Field Crops Research 248 (2020) 107714

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Sprinkler irrigation in lowland rice: Crop yield and its components as a function of water availability in different phenological phases

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ARTICLE INFO

Keywords:
Oryza sativa L.
Lateral-move irrigation system
Soil physicochemical attributes

ABSTRACT

Efficient water use in agriculture is a global demand, and in this context, the implementation of a sprinkler irrigated rice system has become a reality. Besides saving water, proper management of a sprinkler irrigated system can maintain high levels of productivity. This study aimed to determine the effect of soil water tension on rice crop production, in both vegetative and reproductive stages, as well as to evaluate the effect of soil water availability and physicochemical attributes on biometric and reproductive characteristics associated to rice grain yield under sprinkler irrigation. The experiment was carried out at the Lowland Experimental Station, Embrapa Clima Temperado, Capão do Leão – Rio Grande do Sul, Brazil, during two growing seasons, in an area irrigated by a lateral-move sprinkler irrigation system. The following irrigation managements were evaluated: irrigation, when the mean soil water tension was i) 10 kPa; ii) 20 kPa; iii) 40 kPa; iv) 40 kPa on vegetative and 20 kPa on reproductive stages and v) 40 kPa on vegetative and 10 kPa on reproductive stages. Under sprinkler irrigation, rice plant development was impaired as soil water tension increased, evidenced by a reduction in plant heights. Soil water tension of 10 kPa was adequate to manage the sprinkler irrigation in rice, especially in the reproductive stage and when using cultivars developed for flooded environments. Rice development and yield were affected by increasing soil bulk density and acidity. Rainwater represented approximately 40 % of the water used by sprinkler irrigated rice during the crop cycle, contributing with the reduction of irrigation water use.

1. Introduction

In Southern Brazil and several regions of the world, rice is cultivated under flooded conditions. In this system, a large amount of water is lost through evapotranspiration, surface runoff, seepage, and deep percolation (Vories et al., 2013; Materu et al., 2018).

The search for efficient use of water in rice production systems is a worldwide demand, and several water-saving irrigation techniques have been developed for rice (Nie et al., 2012). The aerobic rice system, for example, features rice grown under non-flooded conditions in non-puddled and unsaturated (aerobic) soil which is responsive to nutrient supply, can be rainfed or irrigated and tolerates occasional flooding (Bouman and Tuong, 2001).

The use of mechanized sprinkler irrigation systems (center-pivot and mechanical lateral-move) in rice production has increased in Southern Brazil, due to the needs of the farmers to reach easy management of the rice irrigation combined with more efficient water use. Such motivation for use has been reported by rice producers who have similarly adopted the sprinkler irrigated rice system in Italy (Spanu et al., 2009), USA (Vories et al., 2017) and India (Mandal et al., 2019).

In a study carried out in Pakistan, Kahlown et al. (2007) concluded that sprinkler irrigation of rice reached 18 % more yield when compared to paddy rice while reducing water consumption by 35 %. In Arkansas (USA), Vories et al. (2013) observed a total irrigation depth of 414 mm for rice production under center pivot irrigation, while in the flood-irrigated rice system, depths of up to 1168 mm were observed. In India, Kumar et al. (2018) observed water savings of around 20 % using sprinkler irrigation when compared to surface irrigation. In the same

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https://doi.org/10.1016/j.fcr.2020.107714
Received 12 September 2019; Received in revised form 19 December 2019; Accepted 2 January 2020

way, Pinto et al. (2016)

In the Western Border of Rio Grande do Sul state, Brazil, studies have shown that the estimated water consumption of rice under sprinkler irrigation was 550 mm throughout the crop cycle, corresponding to approximately half the volume traditionally used in the continuous flooding rice system (Pinto et al., 2016).

Besides saving water, sprinkler irrigation in rice enables the farmer to adopt soil conservation techniques such as no-till farming and crop rotation. Therefore, by adopting a sprinkler system, an irrigated area can be almost triplicated in a rice-soybean production system, utilizing the same volume of water consumed by a rice system under continuous flooding.

Concerning to sprinkler irrigation, its management deserves special attention. According to Kar et al. (2018) irrigation management with a higher soil water tension, reach a reduction of water use; however, it negatively impacts the rice grain yield. In this way, Zain et al. (2014) evaluating the irrigation management with seven soil water tension treatments (0, 5, 10, 15, 20, 25 and 30 kPa), found a reduction of rice yield with the reduction of water availability. Also, Crusciol et al. (2003), observed linear increases in rice grain yield due to an increase in water availability.

It is important to highlight the scarcity of studies evaluating the influence of the soil water tension and the soil physicochemical attributes in the rice crop yield, especially considering different irrigation management for vegetative and reproductive phenological phases. In this context, this study aims to evaluate the effect of soil water availability and physicochemical attributes on the biometric and reproductive characteristics of a lowland rice production system under sprinkler irrigation.

