effects of −40 kPa treatment were more pronounced at anthesis than at the panicle initiation stage (Fig. 5; Table S2), with reductions of 74, 93, and 82 % for photosynthetic rate, transpiration, and stomatal conductance, respectively. Among cultivars, BRS A502 exhibited the highest photosynthetic rate and transpiration values, followed by BRS Esmeralda and BRS A501 CL. Additionally, under the −20 kPa treatment, BRS A502 recorded the highest stomatal conductance value (0.75 mol m^{-2} s^{-1}), whereas BRS A501 CL had the lowest (0.48 mol m^{-2} s^{-1}). At the grain-filling stage, photosynthetic rate, transpiration, and stomatal conductance were significantly affected by both management and cultivar (Fig. 5; Table S2). The −40 kPa treatment led to the lowest values for all three parameters, with reductions of 32, 51, and 33 %, respectively. Notably, at this stage, BRS Esmeralda exhibited the highest values for photosynthetic rate (18.74 μmol m^{-2} s^{-1}), stomatal conductance (0.52 mol m^{-2} s^{-1}), and transpiration (7.79 mmol m^{-2} s^{-1}), followed by BRS A502 and BRS A501 CL.

Irrigation influenced the crop water stress index across all three growth stages (panicle initiation, anthesis, and grain-filling), while cultivar effects were observed specifically at the panicle initiation stage (Table 6). In addition, the interaction between irrigation and cultivar was significant at the grain-filling stage. Under the −20 kPa treatment, the crop water stress index values ranged from 0.10 to 0.18. At the panicle initiation stage, BRS A501 CL exhibited a lower crop water stress index value compared to BRS A502 and BRS Esmeralda. Notably, under the −40 kPa treatment, cultivars BRS A501 CL and BRS A502 exhibited the highest crop water stress index values during the grain-filling stage (average 0.37), compared with BRS Esmeralda. Regarding the chlorophyll index, only the cultivar had a significant effect at panicle initiation and grain-filling (Table 6). At panicle initiation and grain-filling, BRS Esmeralda and BRS A502 outperformed BRS A501 CL by ~11 %.

3.3.3. Effect of irrigation treatments and cultivars on yield and irrigation water productivity

Irrigation influenced shoot dry mass at both anthesis and maturity, while cultivar effects were observed at anthesis (Table 7). The −40 kPa treatment resulted in reductions of 9 and 14 % in shoot dry mass at anthesis and maturity, respectively, compared to the −20 kPa treatment. At anthesis, BRS A502 exhibited superior performance, producing 14 % higher shoot dry mass than BRS Esmeralda. Leaf area index was significantly influenced by irrigation at all growth stages except at maturity (Table 7). The −40 kPa treatment led to reductions in leaf area index,

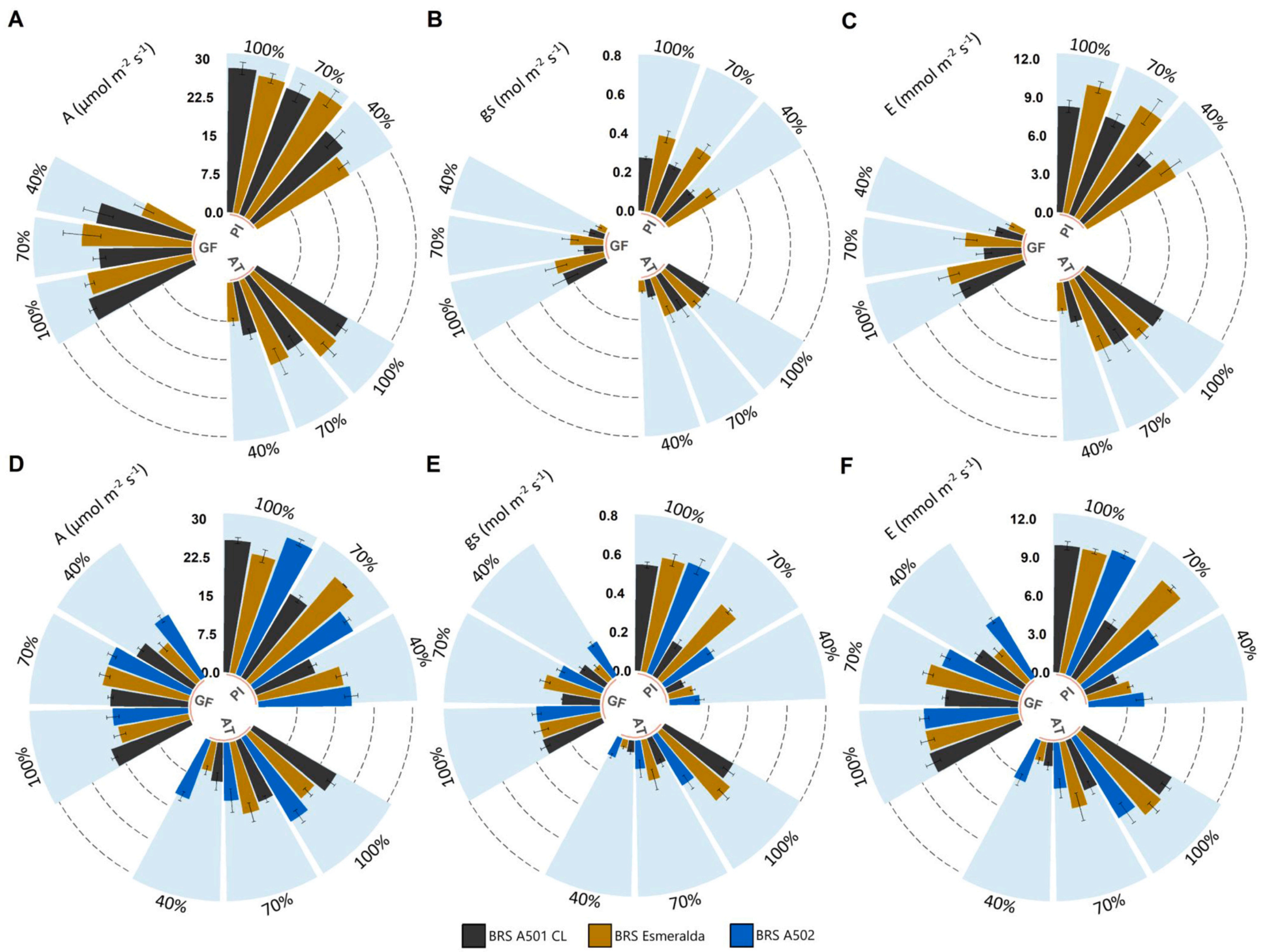

Fig. 2. Average values of photosynthesis, stomatal conductance, and transpiration of three upland rice cultivars subjected to irrigation levels (100, 70, and 40 %) in 2020–2021 (A, B, C) and 2023–2024 (D, E, F). Photosynthesis (A); stomatal conductance (gs); transpiration (E). In the center of each graph: panicle initiation (PI); anthesis (AT); grain-filling (GF).

decreasing it by 50, 17, and 22 % at panicle initiation, heading, and anthesis, respectively, compared to the −20 kPa treatment. Additionally, BRS A502 exhibited a higher leaf area index than BRS Esmeralda at anthesis. Root dry mass was significantly influenced by cultivar at panicle initiation and by both irrigation treatment and cultivar at maturity (Table 7). BRS A502 outperformed BRS A501 CL, exhibiting 33 and 52 % greater root mass at panicle initiation and maturity, respectively. At maturity, the −40 kPa treatment resulted in a 24 % reduction in root mass compared to the −20 kPa treatment.

The grain yield and 1000-grain weight were influenced by irrigation, whereas cultivar affected both yield and yield components (Table 8). Under −40 kPa, grain yield and 1000-grain weight decreased by 22 and 3 %, respectively. Yield components differed among upland rice cultivars. BRS A502 demonstrated superior performance in panicles per m^2 and spikelet fertility, while BRS A501 CL excelled in spikelet fertility and 1000-grain weight. Conversely, BRS Esmeralda exhibited the highest number of spikelets per panicle. These findings suggest that spikelet fertility and panicle density were determinants in maximizing grain yield, as observed in BRS A501 CL and BRS A502.

Irrigation water productivity was influenced only by cultivar, following a trend of BRS A501 CL > BRS A502 > BRS Esmeralda, with values ranging from 1.03 kg m^{-3} in BRS A501 CL to 0.85 kg m^{-3} in BRS Esmeralda (Fig. 6). Notably, there were no differences between the irrigation treatments −20 and −40 kPa.

