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Morphophysiological and productive aspects of sprinkler and surface irrigated rice cultivars

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ABSTRACT: The surface-irrigated rice crop in the continuous flooding system is characterized by increased water volume and low irrigation water productivity. In this sense, the present objective is to evaluate grain yield and irrigation water, in addition to physiological aspects and NPK accumulation in two rice cultivars irrigated by sprinkler and surface irrigation. The experiment was conducted under field conditions during the 2019/20 and 2020/21 agricultural crops, in Santa Maria, RS, Brazil, at the Department of Plant Science of the Universidade Federal de Santa Maria (29°43’8.8” S and 53°43’18.6” W). The experimental design used was randomized blocks, with four replications. Sprinkler and surface irrigation systems (continuous and intermittent) were tested for factor A. For factor D, second ones were tested as rice cultivars IRGA 424 RI and IRGA 431 CL, in a 3 × 2 factorial. In the agricultural season, the soil scarification treatment with sprinkler irrigation was added, in a 4 × 2 factorial. Sprinkler irrigation reduces water use, however, with a reduction in morphophysiological parameters and grain yield. In the presence of physical roots from the soil to root growth, scarification provides an increase in irrigation grain yield parameters, when irrigated by rice sprinklers, when it increases in higher irrigation productivity. The IRGA 431 CL cultivar provides a reduction in water use and greater irrigation water productivity, without prejudice to the crop’s grain yield.

Key words: deep tillage; continuous irrigation; intermittent irrigation; irrigation water productivity; sprinkler irrigation

Aspectos morfofisiológicos e produtivos de cultivares de arroz irrigadas por aspersão e superfície

RESUMO: A cultura do arroz irrigado por superfície no sistema de inundação contínua se caracteriza pelo elevado volume de água e pela baixa produtividade da água de irrigação. Nesse sentido, o presente trabalho objetivou avaliar a produtividade de grãos e da água de irrigação, além de aspectos morfofisiológicos e acúmulo de NPK em duas cultivares de arroz irrigadas por aspersão e por superfície. O experimento foi conduzido sob condições de campo durante as safras agrícolas de 2019/20 e 2020/21, em Santa Maria - RS, no Departamento de Fitotecnia da Universidade Federal de Santa Maria (29° 43’08.8” S 53°43’18.6” W). O delineamento experimental utilizado foi o de blocos ao acaso, com quatro repetições. Foram testados para o fator A sistemas de irrigação por aspersão e superfície (contínua e intermitente). Para o fator D foram testadas as cultivares de arroz IRGA 424 RI e IRGA 431 CL, em um fatorial 3 × 2. Na segunda safra agrícola foi adicionado o tratamento escarificação do solo com irrigação por aspersão, em um fatorial 4 × 2. A irrigação intermitente reduz uso de água sem prejuízo a produtividade de grãos. A irrigação por aspersão reduz o uso de água, no entanto, com redução dos parâmetros morfofisiológicos e da produtividade de grãos. Na presença de impedimentos físicos do solo ao crescimento de raízes, a escarificação proporciona incremento dos parâmetros morfofisiológicos e da produtividade de grãos de arroz quando irrigado por aspersão, resultando em maior produtividade de água de irrigação. A cultivar IRGA 431 CL proporciona redução do uso de água e maior produtividade da água de irrigação, sem prejuízo a produtividade de grãos da cultura.

Palavras-chave: escarificação; irrigação contínua; irrigação intermitente; produtividade da água de irrigação; irrigação por aspersão

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Introduction

About 75% of global rice (*Oryza sativa* L.) production is grown in irrigated lowlands, where fields are generally flooded throughout the growing season (IRRI, 2017). In the state of Rio Grande do Sul, the irrigation system traditionally used is surface irrigation by continuous flooding system, in which rice is sown in dry soil conditions and flooded when the plants contain three to four fully developed leaves (V3/V4) according to Counce et al. (2000). The water blade is maintained until about 20 days before harvest, requiring a volume of irrigation water that can range from 5,000 to 15,000 m^3 ha^{-1} (Massey et al., 2014; Avila et al., 2015; Carracelas et al., 2019), depending on the soil and climate conditions of cultivation.

Although growing rice with soil waterlogging is associated with several benefits to the crop, such as weed control, increased soil nutrient availability o and thermal insulation/protection during microsporogenesis (Yoshida, 1981), it is linked to a number of issues, including high water use and low irrigation water productivity (Avila et al., 2015; Carracelas et al., 2019). In this sense, the search for alternative irrigation systems that are more efficient in terms of water use and labor needs, and that, at the same time, maintain the crops grain yield, has been a constant challenge for research and for the production sector.

An alternative irrigation system to continuous irrigation consists of temporarily suppressing the supply of water to the crop, allowing the height of the water sheet to be reduced until it reaches a level near or equal to the ground level. In this way, the soil remains waterlogged or at least saturated during the entire crop cycle. This system, called intermittent irrigation, can be used throughout the entire crop cycle without damaging grain yields, conferring water use savings that can range from 22 to 76% (Massey et al., 2014; Avila et al., 2015; Carracelas et al., 2019).

Another irrigation system with positive effects on water use economy is sprinkler irrigation, such as center pivot irrigation, in which rice is grown throughout the cycle in oxidized soil, although the soil water content is kept as close to saturation as possible (Pinto et al., 2020). In the western border of the state of Rio Grande do Sul, Brazil, Pinto et al. (2020) estimated that the volume of water used by sprinkler irrigation was 5,500 m^3 ha^{-1} throughout the rice crop cycle, corresponding to approximately half the volume traditionally used in the production system by continuous flooding.

Despite the substantial water savings, the substitution of flood irrigation for sprinkler irrigation brings changes to the environment and the rice production system, which requires adjustments in crop management. An important aspect is that in the oxidized soil condition chemical and biological modifications caused by flooding are not present and benefit the rice crop, which may have consequences on grain productivity (Pinto et al., 2020). Another aspect is related to the naturally unfavorable physical conditions of these soils, such as the presence of a compacted layer near the surface (Sartori et al., 2016), which can restrict root growth and limit water availability to plants.

Thus, management practices that enable the improvement of soil physical attributes are important for the adequate agronomic performance of the crop in this cropping system. Some studies point out that soil scarification has provided improvement of the root environment of plants in lowland crop rotation, such as breaking up the compacted layer, reducing soil density, increasing macroporosity and soil water infiltration capacity (Giacomeli et al., 2017; Fin et al., 2018), being an alternative for areas cultivated with sprinkler irrigated rice with soil physical limitations.