2. Materials and methods

2.1. Experimental area

The experiment was carried out at the Lowland Experimental Station, Embrapa Clima Temperado, Capão do Leão, Rio Grande do Sul state, Brazil. The experimental area was irrigated by a Valley mechanical lateral-move irrigation system (Valmont Industries, NE USA), composed of 5 spans equipped with Senninger (Clermont, FL USA) I-Wob sprinklers coupled to 68.9 kPa pressure regulators.

According to Natural Resources Conservation Service (NRCS, 2003), the soil of the experimental area was classified as Typic Albaqualf. This soil is characteristic of lowlands traditionally cultivated with flooded / paddy rice. The climate is classified as “Cfa”, that is, temperate humid with hot summers, the mean annual precipitation varies between 1600 and 1900 mm (Alvares et al., 2013).

The experiment was repeated during two growing seasons, 2011 and 2012, using different and adjacent areas to avoid rice monoculture. In 2011 the dimensions of the experimental plots were 20 m width by 40 m length; in the following season, the width of plots was reduced to 7 m to facilitate the mechanized application of agrochemicals.

The experimental areas were intercropped with winter pastures, ryegrass (*Lolium multiflorum*) and birdsfoot trefoil (*Lotus corniculatus*), in both growing seasons. A burndown herbicide was applied approximately 30 days before sowing rice. The irrigated rice cultivar BRS Pampa was sowed at a density of 100 kg ha^{-1} of viable seeds, with 17.5 cm row spacing, in a no-tillage system.

2.2. Crop management

Essential fertilization, 350 kg ha^{-1} of the NPK formulation 5-20-20, was applied in the sowing furrow at the same time that the rice was sowed, in both years of the experiment. Since specific fertilizer recommendations for rice in sprinkler irrigation systems were not yet available, fertilization was established based on the results of soil chemical analysis, and considered a high expectation of crop response to fertilization, as recommended for rice in the flood irrigation system (SOSBAI, 2010).

In the 2011 harvest, sowing was carried out on 11/04/2011 and the emergence occurred on 11/18/2011; nitrogen fertilization was performed on 12/07/2011 (four-leaf stage - V4) using 85 kg ha^{-1} of urea, and on 01/10/2012 at the panicle initiation stage (R1), using 100 kg ha^{-1} of urea; harvest occurred on 28/03/2012. In 2012, rice was sown on 10/15/2012 and on 11/06/2012 emergence occurred; nitrogen fertilization was carried out on 11/23/2012 (130 kg ha^{-1} of urea), and 01/09/2013 (66 kg ha^{-1} of urea), in the V4 and R1 stages, respectively; harvest occurred on 03/25/2013. Rice growth stages were monitored using the scale of Counce et al. (2000).

2.3. Irrigation management

Soil water tension (SWT) was monitored using Watermark® sensors, which were installed at depth of 0.10 m, based on the effective depth of the rice root system. In the first year, 12 Watermark® sensors were installed per experimental plot. In the following year, 14 Watermark® sensors were used per plot. Soil water tension data were recorded by datalogger at one-hour regular intervals, throughout the crop cycle. Each experimental plot corresponded to a different irrigation management.

In 2011 three irrigation managements were evaluated:

a) 20 kPa – irrigation when the average soil water tension was 20 kPa throughout the crop cycle.
b) 40/20 kPa – irrigation when the average soil water tension was 40 kPa during the vegetative stage (from emergence to panicle differentiation (R1)), and when the average soil water tension was 20 kPa, during the reproductive stage (from R1 to harvest maturity (R9)).
c) 40 kPa – irrigation when the average soil water tension was 40 kPa throughout the crop cycle.

In 2012 four irrigation managements were evaluated; a) 20 kPa or b) 40 kPa throughout the cropping cycle, as in the previous growing season, and additionally:

a) 10 kPa – irrigation when the average soil water tension was 10 kPa throughout the crop cycle.
b) 40/10 kPa – irrigation when the average soil water tension was 40 kPa during the vegetative stage (E to R1), and when the average soil water tension was 10 kPa, during the reproductive phase (R1 to R9).

2.4. Measurements

In each experimental plot, the installation point of the Watermark® sensors corresponded to the center of an experimental unit with an area of 4 m^2. Thus, variables of plant development and yield, and soil physicochemical attributes were determined in 36 (2011) and 56 (2012) experimental units.

Plant height (PH) was measured from the soil surface to the end of the panicle in 10 plants. The number of stalks per meter (SM) were counted per linear meter in three rows (3 subsamples). To determine whole grains per panicle (WGP), spikelet sterility (ST) and 1000-grain weight (1000-GW), a sample of 25 panicles was collected. Each 4 m^2 area of the experimental units was harvested to obtain crop yield.