4. Discussion

To our knowledge, this is among the first studies of Brazilian upland rice cultivars subjected to different irrigation treatments, as previous research only analyzed one irrigation threshold (Crusciol et al., 2013; Stone et al., 1999) and deficit irrigation at specific growth stages (Guimarães et al., 2016; Lanna et al., 2020; Quiloango-Chimarro et al., 2022). Given the potential of upland rice to be integrated into crop rotations under low rainfall, water-saving irrigation strategies are essential. Two complementary approaches were employed in this study to assess the physiological and morphological responses of upland rice cultivars. This enables a more comprehensive analysis for the future design of irrigation management strategies.

4.1. Water-saving irrigation strategies impact physiological responses depending on the phenological stage

Both experiments demonstrate that under 70 and 40 % (Experiment A) and −40 kPa (Experiment B), the photosynthetic rate, transpiration, and stomatal conductance are significantly reduced. In crops such as soybean (França et al., 2024), pearl millet (de Almeida et al., 2022), and common beans (Calvache et al., 1997), irrigation strategies have been tested during the entire growing season. However, physiological responses in rice have been studied when deficit irrigation was applied at

Table 4
Average values of crop water stress index and chlorophyll index of three upland rice cultivars subjected to various irrigation levels (100, 70, and 40 %).

Treatment	Crop water stress index			Chlorophyll index		
	PI	AT	GF	PI	AT	GF
2020–2021						
Irrigation (M)						
100 %	0.15 b	0.32 b	0.31 b	42.16 a	48.82 a	49.53 a
70 %	0.33 b	0.48 b	0.52 ab	42.94 a	47.97 a	46.79 b
40 %	0.67 a	0.73 a	0.67 a	43.08 a	45.49 b	44.54 b
Cultivar (C)						
BRS A501 CL	0.42 a	0.56 a	0.53 a	40.98 b	44.91 b	44.93 b
BRS Esmeralda	0.35 a	0.46 a	0.47 a	44.47 a	49.94 a	48.98 a
Significant level						
Irrigation (M)	**	**	*	ns	*	**
Cultivar (C)	ns	ns	ns	**	**	**
MXC	ns	ns	ns	ns	ns	ns
2023–2024						
Irrigation (M)						
100 %	0.19 b	0.17	0.31	43.06 a	46.87 a	43.84 a
70 %	0.26 b	0.34	0.39	42.88 a	44.60 ab	43.53 a
40 %	0.64 a	0.72	0.52	42.62 a	44.24 b	44.52 a
Cultivar (C)						
BRS A501 CL	0.37 a	0.44	0.32	42.19 b	46.71 a	42.91 b
BRS Esmeralda	0.37 a	0.37	0.48	43.67 a	44.76 ab	44.58 a
BRS A502	0.32 a	0.42	0.39	42.59 b	44.07 b	44.23 a
Irrigation×Cultivar						
100 %×BRS A501 CL	0.19	0.21c	0.26 b	43.20	47.83	41.95
100 %×BRS Esmeralda	0.20	0.12c	0.33 b	43.35	46.37	43.25
100 %×BRS A502	0.17	0.18c	0.34 b	42.53	46.40	45.38
70 %×BRS A501 CL	0.31	0.33 bc	0.38 b	41.23	46.05	43.55
70 %×BRS Esmeralda	0.23	0.21 c	0.37 b	43.88	44.53	43.55
70 %×BRS A502	0.23	0.46 ab	0.41 ab	43.55	43.20	43.48
40 %×BRS A501 CL	0.69	0.77 a	0.33 b	42.40	46.47	42.75
40 %×BRS Esmeralda	0.67	0.79 a	0.74 a	43.78	43.37	46.95
40 %×BRS A502	0.57	0.62 a	0.40 b	41.68	42.90	43.85
Significant level						
Irrigation (M)	**	**	*	ns	*	ns
Cultivar (C)	ns	ns	**	*	*	*
M×C	ns	**	**	ns	ns	ns

Means within a column followed by different letters differ significantly according to the Tukey–Kramer test at $p < 0.05$. ANOVA significance levels: $p < 0.05$ (*), $p < 0.01$ (**). Panicle initiation (PI); anthesis (AT); grain filling (GF); not significant (ns).

specific phenological stages. For example, it was demonstrated that deficit irrigation limits physiological parameters of upland rice under terminal stress (Olalekan Suleiman et al., 2022; Quiloango-Chimarro et al., 2022) and at vegetative and flowering stages (Alou et al., 2018; Wang et al., 2023). For irrigation using different water potential thresholds, previous research primarily focused on assessing mechanisms that maintain physiological functions (Kumar et al., 2017). In contrast, this study expands on that by evaluating the consequences of water stress, including gas exchange traits, temperature responses, and chlorophyll index.

The severity of the impact varied with both the water stress intensity and phenological stage. At panicle initiation and grain-filling stages, gas exchange declined similarly under the 40 % and −40 kPa treatments, but in Experiment A, soil water potential dropped until −80 kPa before irrigation (data not shown). This is consistent with a previous study, showing that physiological traits change with irrigation thresholds since −46 kPa (dos Santos et al., 2018). Therefore, a threshold between −20 and −30 kPa for upland rice cultivation is recommended to avoid significant reductions (Froes de Borja Reis et al., 2018). At anthesis, reductions in gas exchange, particularly stomatal conductance, were more pronounced, consistent with Vijayaraghavareddy et al. (2020). The stronger decline under −40 kPa compared with 40 % treatment suggests that the latter triggered non-stomatal limitations. Genotypic differences were also evident; BRS Esmeralda performed better under severe stress, suggesting greater drought tolerance, whereas BRS A502 showed advantages under less stressful conditions. Mechanistically, sustaining higher photosynthesis at anthesis enhances carbon flux to reproductive organs and prevents pollen sterility (Centritto et al., 2009). These findings indicate that cultivar choice and soil moisture management at anthesis influence aerobic rice systems.

Similar patterns were observed for the crop water stress index, with stress intensities peaking at anthesis compared with panicle initiation and grain filling. This corroborates that anthesis is the most sensitive stage to water stress (Vijayaraghavareddy et al., 2020), likely due to its critical function in yield determination (Boonjung and Fukai, 1996). This could be because crop water stress index is closely related to photosynthetic rate and stomatal conductance, such that a high crop water stress index value reflects the stomatal closure induced by water stress (Gutiérrez et al., 2018; Jackson et al., 1981; Ramírez-Cuesta et al., 2022b). For cultivars, it was observed that the crop water stress index exhibited reduced sensitivity compared to gas exchange parameters. This could be attributed to the greater variability in canopy temperature due to external factors such as wind or radiation fluctuations (Ramírez-Cuesta et al., 2022a). Furthermore, the crop water stress index estimation procedure may introduce discrepancies such as over- or under-estimation of water stress (Jamshidi et al., 2021; Luan et al., 2021). Therefore, considering the responses of the crop water stress index to irrigation treatments, it could serve as a tool for irrigation scheduling in aerobic rice.

The chlorophyll index responded to irrigation only in Experiment A, likely due to differences in stress duration and intensity between experiments. In this case, values progressively declined under stress, particularly at grain filling, in agreement with Zhang et al. (2024). Conversely, other studies reported increases in chlorophyll under moderate or stage-specific deficits (Gao et al., 2024; Sreekanth et al., 2024), indicating that responses depend on stress conditions. Cultivar differences were also significant, although each experiment favored a distinct cultivar. These findings emphasize that both genotype and stress dynamics shape chlorophyll responses. This underscores the need to expand studies on irrigation strategies under aerobic conditions, as the chlorophyll index is widely used to assess drought tolerance in rice (Larkunthod et al., 2018; Qu et al., 2016; Singh et al., 2017).

4.2. Irrigation strategy and cultivar impact on shoot mass, leaf area index, and root mass

At maturity, shoot mass was more negatively affected under the 70 and 40 % treatments in Experiment A than under the −40 kPa treatment in Experiment B. Reductions in shoot mass are closely linked to yield losses (Bouman et al., 2005). In Experiment B, declines became evident from anthesis onward, consistent with previous findings where shoot mass decreased under −40 kPa compared with −20 and −30 kPa from 75 DAS in cultivars with similar growing season durations (Kumar et al., 2017). These patterns suggest that lower photosynthetic rate, stomatal conductance, and transpiration at anthesis limited carbon assimilation, thereby constraining shoot mass production.

The leaf area index is a critical parameter in cereals, as it directly influences the capacity of the crop to intercept photosynthetically active radiation (Shi et al., 2022), which is a primary determinant of grain

Table 5
Average values of grain yield and grain yield components of three upland rice cultivars subjected to various irrigation levels (100, 70, and 40 %).