Aiming to rationalize the use of water resources, another strategy that can be used associated with irrigation systems is the use of cultivars that have higher water productivity, due to their shorter biological cycle and high grain yield. However, there is great variability in morpho-physiological responses in cultivars when subjected to conditions of lower soil water availability, which will depend on the period (phenological stage), duration and frequency in which it occurs (Streck et al., 2019). In view of the above, the present work was developed in two cycles, with the objective of evaluating grain and water productivity, as well as morphophysiological aspects and NPK accumulation in two spray- and surface-irrigated rice cultivars.

Materials and Methods

The experiment was conducted under field conditions during the months of October to March of the 2019/20 and 2020/21 agricultural crops, in Santa Maria, RS, Brazil, at the Department of Plant Science of the Universidade Federal de Santa Maria (29°43'8.8" S and 53°43'18.6" W), with an average altitude of 153 m. The regions climate, according to the Köppen classification, is Cfa, humid subtropical, with no defined dry season and hot summers, with an average annual rainfall of 1,688 mm (Climate-data, 2021). The soil is classified as Planossolo Háplico Distrófico gleissolico (Santos et al., 2018), possessing the following physicochemical characteristics in the 0-0.2 m depth layer: clay = 20.0%; silt = 50.2%; sand = 29.8%; OM = 2.1; pH in water (1:1) = 6.9; base saturation = 83.7; Al saturation = 0%; P-Mehlich = 11.6 mg dm^{-3}; K = 34.5 mg dm^{-3}; S = 7.3; and, CTC pH7 = 14.2 $cmol_c$ dm^{-3}. As soil physical-water parameters: field capacity (FC) = 0.36 m^3 m^{-3}; permanent wilting point (PWP) = 0.18 m^3 m^{-3}; available water (AW) = 0.73 m^3 m^{-3}; and, basic soil infiltration speed (BIS) = 1.35 mm h^{-1}.

The experiment was set up in a randomized block design. The soil in the experimental area was systematized, with no slope or contour lines in the plots. In the 2019/20 crop the experiment was composed of a 3 × 2 factorial with four repetitions. The factor A levels were composed of three irrigation systems: conventional sprinkling, continuous surface irrigation, and intermittent surface irrigation. For factor D the IRGA 424 RI and IRGA 431 CL rice cultivars were tested, thus totaling 24 experimental plots.

In the 2020/21 crop a new treatment was inserted, through soil scarification and conventional sprinkler irrigation, composing a 4 × 2 factorial with four repetitions. Scarification was performed in August 2020, using a KLR model AS5AL brand scarifier, which operated at an average depth of 0.3 m.

For continuous irrigation, the soil was flooded at the V3 stage of the rice crop, and a water sheet of 0.1 m was maintained until the R7 stage, after which irrigation was suppressed. In intermittent irrigation, the soil was flooded at the V3 stage of the rice crop, and a water sheet of 0.1 m was maintained until the V6 stage, when irrigation was suppressed and resumed when the soil had no free water sheet under the surface, but when it was still saturated. This process was carried out until the R7 stage, when irrigation was stopped. For conventional sprinkler irrigation, starting at the V3 stage, irrigation rates were provided by monitoring the volumetric water content in the soil, and irrigation was suppressed at the R9 stage of the crop.

The criterion used for irrigation in the conventional sprinkler irrigation treatment in the 2019/20 crop year was the volumetric soil moisture at field capacity, in which the application of a fixed net blade of 8 mm day^{-1} was performed, with an irrigation system application intensity (Ia) of 4 mm h^{-1}, every day that water content equal to or less than 0.36 m^3 m^{-3} was reached. In the 2020/21 crop, the criteria for irrigation was changed, due to the verification of the need to change the frequency at which irrigations were performed, as well as to increase the volumetric water content in the soil to values close to saturation, being provided a daily net irrigation blade sufficient to raise the volumetric water content in the soil to total porosity (0.46 m^3 m^{-3}).

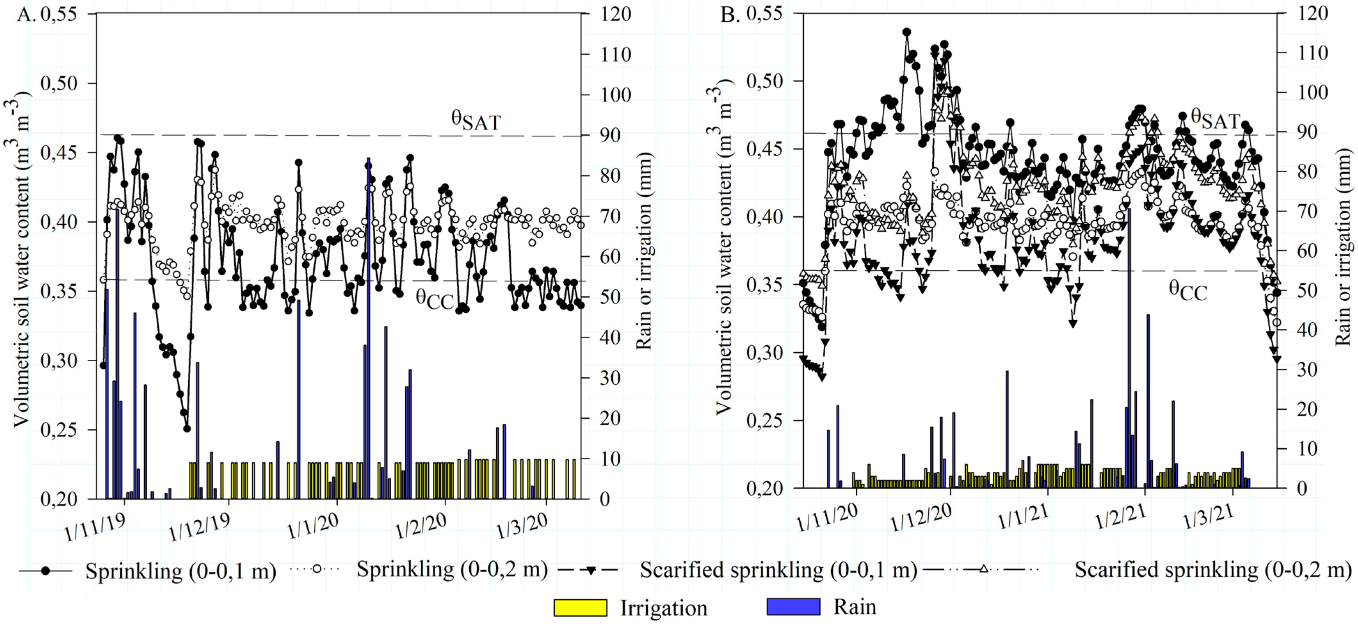
To monitor soil moisture volume, model CS-616 probes (Campbell Scientific, USA) were installed at depths of 0-0.1 and 0-0.2 m, connected to a Datalogger (model CR1000, Campbell Scientific, USA) (Figure 1).

For the conventional sprinkler irrigation plots, Trigre model Pingo Setorial 4.0 sectorial sprinklers were used, with a flow rate of 0.62 m^3 h^{-1}, with 8 m spacing between sprinklers and 12 m between rows, with 100% overlap, providing a uniformity coefficient of 85% (Christiansen, 1942).

The experimental units for continuous and intermittent surface irrigation were composed of 45.9 m² (1.53 × 30 m). The experimental units for conventional sprinkler irrigation consisted of 360 m² (12 × 30 m) in the 2019/20 season and 180 m² (6 × 30 m) in the 2020/21 season.

The soil for conducting the experiment during the 2019 off-season was kept fallow and prior to sowing, harrowing and soil leveling operations were performed. The 2019/20 crop rice harvest was conducted in March on dry soil. In May 2020, 3 t ha^{-1} of dolomitic limestone (PRNT 60%) was applied on the surface. Afterwards, the sowing of ryegrass and Persian clover was carried out in amounts of 40 and 8 kg ha^{-1}, respectively. Desiccation of the cover plants was carried out in the month of August 2020. At the time of desiccation, the aboveground dry matter accumulation of the cover crops was 1,956 kg ha^{-1}.

Rice sowing was performed on October 24 and 14, 2020 and 2021, respectively, at a density of 100 kg ha^{-1} of seeds, with inter-row spacing of 0.17 m. Base fertilization was performed according to the technical recommendations for the crop (Sosbai, 2018), consisting of 7 kg ha^{-1} of N, 70 kg ha^{-1} of P_2O_5, and 105 kg ha^{-1} of K_2O in the 2019/20 crop and by 20 kg ha^{-1} of N, 80 kg ha^{-1} of P_2O_5, and 80 kg ha^{-1} of K_2O in the 2020/21 crop. Covering fertilization in the 2019/20 crop was composed of 90 kg ha^{-1} of N at V3 and 30 kg ha^{-1} of N at V6 and R0. In the 2020/21 crop it was composed of 90 kg ha^{-1} of N at V3, 30 kg ha^{-1} of N + 25 kg ha^{-1} of K_2O at V6, and 30 kg ha^{-1} of N



θ_{SAT} = Volumetric soil water content at saturation. θ_{FC} = Volumetric soil water content at field capacity.

Figure 1. Volumetric soil water content in the sprinkler irrigation system grown with rice in the 2019/20 (A) and 2020/21 (B) agricultural seasons.

+ 25 kg ha^{-1} of K2O at R0. The other cultural treatments were carried out according to the technical recommendations for the crop (Sosbai, 2018).

Rice plant dry matter of the aerial part (DMAP) was determined by collecting a 0.17 m² (0.17 × 1 m) sample at V6 and R4 stages. In the same area, a metal rectangle of volume 0.012 m³ (0.3 × 0.2 × 0.2 m) was inserted into the soil for collection of the soil monolith and determination of root dry matter (RDM). After being washed, the roots and aboveground parts of the plants were taken to a forced ventilation oven at 65 °C until they reached constant mass. Afterwards, they were weighed on a 0.1 g precision balance and the data obtained were transformed to kg ha^{-1}.

The DMAP was ground in a Willey mill to determine the nitrogen (N), phosphorus (P), and potassium (K) contents in the tissue, according to the methodology described by Tedesco et al. (1995). Based on these results and the DMAP data, we determined the amounts of N, P, and K accumulated in the aboveground part of the rice plants.

Net carbon assimilation rate, stomatal conductance, intercellular CO_2 concentration, and transpiration rate were evaluated. The evaluations were performed in the middle third of the last fully expanded leaf of rice plants at the phenological stage R0, using a portable Infra Red Gas Analyzer (IRGA), WALS brand, model GFS-3000, using a photosynthetic radiation of 1,500 µmol m^{-2} s^{-1} and CO_2 concentration of 400 µmol mol^{-1}.

In the sprinkler-irrigated treatments in the 2020/21 crop experiment, unformed soil samples were collected at 0-0.05, 0.05-0.1, 0.1-0.15, 0.15-0.2, and 0.2-0.3 m depth layers for determination of soil physical-water properties: density, macroporosity, microporosity, total porosity, field capacity and permanent wilting point, and water content at the points of the soil water retention curve according to the methodology proposed by Donagema et al. (2011). The evaluation was performed at the R4 stage of the rice crop.

Grain yield was determined by harvesting a 4.08 m^2 (4 × 1.02 m) area when the grains had an average moisture content of 22%. After sorting, cleaning, and weighing the shelled grains, the data were corrected to 13% humidity and converted to kg ha^{-1}.

To measure the volume of water used in the continuous and intermittent irrigation systems, 1” diameter water flow meters were installed to allow independent management of each experimental unit. For sprinkler irrigation, the gross volume of water used in each irrigation was quantified. Irrigation water productivity was determined using the relationship between rice grain yield at 13% moisture (kg ha^{-1}) and water use (m³ ha^{-1}) (Fernández et al., 2020).

The results were subjected to the test of the mathematical model assumptions. The analysis of variance of the data was performed using the F test, and the averages of the factors, when significant, were submitted to the Scott Knott test at 5% error probability using the SISVAR statistical package.