Treatment	Shoot dry mass (Mg ha^{-1})	Grain yield (Mg ha^{-1})	Panicles per m^2	Spikelets per panicle	Spikelet fertility (%)	1000-grain weight (g)
2020–2021						
Irrigation (M)						
100 %	19.3	8.8 a	373.2 a	143.7 a	74.3 a	22.7 a
70 %	12.8	3.9 b	333.8 a	106.3 b	52.7 b	21.0 a
40 %	7.6	0.4c	174.3 b	38.1c	33.3c	18.5 b
Cultivar (C)						
BRS A501 CL	14.2	4.7 a	335.7 a	78.8 b	58.6 a	20.9 a
BRS Esmeralda	12.3	4.0 a	251.8 b	113.3 a	48.2 b	20.5 a
Irrigation×Cultivar						
100 %×BRS A501 CL	20.7 a	9.3	418.5	122.6	122.6	23.1
100 %×BRS Esmeralda	18.0 b	8.3	328.0	165.0	165.0	22.2
70 %×BRS A501 CL	14.0c	4.4	376.0	85.7	85.7	21.8
70 %×BRS Esmeralda	11.6 d	3.4	291.5	126.9	126.9	20.3
40 %×BRS A501 CL	7.9 e	0.4	212.5	28.3	28.3	17.9
40 %×BRS Esmeralda	7.4 e	0.4	136.0	47.9	47.9	19.0
Significant level						
Irrigation (M)	**	**	**	**	**	**
Cultivar (C)	**	ns	**	**	**	ns
M×C	*	ns	ns	ns	ns	ns
2023–2024						
Irrigation (M)						
100 %	14.8 a	7.0	361.5 a	133.9 a	84.9 a	21.8 a
70 %	10.9 b	3.8	358.7 a	115.2 a	71.2 b	20.2 a
40 %	6.1c	0.2	269.0 b	75.6 b	13.4c	14.2 b
Cultivar (C)						
BRS A501 CL	10.3 a	3.3	344.1 a	93.6 b	56.3 a	20.2 a
BRS Esmeralda	10.1 a	3.6	266.7 b	130.5 a	52.2 a	18.3 ab
BRS A502	11.3 a	4.0	378.4 a	100.5 ab	61.0 a	17.7 b
Irrigation×Cultivar						
100 %×BRS A501 CL	15.0	7.2 a	362.1	108.3	88.0	23.6
100 %×BRS Esmeralda	13.7	6.3 b	318.2	161.5	79.9	21.2
100 %×BRS A502	15.9	7.6 a	404.1	132.0	86.9	20.6
70 %×BRS A501 CL	9.9	2.7c	372.3	99.0	63.4	20.1
70 %×BRS Esmeralda	11.0	4.4 bc	301.0	146.8	73.4	21.2
70 %×BRS A502	11.8	4.3 c	402.9	99.9	76.8	19.2
40 %×BRS A501 CL	6.2	0.2 d	298.0	73.6	17.4	17.0
40 %×BRS Esmeralda	5.7	0.0 d	181.0	83.4	3.4	12.4
40 %×BRS A502	6.3	0.3 d	328.1	69.8	19.4	13.3
Significant level						
Irrigation (M)	**	**	**	**	**	**
Cultivar (C)	ns	ns	**	**	ns	**
M×C	ns	*	ns	ns	ns	ns

Means within a column followed by different letters differ significantly according to the Tukey–Kramer test at $p < 0.05$. ANOVA significance levels: $p < 0.05$ (*), $p < 0.01$ (**). Not significant (ns).

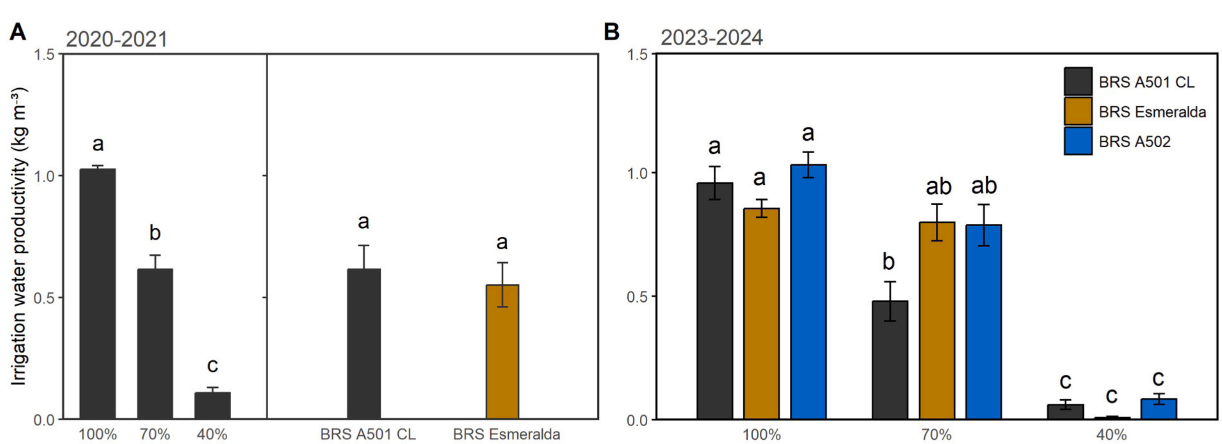

Fig. 3. Average values of irrigation water productivity of three upland rice cultivars subjected to irrigation levels (100, 70, and 40 %) in 2020–2021 (A) and 2023–2024 (B).

yield (Cao et al., 2024). Leaf area index was limited at −40 kPa at key stages, such as panicle initiation, which is critical for sustaining canopy development until late grain filling (Peltonen-Sainio et al., 1997). This limitation, compounded by restricted stomatal conductance, further reduces photosynthetic source capacity (Kashiwagi et al., 2021). Regarding cultivars, BRS A502 exhibited superior leaf area index performance at anthesis, which is advantageous as higher dry matter accumulation up to this stage suggests greater mobilization of

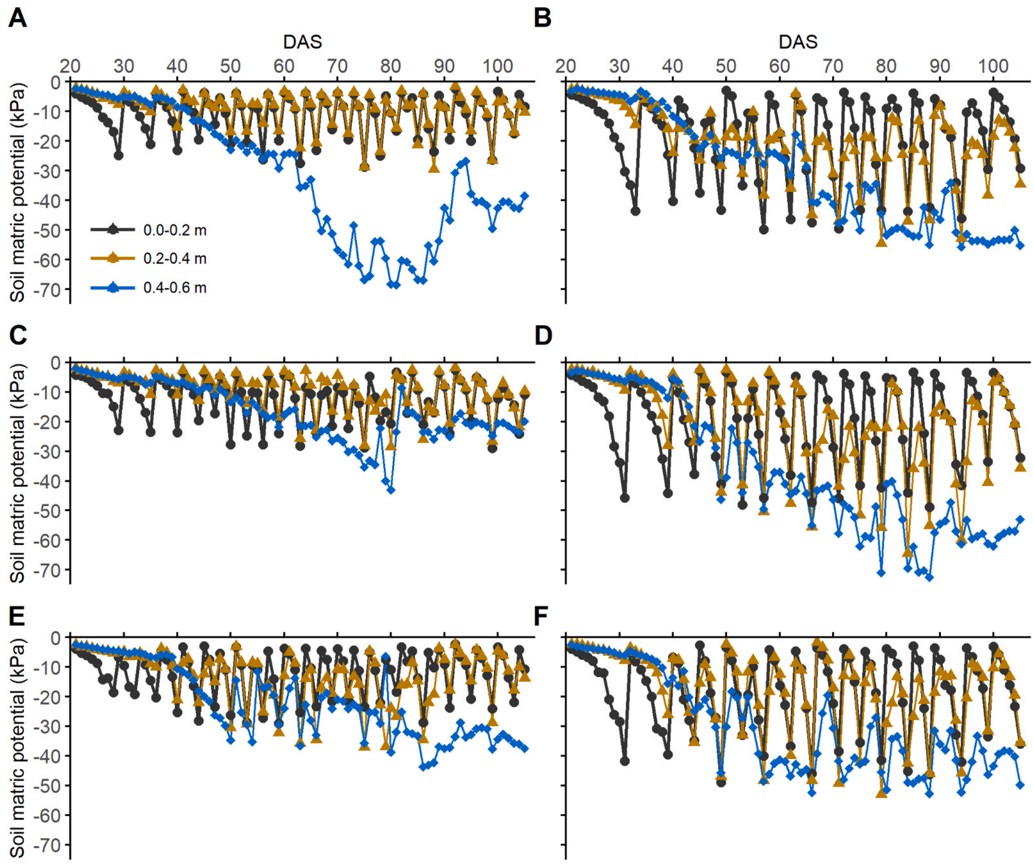

Fig. 4. Soil water potential of three upland rice cultivars under −20 kPa (A, C, E) and −40 kPa (B, D, F). BRS A501 CL (A, B); BRS Esmeralda (C, D); BRS A502 (E, F).

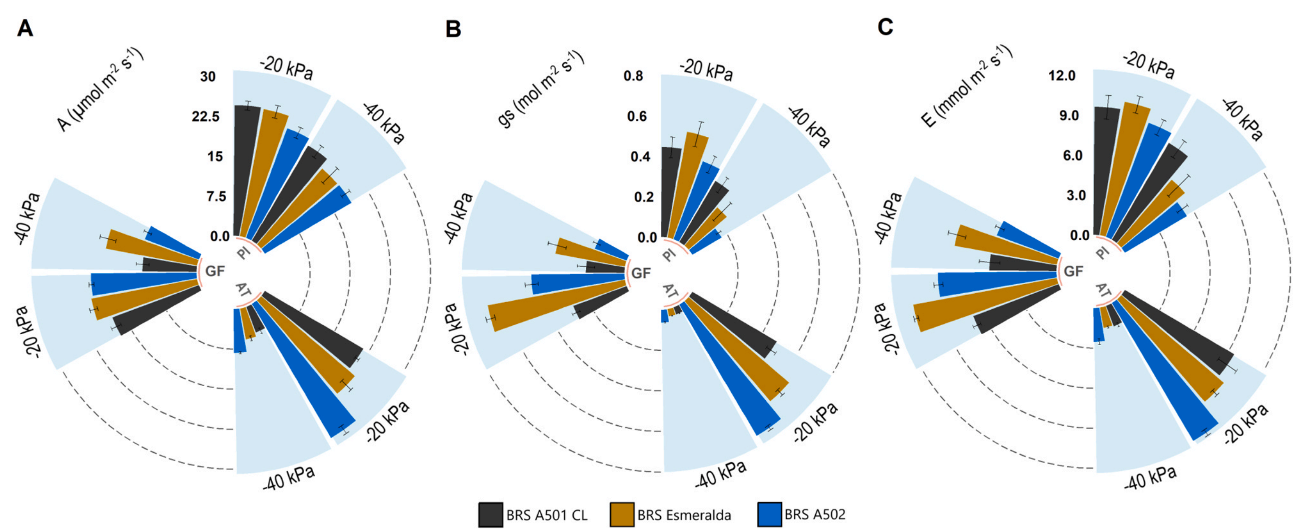

Fig. 5. Average values of photosynthesis (A), stomatal conductance (B), and transpiration (C) of three upland rice cultivars subjected to different soil water potential thresholds (−20 and −40 kPa). Photosynthesis (A); stomatal conductance (gs); transpiration (E). In the center of each graph: panicle initiation (PI); anthesis (AT); grain-filling (GF).

pre-anthesis assimilates (Inoue et al., 2004). Therefore, the advancements in the Brazilian breeding program are evident, as the cultivars followed a clear trend in leaf area index according to their release year (2012 < 2018 < 2020).

Root dry mass is a critical morphological trait of the root system (Liu et al., 2020). Reductions in dry mass observed at maturity under −40 kPa may limit nutrient and water uptake, ultimately compromising grain yield (Meng et al., 2021). Differences among cultivars were evident at both panicle initiation and maturity, supporting its use as a criterion for screening drought tolerance (Albert et al., 2024; Kondhia et al., 2015). BRS A501 CL exhibited the lowest root biomass compared with BRS Esmeralda and BRS A502. Interestingly, the soil water potential of A501 CL in the third layer (0.40–0.60 m) was lower than in the other cultivars. This could be because cultivars with lower root biomass may develop greater root length (Vijayaraghavareddy et al., 2020), thereby reducing soil moisture in deeper layers. Although root mass was

Table 6
Average values of crop water stress index and chlorophyll index of three upland rice cultivars subjected to different soil water potential thresholds (−20 and −40 kPa).

Treatment	Crop water stress index			Chlorophyll index		
	PI	AT	GF	PI	AT	GF
Irrigation (M)						
−20 kPa	0.18 b	0.20 b	0.10	43.09 a	50.02	44.83 a
−40 kPa	0.59 a	0.63 a	0.33	42.32 a	48.83	44.75 a
Cultivar (C)						
BRS A501 CL	0.27 b	0.41 a	0.25	40.49 b	48.79	42.53 b
BRS Esmeralda	0.42 a	0.43 a	0.18	44.74 a	50.14	44.14 ab
BRS A502	0.42 a	0.38 a	0.23	43.06 a	49.64	47.71 a
Irrigation×Cultivar						
−20 kPa×BRS A501 CL	0.15	0.20	0.07c	40.93	50.35	42.85
−20 kPa×BRS Esmeralda	0.24	0.23	0.08c	44.65	51.50	43.90
−20 kPa×BRS A502	0.15	0.18	0.16 bc	43.70	48.95	47.75
−40 kPa×BRS A501 CL	0.43	0.70	0.43 a	39.90	46.70	42.20
−40 kPa×BRS Esmeralda	0.65	0.63	0.27 bc	44.87	49.23	44.38
−40 kPa×BRS A502	0.70	0.58	0.30 ab	42.20	50.57	47.68
Significant level						
Irrigation (M)	**	**	**	ns	ns	ns
Cultivar (C)	*	ns	ns	*	ns	*
M×C	ns	ns	*	ns	ns	ns

Means within a column followed by different letters differ significantly according to the Tukey–Kramer test at $p < 0.05$. ANOVA significance levels: $p < 0.05$ (*), $p < 0.01$ (**). Panicle initiation (PI); anthesis (AT); grain filling (GF); not significant (ns).

not assessed in Experiment A, it can be inferred that BRS A501 CL had a limitation in water uptake efficiency due to its root system in the shallow layer under water stress (higher yield penalty). Therefore, future studies should incorporate additional root traits to elucidate the role of the root system in soil water dynamics and its impact on yield performance.

4.3. Impacts of water-saving irrigation strategies on grain yield and irrigation water productivity

Grain yield was affected by the water-saving irrigation treatments compared to the reference treatment in each experiment. However, yield reductions were more pronounced in Experiment A (Table 5) than in Experiment B (Table 8). These differences could be attributed to the fact that rice is more susceptible to water stress than other crops (Kato and Katsura, 2014). For example, in an experiment conducted by the same research group (de Almeida et al., 2024), a 40 % deficit irrigation treatment reduced soybean yield by 49 %, while upland rice showed a 96 % reduction compared to the full irrigation treatment (100 %). Although efforts to improve drought tolerance in upland rice cultivars have been made (Heinemann et al., 2019), deficit irrigation (70 % and 40 %) may only be viable if applied during specific growth stages (Alou et al., 2018; Quiloango-Chimarro et al., 2022). In Experiment B, the yield penalty under −40 kPa was similar to that observed by Kumar et al. (2017) using the same threshold, who also noted that the grain yield of cultivars Apo and Annada under −40 kPa was comparable to that under continuous flooding. In addition, the yield penalty under −40 kPa is lower than the typical range observed in central Brazil (Pinheiro et al., 2006), showing promising potential to be further tested across a wider range of cultivars. Overall, recently released cultivars (BRS A502 and BRS A501 CL) maintained higher grain yield performance than BRS Esmeralda, mainly through greater panicles per m^2 and spikelet fertility. This result was expected, as modern, high-yielding cultivars are typically characterized by increased tillering and a larger leaf area index (Park et al., 2022; Zhou et al., 2022).

Irrigation water productivity largely followed grain yield trends in both experiments, confirming that irrigation water productivity in aerobic rice is strongly yield-driven under drought conditions (Kumar et al., 2019). In Experiment B, however, irrigation water productivity was stable across the −20 and −40 kPa treatments, contrasting with previous reports of optimal values at −30 kPa and declines at −20 kPa (Kumar et al., 2017). These differences are likely explained by climatic conditions, particularly temperature and evaporative demand (Fukai and Mitchell, 2022), given that their study was conducted under the climatological conditions of Eastern India. Results indicated that cultivar BRS A502 performed better in Experiment B, consistent with its higher yield potential, the main determinant of irrigation water productivity (Bouman et al., 2007). This is supported by studies showing that rice cultivars with similar growing season durations generally have comparable water requirements (Liu et al., 2019; López-López et al., 2018), as observed in our study (Table 3). Overall, although in this study irrigation water productivity was not superior under −40 kPa, this treatment could be useful to be explored under field conditions and in future research to configure combinations based on crop growth stages.