Results and Discussion

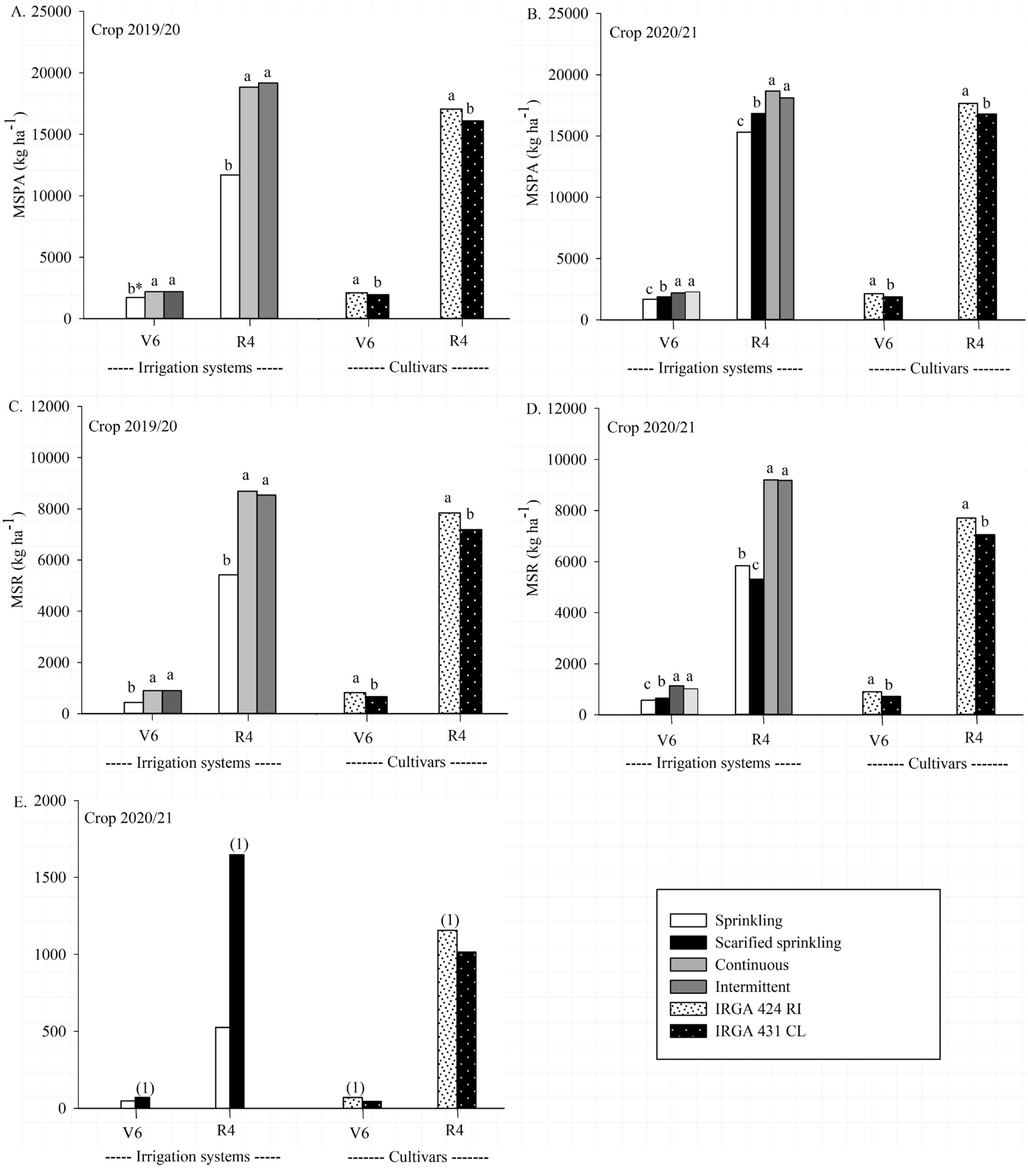
In the two crops analyzed, the accumulation of MSPA was significantly influenced by irrigation systems and cultivars (Figures 2A and 2B). Continuous and intermittent irrigation provided the highest averages at the V6 and R4 stages, but did not differ statistically. This result is attributed to the intensity of the intermittence used, because irrigation was resumed when the soil was not waterlogged, but still saturated (micro and macro pores).

In this sense, the chemical changes in the soil provided by flooding, such as the increase in pH, electrical conductivity, and the consequent increase in the availability of nutrients in the soil solution (Ponnamperuma, 1977), which benefit the rice crop, have possibly not been altered with the implementation of intermittent irrigation, providing growth and development conditions similar to those obtained by continuous irrigation.

On the contrary, when rice was grown in oxidized soil, by sprinkling, there was a reduction in the accumulation of DMAP, obtaining the lowest averages in the V6 and R4 stages in both crops. However, when grown in scarified soil, in the 2021/21 season (Figure 2B), there was an increase in the accumulation of DMAP, however, with values even lower than those obtained by continuous and intermittent irrigation. The reduction in DMAP accumulation when rice was grown in oxidized soil may be related, in part, to the absence of chemical changes caused by watering the soil, in which, under oxidized conditions, there is a reduction in the availability of nutrients in the soil solution.

When the soil is waterlogged, chemical and biological changes occur compared to the oxidized environment. In this condition, after oxygen consumption, the anaerobic microorganisms start using oxidized inorganic compounds as electron receptors, mainly Fe^{3+} and Mn^{4+} from the oxide surfaces, which are reduced to Fe^{2+} and Mn^{2+}, increasing their concentration in the soil solution (Ponnamperuma, 1977). Although phosphorus (P) is not directly involved in oxireduction reactions, its availability in solution is increased by being chemically bound to oxidized substances, such as Fe and Mn oxides (Ponnamperuma, 1977). Potassium (K) is also not directly involved in the oxireduction reactions, however, it has its availability increased due to its displacement from exchange sites into the soil solution by Fe^{2+} and Mn^{2+} cations, and the release of K from the non-exchangeable and structural soil fractions (Ponnamperuma, 1977).

Regarding nitrogen (N), under aerobic conditions, NH_4^+ from the mineralization of organic matter or the application of ammonia fertilizers (urea) is nitrified (NO_3^-). However, because it is very mobile in soil, NO_3^- can be lost by leaching, due to not forming strong enough bonds with the permanent soil charges to retain it in the root exploration layers (Buresh et al., 2008). In addition, NO_3^- can be lost through denitrification if there are periods of excess soil moisture (Buresh et al., 2008). In the flooded environment, the absence of oxygen interrupts the nitrification process, favoring the absorption and the accumulation of this nutrient by the plants, a condition favored by continuous and intermittent irrigation.