4.4. Novelties and prospects

Upland rice under aerobic conditions is highly dependent on rainfall distribution. Kadiyala et al. (2015) reported that grain yield decreases

Table 7
Average values of shoot dry mass, leaf area index, and root dry mass of three upland rice cultivars subjected to different soil water potential thresholds (−20 and −40 kPa).

Treatment	Shoot dry mass (kg ha^{-1})				Leaf area index				Root dry mass (g $plant^{-1}$)	
	PI	H	AT	PM	PI	H	AT	PM	PI	PM
Irrigation (M)										
−20 kPa	3.6	7.3	9.0 a	14.3 a	2.0 a	3.0 a	3.2 a	2.7	1.3 a	2.1 a
−40 kPa	3.2	7.2	8.2 b	12.3 b	1.0 b	2.5 b	2.5 b	2.5	1.5 a	1.6 b
Cultivar (C)										
BRS A501 CL	3.1	7.4	8.5 ab	13.1 a	1.5 a	2.7 a	2.8 ab	2.4	1.2 b	1.2 b
BRS Esmeralda	3.4	7.1	7.8 b	12.8 a	1.8 a	2.5 a	2.5 b	2.6	1.4 ab	1.9 a
BRS A502	3.6	7.3	9.1 a	13.9 a	1.3 a	2.9 a	3.4 a	2.8	1.8 a	2.5 a
Significant level										
Irrigation (M)	ns	ns	*	*	**	*	*	ns	ns	*
Cultivar (C)	ns	ns	*	ns	ns	ns	*	ns	*	**
M×C	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Means within a column followed by different letters differ significantly according to the Tukey–Kramer test at $p < 0.05$. ANOVA significance levels: $p < 0.05$ (*), $p < 0.01$ (**). Panicle initiation (PI); heading (H); anthesis (AT); maturity (PM); not significant (ns).

Table 8
Average values of grain yield and grain yield components of three upland rice cultivars subjected to different soil water potential thresholds (−20 and −40 kPa).

Treatment	Grain yield (Mg ha^{-1})	Panicles per m^2	Spikelets per panicle	Spikelet fertility (%)	1000-grain weight (g)
Irrigation (M)					
−20 kPa	6.8 a	342.1 a	126.7 a	80.9 a	22.3 a
−40 kPa	5.3 b	340.2 a	128.7 a	78.4 a	21.7 b
Cultivar (C)					
BRS A501 CL	6.3 a	339.7 b	115.6 b	84.0 a	23.5 a
BRS Esmeralda	5.5 b	295.1 c	151.4 a	72.8 b	21.7 b
BRS A502	6.4 a	388.7 a	116.1 b	82.2 a	20.8 b
Significant level					
Irrigation (M)	*	ns	ns	ns	*
Cultivar (C)	*	**	**	**	**
M×C	ns	ns	ns	ns	ns

Means within a column followed by different letters differ significantly according to the Tukey–Kramer test at $p < 0.05$. ANOVA significance levels: $p < 0.05$ (*), $p < 0.01$ (**). Not significant (ns).

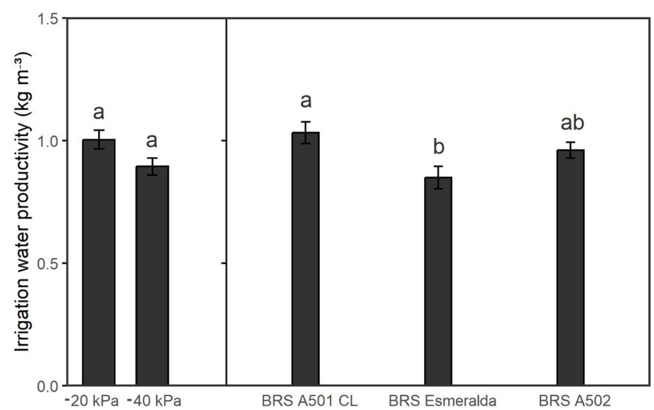

Fig. 6. Average values of irrigation water productivity of three upland rice cultivars subjected to different soil water potential thresholds (−20 and −40 kPa).

by 38 % in years with poor rainfall distribution compared to 19 % in years with adequate rainfall distribution in India. This effect is even more pronounced in Brazil, where the yield penalty of upland rice ranges between 36 % and 90 % (Pinheiro et al., 2006). Consequently, farmers occasionally employ supplemental irrigation to mitigate severe water stress (Froes de Borja Reis et al., 2018). However, in countries like Australia, where irrigation water has become costly (Champness et al., 2023), strategies to reduce water input in upland rice cultivation are essential. In this experiment, the −40 kPa treatment reduced water input by 93 mm and decreased the number of irrigations by 10, demonstrating not only a reduction in water use but also the maintenance of irrigation water productivity and a reduction in energy required for pumping.

As mentioned above, upland rice often loses farmers' interest due to its high variability in grain yield. For example, in China, groundwater sustainability deteriorated rapidly after 2009, due to the conversion of large upland areas into paddy rice fields (Zhang et al., 2024). Cultivars well-adapted to aerobic conditions, as highlighted by Fukai and Mitchell (2024), combined with water-saving strategies, could help reduce the expansion of flooded systems. It is worth mentioning that upland rice irrigated systems can achieve yields comparable to those of lowland rice (Kadiyala et al., 2015). Another factor to be considered is the continuous expansion of irrigation. For example, in sub-Saharan Africa, where upland rice accounts for 38 % of total rice production and plays a crucial role in subsistence agriculture, it is expected to potentially add 30 million ha of irrigated land (Frimpong et al., 2023). This study highlights the need to guide breeding programs and farmers in developing tailored irrigation strategies for upland rice, as each cultivar responds differently to the tested approaches. Additionally, policymakers and industry stakeholders should consider providing support, as adequate irrigation in upland rice could be based on potential thresholds that require tools such as soil moisture sensors and canopy temperature monitoring.

5. Conclusions

In Experiment A, the irrigation level of 100 % (Control) with ~786 mm of water resulted in an average annual yield of 7.9 Mg ha^{-1}, corresponding to an irrigation water productivity of 0.88 kg m^{-3}. Grain yield and irrigation water productivity decreased by 51–96 % and 32–92 %, respectively, under irrigation levels reduced to 70 and 40 % of the irrigation water applied in the Control treatment. The main constraints causing these large reductions in grain yield and irrigation water productivity were declines in physiological traits, which led to lower grain yield components, particularly spikelet fertility.

In Experiment B, when irrigation was triggered at different soil water potential thresholds, the reference treatment (−20 kPa) with ~683 mm of water resulted in an average grain yield of 6.8 Mg ha^{-1} and irrigation water productivity of 1.0 kg m^{-3}. The irrigation threshold of −40 kPa with ~590 mm of irrigation water applied resulted in an average grain yield of 5.3 Mg ha^{-1} and irrigation water productivity of 0.89 kg m^{-3}.

Collectively, water-saving treatments in Experiment A (70 and 40 % of full irrigation) reduced upland rice yield and irrigation water productivity, whereas a −40 kPa irrigation threshold in Experiment B maintained irrigation water productivity. Although the −40 kPa irrigation threshold reduced yield by 22 %, it represents a viable strategy to reduce water use in water-limited environments. Implementing this irrigation strategy requires support from policymakers and industry stakeholders to ensure access to tools, such as soil moisture sensors and canopy temperature monitoring.

CRediT authorship contribution statement

Carlos Alberto Quiloango-Chimarro: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Tainá Ferreira da Rocha:** Writing – review & editing, Validation, Investigation. **Jéfferson de Oliveira Costa:** Writing – review & editing, Visualization, Validation, Formal analysis. **Alexandre Bryan Heinemann:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Alice da Silva Gundim:** Writing – review & editing, Validation, Investigation. **Rubens Duarte Coelho:** Writing – review & editing, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests. Carlos Alberto Quiloango Chimarro reports financial support and article publishing charges were provided by Foundation of Agrarian Studies Luiz de Queiroz. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2025.109914.

Data availability

Data will be made available on request.

References

Albert, D., Vijayaraghavareddy, P., Sreeman, S., 2024. Seed size, an imperative trait for seed vigor and drought tolerance in rice. Cereal Res. Commun. 52, 559–568. https://doi.org/10.1007/s42976-023-00403-4.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements. FAO Irrig. Drain. Pap. 56.

de Almeida, A.M., Coelho, R.D., da Silva Barros, T.H., de Oliveira Costa, J., Quiloango-Chimarro, C.A., Moreno-Pizani, M.A., Farias-Ramírez, A.J., 2022. Water productivity and canopy thermal response of pearl millet subjected to different irrigation levels. Agric. Water Manag. 272, 107829. https://doi.org/10.1016/j.agwat.2022.107829.

de Almeida, A.M., Coelho, R.D., da Silva Barros, T.H., Quiloango-Chimarro, C., Azevedo, A.T., de Oliveira Costa, J., 2024. Water use efficiency and canopy temperature response of soybean subjected to deficit irrigation. Ital. J. Agrometeorol. 3–16. https://doi.org/10.36253/ijam-2445.

Alou, I.N., Steyn, J.M., Annandale, J.G., van der Laan, M., 2018. Growth, phenological, and yield response of upland rice (*oryza sativa* L. cv. Nerica 4®) to water stress during different growth stages. Agric. Water Manag. 198, 39–52. https://doi.org/10.1016/j.agwat.2017.12.005.

Antolin, L.A.S., Silva, E.H.F.M., da, Zanon, A.J., Ribeiro, B.S.M.R., Marin, F.R., 2025. How much would irrigation increase maize production in Brazil. Sci. Agric. 82, e20240083. https://doi.org/10.1590/1678-992X-2024-0083.

Arf, O., Rodrigues, R.A.F., Crusciol, C.A.C., Sá, M.E., de, Buzetti, S., 2003. Soil management and nitrogen fertilization for sprinkler-irrigated upland rice cultivars. Sci. Agric. 60, 345–352. https://doi.org/10.1590/S0103-90162003000200020.

Boonjung, H., Fukai, S., 1996. Effects of soil water deficit at different growth stages on rice growth and yield under upland conditions. 2. phenology, biomass production and yield. F. Crop. Res. 48, 47–55. https://doi.org/10.1016/0378-4290(96)00039-1.

Bouman, B.A.M., Humphreys, E., Tuong, T.P., Barker, R., 2007. Rice and water. Adv. Agron. 92, 187–237. https://doi.org/10.1016/S0065-2113(04)92004-4.

Bouman, B.A.M., Peng, S., Castañeda, A.R., Visperas, R.M., 2005. Yield and water use of irrigated tropical aerobic rice systems. Agric. Water Manag 74, 87–105. https://doi.org/10.1016/j.agwat.2004.11.007.

Breseghello, F., de Mello, R.N., Pinheiro, P.V., Soares, D.M., Lopes Junior, S., Nakano Rangel, P.H., Guimarães, E.P., de Castro, A.P., Colombari Filho, J.M., de Magalhães Júnior, A.M., 2021. Building the embrapa rice breeding dataset for efficient data reuse. Crop Sci. 61, 3445–3457. https://doi.org/10.1002/csc2.20550.

Calvache, M., Reichardt, K., Bacchi, O.O.S., Dourado-Neto, D., 1997. Deficit irrigation at different growth stages of the common bean (*Phaseolus vulgaris* L., cv. Imbabello). Sci. Agric. 54, 1–16. https://doi.org/10.1590/s0103-90161997000300002.

Cao, Y., Zhang, Y., Tian, J., Li, X., Tang, Z., Yang, X., Zhang, X., Ma, N., 2024. Strong agricultural resilience to 2022 Southern China drought. Earth's Futur. 12, e2023EF004243. https://doi.org/10.1029/2023EF004243.

Castro, A.P., de, Morais, O.P., de, Breseghello, F., Lobo, V.L., da, S., Guimarães, C.M., Bassinello, P.Z., Colombari Filho, J.M., Santiago, C.M., Furtini, I.V., Torga, P.P., Utumi, M.M., Pereira, J.A., Cordeiro, A.C.C., Azevedo, R., de, Sousa, N.R.G., Soares, A.A., Radmann, V., Peters, V.J., de CASTRO, A.P., de MORAIS, O.P., Breseghello, F., Lobo, V.L., da, S., Guimarães, C.M., Bassinello, P.Z., Colombari Filho, J.M., Santiago, C.M., Furtini, I.V., Torga, P.P., 2014. BRS esmeralda: cultivar de arroz de terras altas com elevada produtividade e maior tolerância à seca. Embrapa Arroz e FeijãoComun. Técnico 4.

Centritto, M., Lauteri, M., Monteverdi, M.C., Serraj, R., 2009. Leaf gas exchange, carbon isotope discrimination, and grain yield in contrasting rice genotypes subjected to water deficits during the reproductive stage. J. Exp. Bot. 60, 2325–2339. https://doi.org/10.1093/jxb/erp123.

Champness, M., Ballester, C., Hornbuckle, J., 2023. Effect of soil moisture deficit on aerobic rice in temperate Australia. Agronomy 13, 168. https://doi.org/10.3390/agronomy13010168.

CONAB, C., 2021. Acompanhamento da safra brasileira: Comparativo de área, produtividade e produção – Arroz irrigado, p. 125 vol 6.

Costa, J.D.O., Coelho, R.D., Barros, T.H.D.S., Fraga Júnior, E.F., Fernandes, A.L.T., 2020. Canopy thermal response to water deficit of coffee plants under drip irrigation. Irrig. Drain. 69, 472–482. https://doi.org/10.1002/ird.2429.

Crusciol, C.A.C., Soratto, R.P., Nascente, A.S., Arf, O., 2013. Root distribution, nutrient uptake, and yield of two upland rice cultivars under two water regimes. Agron. J. 105, 237–247. https://doi.org/10.2134/agronj2012.0298.

Dane, J.H., 2002. 3.3 water retention and storage, 3.3. 2 laboratory. Methods Soil Anal. Part 4 Phys. Methods 675–720.

FAO, 2022. FAO cereal supply and demand brief [WWW Document] (URL). 〈https://www.fao.org/worldfoodsituation/csdb/en/〉.

Fernández, J.E., Alcon, F., Diaz-Espejo, A., Hernandez-Santana, V., Cuevas, M.V., 2020. Water use indicators and economic analysis for on-farm irrigation decision: a case study of a super high density olive tree orchard. Agric. Water Manag 237, 106074. https://doi.org/10.1016/j.agwat.2020.106074.

França, A.C.F., Coelho, R.D., da Silva Gundim, A., de Oliveira Costa, J., Quiloango-Chimarro, C.A., 2024. Effects of different irrigation scheduling methods on physiology, yield, and irrigation water productivity of soybean varieties. Agric. Water Manag. 293, 108709. https://doi.org/10.1016/j.agwat.2024.108709.

Frimpong, F., Asante, M.D., Peprah, C.O., Amankwaa-Yeboah, P., Danquah, E.O., Ribeiro, P.F., Aidoo, A.K., Agyeman, K., Asante, M.O.O., Keteku, A., 2023. Water-smart farming: review of strategies, technologies, and practices for sustainable agricultural water management in a changing climate in West Africa. Front. Sustain. Food Syst. 7, 1110179. https://doi.org/10.3389/fsufs.2023.1110179.

Froes de Borja Reis, A., Estevam Munhoz de Almeida, R., Cocco Lago, B., Trivelin, P.C., Linquist, B., Favarin, J.L., 2018. Aerobic rice system improves water productivity, nitrogen recovery and crop performance in Brazilian weathered lowland soil. F. Crop. Res. 218, 59–68. https://doi.org/10.1016/j.fcr.2018.01.002.

Fukai, S., Mitchell, J., 2022. Factors determining water use efficiency in aerobic rice. Crop Environ. 1, 24–40. https://doi.org/10.1016/j.crope.2022.03.008.

Fukai, S., Mitchell, J., 2024. Genotypic adaptation to soil water deficit in rice-a comparison of desirable traits for aerobic production and lowland drought resistance. Crop Environ.

Furtini, I.V., Castro, A.P., de, Lacerda, M.C., Breseghello, F., Utumi, M.M., Silveira Filho, A., Pereira, J.A., Abreu, G.B., Cordeiro, A.C.C., Sousa, N.R.G., 2022. BRS A502: an upland rice cultivar for intensive sustainable cropping systems in the Brazilian cerrado. Crop Breed. Appl. Biotechnol. 22, e41792234. https://doi.org/10.1590/1984-70332022v22n3c27.

Gao, C., Lin, M., He, L., Tang, M., Ma, J., Sun, W., 2024. The impact of Water-Saving irrigation on rice growth and comprehensive evaluation of irrigation strategies. Agronomy 14, 1363. https://doi.org/10.3390/agronomy14071363.

van Genuchten, M.T., 1980. A Closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

van Genuchten, M.T., Leij, F.J., Yates, S.R., 1991. The RETC code for quantifying the hydraulic functions of unsaturated soils. Robert S. Kerr Environmental Research Laboratory. Office Res.