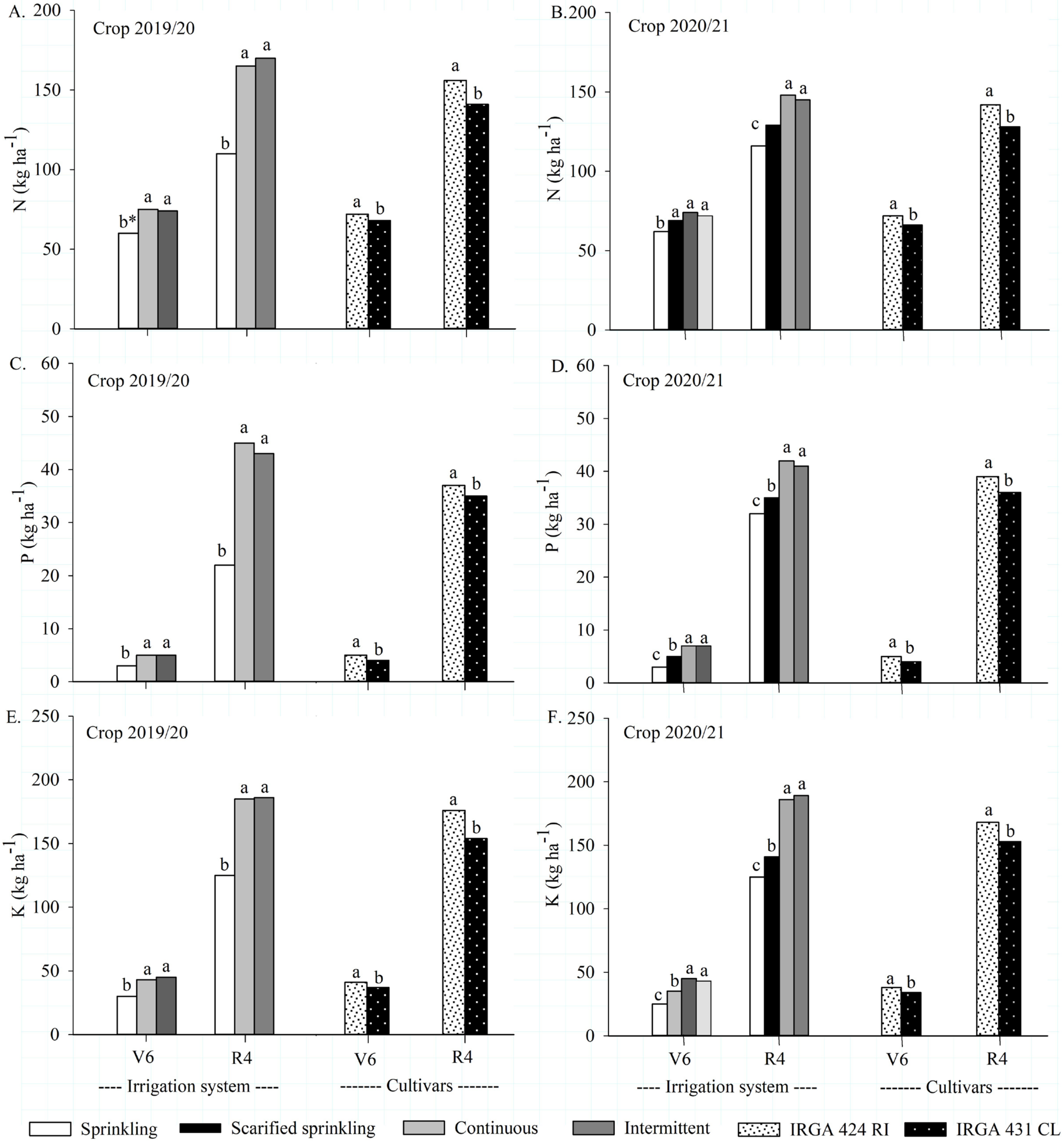
* Averages followed by the same letter do not differ significantly by the Scott Knott test at 5% probability of error. (1) Averages differed by the F test ($p < 0.05$).

Figure 2. Dry matter of the aerial part (A and B) and root in the 0-0.1m layer (C and D) and in the 0.1-0.2 m layer (E) in the phenological stages V6 and R4 of the cultivars IRGA 424 RI and IRGA 431 CL as a function of irrigation systems in the 2019/20 (A and C) and 2020/21 (B, D, and E) harvests.

As a result, there was a reduction in the accumulation of N, P, and K in the aboveground part of the rice plants grown by sprinkler irrigation, with continuous and intermittent irrigation showing the highest averages in both seasons, not statistically different from each other (Figure 3).

Increases in the accumulation of nutrients in the aerial part were verified when sprinkler irrigated rice was grown in scarified soil. This is related, in part, to the attenuation of the physical impediments of the soil provided by scarification (Figure 4), which promoted greater distribution and volume of roots deep in the soil profile (Figure 1).

This is evident when analyzing the accumulation of RDM in the stratified layers of soil (Figure 2E), in which the root system of sprinkler irrigated plants was restricted to the layer 0-0.1 m,