Guimarães, C.M., Stone, L.F., Silva, A.C., de, L., 2016. Evapotranspiration and grain yield of upland rice as affected by water deficit. Rev. Bras. Eng. Agr. ícola e Ambient 20, 441–446. https://doi.org/10.1590/1807-1929/agriambi.v20n5p441-446.

Gutiérrez, S., Diago, M.P., Fernández-Novales, J., Tardaguila, J., 2018. Vineyard water status assessment using on-the-go thermal imaging and machine learning. PLoS One 13, 1–18. https://doi.org/10.1371/journal.pone.0192037.

Heinemann, A.B., Barrios-Perez, C., Ramirez-Villegas, J., Arango-Londoño, D., Bonilla-Findji, O., Medeiros, J.C., Jarvis, A., 2015. Variation and impact of drought-stress patterns across upland rice target population of environments in Brazil. J. Exp. Bot. 66, 3625–3638. https://doi.org/10.1093/jxb/erv126.

Heinemann, A.B., Ramirez-Villegas, J., Rebolledo, M.C., Costa Neto, G.M.F., Castro, A.P., 2019. Upland rice breeding led to increased drought sensitivity in Brazil. F. Crop. Res. 231, 57–67. https://doi.org/10.1016/j.fcr.2018.11.009.

Heinemann, A.B., Ramirez-Villegas, J., Stone, L.F., Silva, A., da Matta, D.H., Diaz, M.E.P., 2021. The impact of el Niño Southern oscillation on cropping season rainfall variability across central Brazil. Int. J. Clim. 41, E283–E304. https://doi.org/10.1002/joc.6684.

Heinemann, A.B., Stone, L.F., Fageria, N.K., 2011. Transpiration rate response to water deficit during vegetative and reproductive phases of upland rice cultivars. Sci. Agric. 68, 24–30. https://doi.org/10.1590/s0103-90162011000100004.

IBGE, 2022. Levantamento Sistemático da Produção Agrícola. [WWW Document]. URL 〈https://sidra.ibge.gov.br/pesquisa/lspa/tabelas〉.

Inoue, T., Inanaga, S., Sugimoto, Y., El Siddig, K., 2004. Contribution of pre-anthesis assimilates and current photosynthesis to grain yield, and their relationships to drought resistance in wheat cultivars grown under different soil moisture. Photosynthetica 42, 99–104. https://doi.org/10.1023/B:PHOT.0000040576.52128.ed.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter, P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17, 1133–1138. https://doi.org/10.1029/WR017i004p01133.

Jamshidi, S., Zand-Parsa, S., Niyogi, D., 2021. Assessing crop water stress index of citrus using in-situ measurements, landsat, and sentinel-2 data. Int. J. Remote Sens. 42, 1893–1916. https://doi.org/10.1080/01431161.2020.1846224.

Kadiyala, M.D.M., Mylavarapu, R.S., Li, Y.C., Reddy, G.B., Reddy, K.R., Reddy, M.D., 2015. Uptake efficiency of 15 N-urea in flooded and aerobic rice fields under semi-