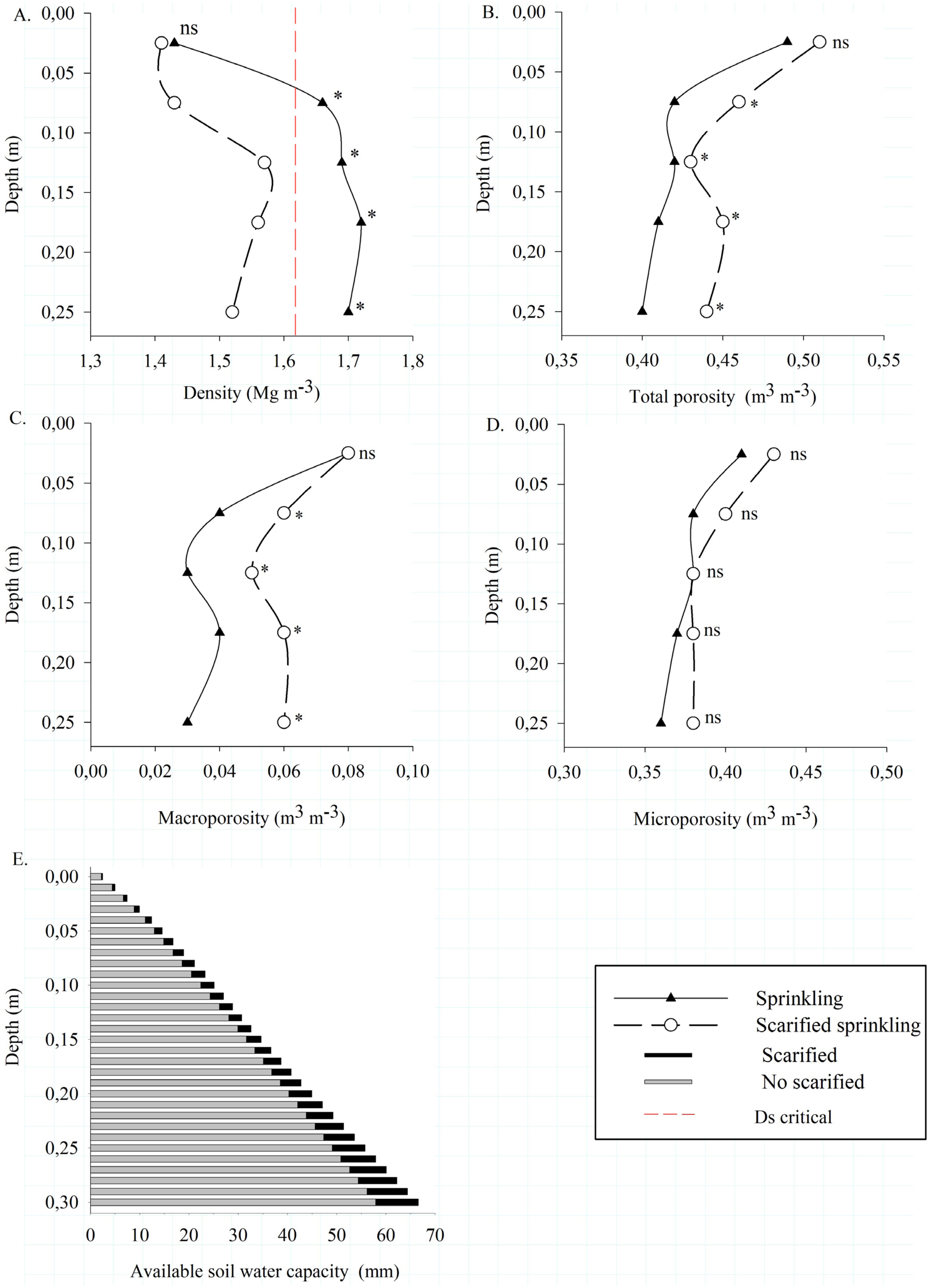


Averages followed by the same letter do not differ significantly by the Scott Knott test at 5% probability of error.

Figure 3. Accumulation of N (A and B), P (C and D), and K (E and F) in the aerial part of irrigated rice plants at phenological stagesV6 and R4 of the cultivars IRGA 424 RI and IRGA 431 CL as a function of irrigation systems in the 2019/20 (A, C, and E) and 2020/21 (B, D, and F) crops.

due to the presence of a layer with a high degree of compaction in the layer 0.05-0.10 m deep, which showed a density value of 1.67 Mg m^{-3}, higher than the critical density considered limiting root growth for this type of soil (Reichert et al., 2009).

When the soil was scarified, the RDM was 8.6% higher when compared to the treatment without scarification, but 24% of the root system was distributed in the 0.1-0.2 m layer, while in the treatment without scarification this value was only 8%. This shows that in addition to providing higher production of RDM, soil scarification enabled greater distribution of roots along the profile, promoting greater access to nutrients located in subsurface soil layers. The highest values of RDM accumulation were seen in a flooded environment by continuous and intermittent irrigation, which did not differ statistically. Regarding cultivars, IRGA 424 was the one that showed the highest accumulation of RDM and nutrients in the aerial tissue, differing statistically from IRGA 431 CL cultivar in both crops.



* Averages differed by the F test ($p < 0.05$). ns Not significant by the F test ($p \geq 0.05$). Sd = soil density.

Figure 4. Density (A), total porosity (B), macroporosity (C), microporosity (D), and available soil water capacity (E) in layers 0-0.5, 0.05-0.1, 0.1-0.15, 0.15-0.2, and 0.2-0.3 m under sprinkler irrigation system in scarified and unscarified soil.

As a reflection of the greater root growth at depth, there was an increase in the water capacity available to plants spray-irrigated on scarified soil when compared to spray-irrigated on non-scarified soil (Figure 4). When considering root growth up to 0.2 m, the available water content was 49 mm, while in the treatment without scarification and with physical limitation at 0.1 m this value was 22 mm, a reduction of 55%. In this sense, the reduced access to water due to the lower volume of soil explored by the root system of the plants, associated with periods of high evapotranspiration demand (greater than 7 mm day^{-1}) at the beginning of January 2020 (Figure 5A) and at the end of December 2020 (Figure 5B), impacted negatively on the physiological parameters of the treatment with non-sparked sprinkler irrigation, promoting a reduction in morpho-physiological variables.

Figure 6 shows a reduction of 44 and 13% in stomatal conductance (Figure 6D), 96 and 32% in transpiration rate (Figure 6C), 5 and 3% in intercellular CO_2 concentration (Figure 6B), and 27 and 14% in net CO_2 assimilation rate (Figure 6A) in the treatment with non-sparked sprinkler irrigation when compared to continuous and intermittent irrigation, which showed the highest averages, with no differences between them in the 2019/20 and 2010/21 crops, respectively (Figure 6).

With the lower availability of water in the soil in the treatment with sprinklers without scarification, there was a need for the plants to reduce water loss via transpiration, leading to the closure of stomata and, consequently, in the reduction of the stomatal conductance value. With the stomata more closed the diffusion of CO_2 into the chloroplasts is lower, limiting the carboxylation efficiency of ribulose-1,5-biphosphate carboxylase oxygenase, thus reducing the net CO_2 assimilation values during the photosynthesis process (Taiz et al., 2017).

There is an improvement in photosynthetic parameters of sprinkler-irrigated plants in non-scarified soil in the 2020/21 crop, which may be related, in part, to the higher availability of water in the soil of this treatment, which was kept close to saturation, unlike the 2019/20 crop in which irrigations were performed when the soil water content reached field capacity. In relation to sprinkler irrigation in the 2020/21 crop, there is an improvement in photosynthetic parameters in the treatment with soil scarification, which may be related to the increased availability of water, reducing the harmful effects to plants caused by periods of high evapotranspiration demand.

When the availability of water to the plants was not limiting, the highest values of photosynthetic rate, intercellular CO_2 concentration, transpiration rate, and stomatal conductance were verified by continuous and intermittent irrigation, which did not differ statistically. No statistical difference was found between IRGA 424 RI and IRGA 431 CL cultivars for the variables photosynthetic rate, intercellular CO_2 concentration, transpiration rate, and stomatal conductance in both crops.

The limitations imposed by the sprinkler-irrigated rice cultivation system, such as the physical restriction on root growth and consequent lower availability of water to the plants, the lower accumulation of nutrients, and the alteration of the morpho-physiological characteristics of the plant promoted a significant reduction in the crop's grain yield, obtaining averages of 9,094 and 10,547 kg ha^{-1} in the 2019/20 and 2020/20 agricultural harvests, respectively (Table 1).

However, by scarifying the soil, and thus promoting improvements in the plant root development environment, an increase in the morphophysiological parameters of the crop was obtained, resulting in an increase in grain yield of 6.3% compared to sprinkling without scarification. When the physical and chemical soil impediments were not limiting for rice cultivation, due to the beneficial effects provided by flooding in continuous and intermittent irrigation, the highest grain yields of the experiment were verified, with values of 12,337 and 12,440 kg ha^{-1} in the 2019/20 crop and 12,039 and 11,844 kg ha^{-1} in the 2020/21 crop, respectively, not statistically different from each other. Although the cultivar IRGA 431 CL showed a reduction in the morphophysiological variables analyzed and accumulation of nutrients in the aerial part, this was not reflected on the grain yield of the crop, not statistically different from the cultivar IRGA 424 RI, which obtained averages of 11,180 and 11,401 kg ha^{-1} in the 2019/20 crop and 11,334 and 11,163 kg ha^{-1} in the 2020/21 crop, respectively.

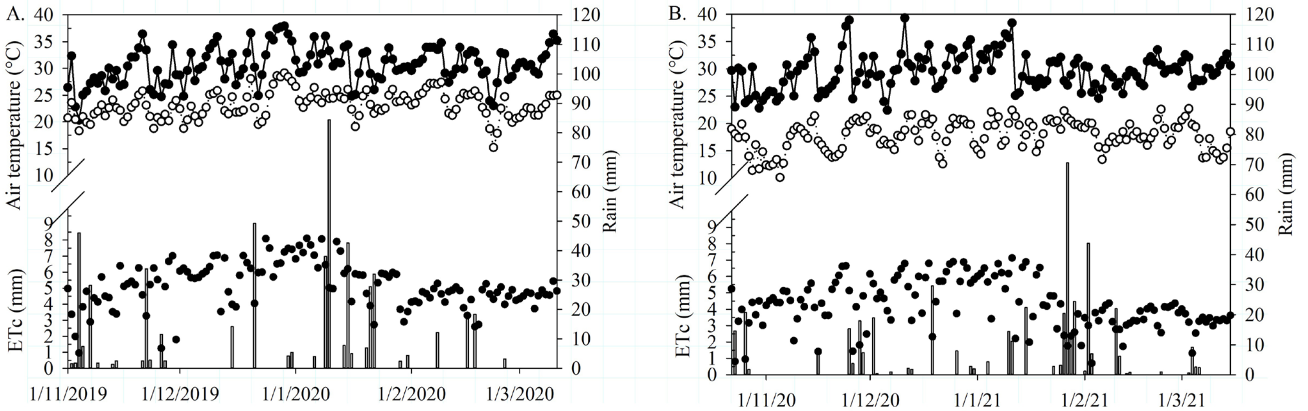
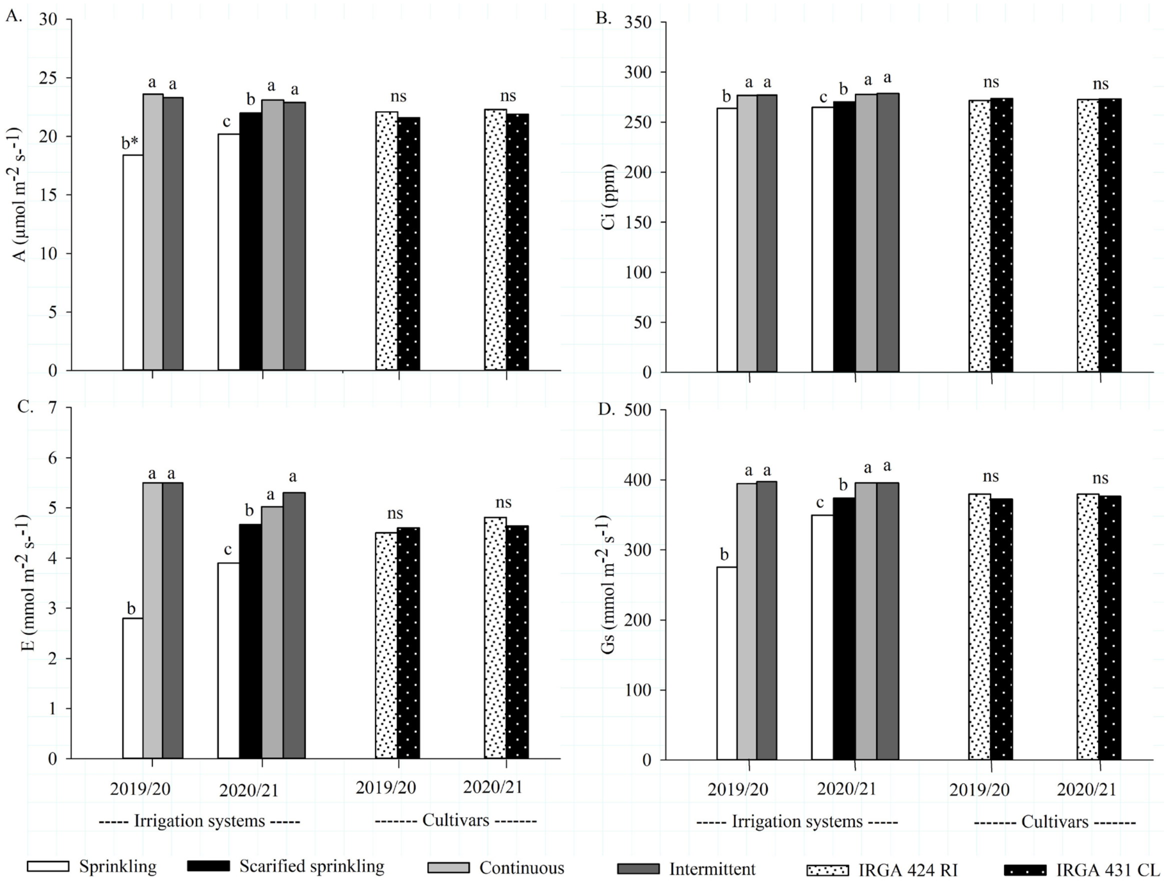


Figure 5. Maximum and minimum air temperature, rainfall, and daily crop evapotranspiration (ETc) in the 2019/20 (A) and 2020/21 (B) crops.