arid conditions. Paddy Water Environ. 13, 545–556. https://doi.org/10.1007/s10333-014-0473-8.
Kashiwagi, J., Yoshioka, Y., Nakayama, S., Inoue, Y., An, P., Nakashima, T., 2021. Potential importance of the ear as a post-anthesis carbon source to improve drought tolerance in spring wheat (Triticum aestivum L). J. Agron. Crop Sci. 207, 936–945. https://doi.org/10.1111/jac.12541.
Kato, Y., Katsura, K., 2014. Rice adaptation to aerobic soils: physiological considerations and implications for agronomy. Plant Prod. Sci. 17, 1–12. https://doi.org/10.1626/pps.17.1.
Khan, M.I.R., Palakolanu, S.R., Chopra, P., Rajurkar, A.B., Gupta, R., Iqbal, N., Maheshwari, C., 2021. Improving drought tolerance in rice: ensuring food security through multi-dimensional approaches. Physiol. Plant 172, 645–668. https://doi.org/10.1111/ppl.13223.
Kondhia, A., Tabien, R.E., Ibrahim, A., 2015. Evaluation and selection of high biomass rice (Oryza sativa L.) for drought tolerance. Am. J. Plant Sci. 6, 1962–1972. https://doi.org/10.4236/ajps.2015.612197.
Kumar, S., Narjary, B., Kumar, K., Jat, H.S., Kamra, S.K., Yadav, R.K., 2019. Developing soil matric potential based irrigation strategies of direct seeded rice for improving yield and water productivity. Agric. Water Manag. 215, 8–15. https://doi.org/10.1016/j.agwat.2019.01.007.
Kumar, A., Nayak, A.K., Pani, D.R., Das, B.S., 2017. Physiological and morphological responses of four different rice cultivars to soil water potential based deficit irrigation management strategies. F. Crop. Res. 205, 78–94. https://doi.org/10.1016/j.fcr.2017.01.026.
Lanna, A.C., Coelho, G.R.C., Moreira, A.S., Terra, T.G.R., Brondani, C., Saraiva, G.R., Lemos, F., da, S., Guimarães, P.H.R., Júnior, O.P.M., Vianello, R.P., 2020. Upland rice: phenotypic diversity for drought tolerance. Sci. Agric. 78, 1–14. https://doi.org/10.1590/1678-992x-2019-0338.
Larkunthod, P., Nounjan, N., Siangliw, J.L., Toojinda, T., Sanitchon, J., Jongdee, B., Theerakulpisut, P., 2018. Physiological responses under drought stress of improved drought-tolerant rice lines and their parents. Not. Bot. Horti Agrobot. Cluj. Napoca 46, 679–687. https://doi.org/10.15835/nbha46211188.
Liu, K., Li, T., Chen, Y., Huang, J., Qiu, Y., Li, S., Wang, H., Zhu, A., Zhuo, X., Yu, F., Zhang, H., Gu, J., Liu, L., Yang, J., 2020. Effects of root morphology and physiology on the formation and regulation of large panicles in rice. F. Crop. Res. 258, 107946. https://doi.org/10.1016/j.fcr.2020.107946.
Liu, H., Zhan, J., Hussain, S., Nie, L., 2019. Grain yield and resource use efficiencies of upland and lowland rice cultivars under aerobic cultivation. Agron. https://doi.org/10.3390/agronomy9100591.
López-López, R., Jiménez-Chong, J.A., Hernández-Aragón, L., Inzunza Ibarra, M.A., 2018. Water productivity of rice genotypes with irrigation and drainage. Irrig. Drain. 67, 508–515. https://doi.org/10.1002/ird.2250.
Luan, Y., Xu, J., Lv, Y., Liu, X., Wang, H., Liu, S., 2021. Improving the performance in crop water deficit diagnosis with canopy temperature spatial distribution information measured by thermal imaging. Agric. Water Manag. 246, 106699. https://doi.org/10.1016/j.agwat.2020.106699.
Luo, L., Mei, H., Yu, X., Xia, H., Chen, L., Liu, H., Zhang, A., Xu, K., Wei, H., Liu, G., Wang, F., Liu, Y., Ma, X., Lou, Q., Feng, F., Zhou, L., Chen, S., Yan, M., Liu, Z., Bi, J., Li, T., Li, M., 2019. Water-saving and drought-resistance rice: from the concept to practice and theory. Mol. Breed. 39. https://doi.org/10.1007/s11032-019-1057-5.
Mahajan, G., Ramesha, M.S., Chauhan, B.S., 2015. Genotypic differences for Water-Use efficiency and weed competitiveness in dry Direct-Seeded rice. Agron. J. 107, 1573–1583. https://doi.org/10.2134/agronj14.0508.
Mallareddy, M., Thirumalaikumar, R., Balasubramanian, P., Naseeruddin, R., Nithya, N., Mariadoss, A., Eazhilkrishna, N., Choudhary, A.K., Deiveegan, M., Subramanian, E., 2023. Maximizing water use efficiency in rice farming: a comprehensive review of innovative irrigation management technologies. Water 15, 1802. https://doi.org/10.3390/w15101802.
de Mendiburu, F., Yaseen, M., 2020. agricolae: Statistical Procedures for Agricultural Research.R package version 1.4.0 [WWW Document]. URL ⟨https://myaseen208.github.io/agricolae/https://cran.r-project.org/package=agricolae⟩.
Meng, T., Zhang, X., Ge, J., Chen, X., Yang, Y., Zhu, G., Chen, Y., Zhou, G., Wei, H., Dai, Q., 2021. Agronomic and physiological traits facilitating better yield performance of japonica/indica hybrids in saline fields. F. Crop. Res. 271, 108255. https://doi.org/10.1016/j.fcr.2021.108255.
Olalekan Suleiman, S., Gajere Habila, D., Mamadou, F., Mutiu Abolanle, B., Nurudeen Olatunbosun, A., 2022. Grain yield and leaf gas exchange in upland NERICA rice under repeated cycles of water deficit at reproductive growth stage. Agric. Water Manag. 264, 107507. https://doi.org/10.1016/j.agwat.2022.107507.
Park, J.-R., Kim, E.-G., Jang, Y.-H., Jan, R., Farooq, M., Ubaidillah, M., Kim, K.-M., 2022. Applications of CRISPR/Cas9 as new strategies for short breeding to drought gene in rice. Front. Plant Sci. 13, 850441. https://doi.org/10.3389/fpls.2022.850441.
Peltonen-Sainio, P., Forsman, K., Poutala, T., 1997. Crop management effects on Pre-and Post-Anthesis changes in leaf area index and leaf area duration and their contribution to grain yield and yield components in spring cereals. J. Agron. Crop Sci. 179, 47–61. https://doi.org/10.1111/j.1439-037X.1997.tb01146.x.
Pinheiro, B.D.S., Castro, E.D.M.D., Guimarães, C.M., 2006. Sustainability and profitability of aerobic rice production in Brazil. F. Crop. Res. 97, 34–42. https://doi.org/10.1016/j.fcr.2005.08.013.
Qu, M., Hamdani, S., Li, W., Wang, S., Tang, J., Chen, Z., Song, Q., Li, M., Zhao, H., Chang, T., 2016. Rapid stomatal response to fluctuating light: an under-explored mechanism to improve drought tolerance in rice. Funct. Plant Biol. 43, 727–738. https://doi.org/10.1071/FP15348.
Quiloango-Chimarro, C.A., Coelho, R.D., Heinemann, A.B., Arrieta, R.G., da Silva Gundim, A., França, A.C.F., 2022. Physiology, yield, and water use efficiency of drip-irrigated upland rice cultivars subjected to water stress at and after flowering. Exp. Agric. 58. https://doi.org/10.1017/S0014479722000205.
van Raij, B., Cantarella, H., Quaggio, J.A., Furlani, a, M.C., 1997. Recomendacoes da adubacao e calagem para o Estado de Sao Paulo.
Ramírez-Cuesta, J.M., Consoli, S., Longo, D., Longo-Minnolo, G., Intrigliolo, D.S., Vanella, D., 2022a. Influence of short-term surface temperature dynamics on tree orchards energy balance fluxes. Precis. Agric. 23, 1394–1412. https://doi.org/10.1007/s11119-022-09891-6.
Ramírez-Cuesta, J.M., Ortuño, M.F., González-Dugo, V., Zarco-Tejada, P.J., Parra, M., Rubio-Asensio, J.S., Intrigliolo, D.S., 2022b. Assessment of peach trees water status and leaf gas exchange using on-the-ground versus airborne-based thermal imagery. Agric. Water Manag. 267, 107628. https://doi.org/10.1016/j.agwat.2022.107628.
Ramirez-Villegas, J., Heinemann, A.B., Pereira de Castro, A., Breseghello, F., Navarro-Racines, C., Li, T., Rebolledo, M.C., Challinor, A.J., 2018. Breeding implications of drought stress under future climate for upland rice in Brazil. Glob. Chang. Biol. 24, 2035–2050. https://doi.org/10.1111/gcb.14071.
Rangel, P.H.N., Castro, A.P., Lacerda, M.C., Fragoso, D. de B, Furtini, I.V., Santos, B.M. dos, Abreu, A.G. de, Cordeiro, A.C.C., Pereira, J.A., Custódio, D.P., 2020. BRS A501 CL: herbicide-tolerant upland rice cultivar. Crop Breed. Appl. Biotechnol. 20. https://doi.org/10.1590/1984-70332020v20n2c20.
dos Santos, C.L., de Borja Reis, A.F., Mazzafera, P., Favarin, J.L., 2018. Determination of the water potential threshold at which rice growth is impacted. Plants 7, 48. https://doi.org/10.3390/plants7030048.
Santos, H.G. dos, Jacomine, P.K.T., Anjos, L.H.C. dos, Oliveira, V.A. de, Lumbreras, J.F., Coelho, M.R., Almeida, J.A. de, Araujo Filho, J.C. de, Oliveira, J.B. de, Cunha, T.J.F., 2018. Brazilian Soil Classification System. Embrapa, Brasília, DF.
Shi, D., Huang, Q., Liu, Z., Liu, T., Su, Z., Guo, S., Bai, F., Sun, S., Lin, X., Li, T., 2022. Radiation use efficiency and biomass production of maize under optimal growth conditions in northeast China. Sci. Total Environ. 836, 155574. https://doi.org/10.1016/j.scitotenv.2022.155574.
da Silva, O.F., Wander, A.E., 2023. Arroz - Estatística de produção [WWW Document]. URL ⟨https://www.embrapa.br/agencia-de-informacao-tecnologica/cultivos/arroz/pre-producao/socioeconomia/estatistica-de-producao⟩.
Simoes-Sousa, I.T., Camargo, C.M.L., Tavora, J., Piffer-Braga, A., Farrar, J.T., Pavelsky, T.M., 2025. The May 2024 flood disaster in Southern Brazil: causes, impacts, and SWOT-based volume estimation. Geophys. Res. Lett. 52, e2024GL112442. https://doi.org/10.1029/2024GL112442.
Singh, B., Reddy, K.R., Redoña, E.D., Walker, T., 2017. Screening of rice cultivars for Morpho-Physiological responses to Early-Season soil moisture stress. Rice Sci. 24, 322–335. https://doi.org/10.1016/j.rsci.2017.10.001.
Sreekanth, D., Pawar, D.V., Kumar, R., Ratnakumar, P., Sondhia, S., Singh, P.K., Mishra, J.S., Chander, S., Mukkamula, N., Kiran Kumar, B., 2024. Biochemical and physiological responses of rice as influenced by alternanthera paronychioides and echinochloa colona under drought stress. Plant Growth Regul. 103, 119–137. https://doi.org/10.1007/s10725-023-01089-8.
Stone, L.F., Silveira, P.M., da, Moreira, J.A.A., Yokoyama, L.P., 1999. Adubação nitrogenada em arroz sob irrigação suplementar por aspersão. Pesqui. Agropecuária Bras. 34, 926–932. https://doi.org/10.1590/S0100-204X1999000600002.
USDA, 1999. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. Nat. Resour. Conserv. Serv. U. S. Dep. Agric.
Vijayaraghavareddy, P., Xinyou, Y., Struik, P.C., Makarla, U., Sreeman, S., 2020. Responses of lowland, upland and aerobic rice genotypes to water limitation during different phases. Rice Sci. 27, 345–354. https://doi.org/10.1016/j.rsci.2020.05.009.
Wang, X.B., Zhang, X.J., Liu, L.H., Feng, G.R., Liu, X.L., Wang, J., Wei, C.Z., 2023. Yield of drip-irrigated rice (*oryza sativa* L.) response to water deficiency in different growth stages. Appl. Ecol. Environ. Res. 21. https://doi.org/10.15666/aeer/2102_11291142.
Xu, G., Lu, D.-K., Wang, H.-Z., Li, Y., 2018. Morphological and physiological traits of rice roots and their relationships to yield and nitrogen utilization as influenced by irrigation regime and nitrogen rate. Agric. Water Manag 203, 385–394. https://doi.org/10.1016/j.agwat.2018.02.033.
You, L., 2012. A tale of two countries: spatial and temporal patterns of rice productivity in China and Brazil. China Econ. Rev. 23, 690–703. https://doi.org/10.1016/j.chieco.2010.10.004.
Zhang, W., Shi, H., Cai, S., Guo, Q., Dai, Y., Wang, H., Wan, S., Yuan, Y., 2024. Rice growth and leaf physiology in response to four levels of continuous drought stress in Southern China. Agronomy 14, 1579. https://doi.org/10.3390/agronomy14071579.
Zhang, Q., Sun, J., Dai, C., Zhang, G., Wu, Y., 2024. Sustainable development of groundwater resources under the large-scale conversion of dry land into rice fields. Agric. Water Manag. 298, 108851. https://doi.org/10.1016/j.agwat.2024.108851.
Zhou, W., Yan, F., Chen, Y., Ren, W., 2022. Optimized nitrogen application increases rice yield by improving the quality of tillers. Plant Prod. Sci. 25, 311–319. https://doi.org/10.1080/1343943X.2022.2061538.