Averages followed by the same letter do not differ significantly by the Scott Knott test at 5% probability of error. ^{ns} Not significant by Scott-Knott test ($p \geq 0.05$).

Figure 6. Net carbon assimilation rate (A), intracellular CO_2 concentration (B), transpiration rate (C), and stomatal conductance (D) of irrigated rice plants at the R0 stage of IRGA 424 RI and IRGA 431 CL cultivars as a function of irrigation systems in the 2019/20 and 2020/21 crops.

Table 1. Grain yield, water productivity and volume of water used for irrigation of irrigated rice cultivars IRGA 424 RI and IRGA 431 CL as a function of irrigation systems in the 2019/20 and 2020/21 crops.

Irrigation systems	Grain productivity (kg ha^{-1})		Water productivity (kg m^{-3})	
	Crop 2019/20	Crop 2020/21	Crop 2019/20	Crop 2020/21
Sprinkling	9,094 b*	10,547 c	1.8 b*	2.5 b
Scarified sprinkling	-	11,255 b	-	2.7 a
Continuous	12,337 a	12,039 a	1.5 c	1.5 d
Intermittent	12,440 a	11,844 a	1.9 a	1.9 c
Cultivars				
IRGA 424 RI	11,180 ^{ns}	11,334 ^{ns}	1.6 b	2.1 b
IRGA 431 CL	11,401	11,163	1.9 a	2.2 a
CV%	2.3	4.1	2.9	3.4

Irrigation systems	Cultivars		Average	CV (%)
	IRGA 424 RI	IRGA 431 CL		
	Water volume for irrigation (m³ ha^{-1})			
	2019/20			
Sprinkling	5,178 cA^{1}	4,690 cB	4,934	1.1
Continuous	8,670 aA	7,810 aB	8,240	
Intermittent	6,868 bA	6,182 bB	6,525	
Average	6,905	6,227		
	2020/21			
Sprinkling	4,264 cA	4,004 cB	4,134	1.7
Continuous	8,287 aA	7,451 aB	7,869	
Intermittent	5,982 bA	5,427 bB	5,704	
Average	6,178	5,627		

* Averages followed by the same letter do not differ by the Scott Knott test at 5% probability of error. ^{ns} Not significant by Scott-Knott test ($p \geq 0.05$). ^{1} Averages followed by the same lower case letter in the column and capital in the row do not differ by the Scott Knott test at 5% probability of error.

Regarding the irrigation parameters, there was interaction among the factors for water use, obtaining statistical difference for irrigation systems and cultivars (Table 1). Continuous irrigation provided the highest irrigation water use, averaging 8,240 and 7,869 m^3 ha^{-1} in the 2019/20 and 2020/21 crops, respectively. Intermittent irrigation showed 21 and 28% reduction in water use, with averages of 6,525 and 5,704 m^3 ha^{-1} in the 2019/20 and 2020/21 crops, respectively. Sprinkler irrigation showed the greatest reduction in water use, with averages of 5,704 and 4,134 m^3 ha^{-1}, corresponding to a reduction of 40 and 47% in the 2019/20 and 2020/21 crops, respectively.

The lower water use by the treatments with sprinkler and intermittent irrigation is a result of the greater use of rainfall during the growing season, in which in the 2019/20 and 2020/21 harvests were 7,016 and 4,424 m^3 ha^{-1}, respectively. Although the volume of rainfall in the 2020/21 harvest was lower, they were events of lower intensity, however, better distributed throughout the growing season, allowing for better utilization. In the 2019/20 crop, on the other hand, rainfall distribution was irregular, with highlights for the months of December 2019 and February 2020, with accumulated precipitation of 813 and 880 m^3 ha^{-1}, a reduction of 53 and 63% of rainfall volume in relation to the climatological normal for these periods, respectively. Thus, in years with higher rainfall volumes and more uniform distribution throughout the growing season, the treatments with sprinkler and intermittent irrigation may have the potential to save water use.

Irrigation water productivity is higher in systems that maintain grain yields with lower water use (Hassen et al., 2017). Given this, due to the reduction in grain yield provided by the sprinkler irrigation system in the 2019/20 crop, the highest water yield was obtained by intermittent irrigation, with a value of 1.9 kg m^{-3}, followed by sprinkler irrigation (1.8 kg m^{-3}) and continuous (1.5 kg m^{-3}) (Table 1). In the 2020/21 crop, the increase in grain yield provided by soil scarification associated with sprinkler irrigation resulted in obtaining the highest value of irrigation water productivity, averaging 2.7 kg m^{-3}, followed by sprinkler irrigation (2.5 kg m^{-3}), intermittent irrigation (1.9 kg m^{-3}), and continuous irrigation, which obtained the lowest value of irrigation water productivity (1.5 kg m^{-3}). Among cultivars, IRGA 431 CL obtained a 16% increase on irrigation water productivity over IRGA 424 RI in the 2019/20 crop and a 5% increase in the 2020/21 crop. In this sense, IRGA 431 CL, for having a shorter biological cycle, obtained less water use for irrigation, having grain yield equivalent to that obtained by IRGA 424 RI, being a viable management strategy when aiming to reduce water use.

Conclusions

Intermittent irrigation provides reduced water use without impairing the grain yield of the crop when compared to continuous irrigation.

Sprinkler irrigation promotes a reduction in morphophysiological characteristics of the rice plant and grain yield when compared to flooded cultivation.

In the presence of physical soil impediments to root growth, scarification provides greater accumulation of aboveground and root dry matter, nutrient accumulation, photosynthesis-related parameters, and grain yield of rice when irrigated by sprinkler irrigation, resulting in higher irrigation water yield.

The IRGA 431 CL cultivar provides reduced water use and higher irrigation water productivity, without damaging the grain yield of the crop, when compared to IRGA 424 RI.

Compliance with Ethical Standards

Author contributions: Conceptualization: BBA, EM; Data curation: BBA, JGP, MHP, AGF; Formal analysis: BBA, RG; Investigation: BBA, EM, JGP, MHP, AGF; Methodology: BBA, EM; Project administration: BBA, EM; Resources: BBA, EM; Supervision: BBA, EM; Validation: BBA, EM, RG; Visualization: BBA; Writing - original draft: BBA; Writing - review & editing: EM, RG.

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