Soil samples with a preserved structure were collected at a depth of 3 cm, to represent the 0 − 10 cm layer, using stainless steel cylinders (3 cm high and 4.7 cm diameter). These samples were used to determine soil bulk density, macro, micro, and total porosity according to the methodology described in Donagema et al. (2011). Soil samples with no preserved structure were also collected at the same soil layer to determine the following chemical attributes: pH in water, exchangeable

Al, Ca e Mg, available P, and removable K according to the methods described in Tedesco et al. (1995).

2.5. Data analysis

To evaluate the effect of water availability on yield, plant stature and yield components, multiple linear regression models were adjusted for each of these variables (Z), as a function of mean soil water tension in the vegetative (SWTv) and reproductive (SWTr) stages - X and Y of the equation, respectively, using the mean values of the SWTv and SWTr determined in each experimental unit, totaling 36 replications in 2011 and 56 replications in 2012. The relationship between rice yield as well its components and soil physicochemical attributes was evaluated by the Pearson correlation.

3. Results

3.1. Rice vegetative development

Rice plant growth was negatively influenced by the water deficit. In both growing seasons the height of rice plants decreased with the increase of SWTv and SWTr. In contrast, rice tillering was not affected by soil water availability; there was no significant effect of the SWTv and SWTr on the number of stalks per meter in both years (Table 1).

3.2. Rice development and yield as function of soil water tension

Rice yield values as a function of soil water tension in the vegetative and reproductive stages, in the two years of the experiment, are shown in Fig. 1.

According to the multiple linear regression models, soil water tension has a significant effect on rice yield in both stages. The increase in SWT from 0–40 kPa resulted in a decrease in rice yield of up to 6000 kg ha^{-1} (Fig. 1A and B).

In the two growing seasons, the highest productivity was obtained when SWTv and SWTr were below 10 kPa. A more pronounced decrease in yield was found when SWT was up to 15 kPa, above this tension the decrease in yield due to increasing SWT presented lower albeit prominent rates, remaining around 50 % of the maximum yield. Lowest yields occurred when SWTr were higher than 25 kPa, even with SWTv ranging from 0–40 kPa, showing the rice plants to be more sensitive to the water deficit during the reproductive stage (Figs. 1A and 1B).

In terms of yield components, only the number of whole grains per panicle showed a sensitivity to water deficiency (Table 2). In both years, an increase in soil water tension during the vegetative and reproductive stages resulted in a decrease in the number of whole grains per panicle.

3.3. Soil physico-chemical attributes and rice development and yield

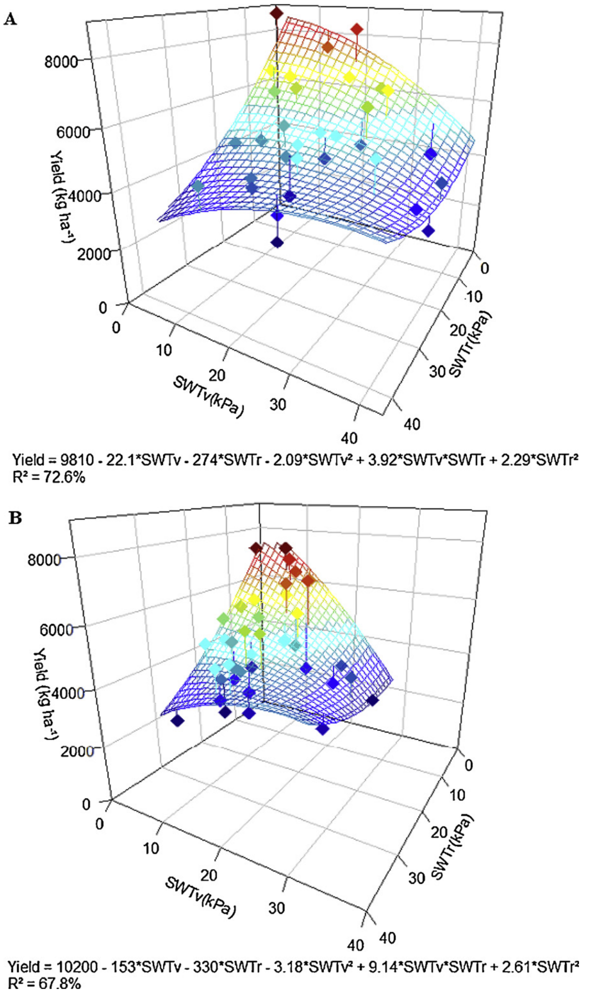

Fig. 1. Relationship between sprinkler irrigated rice yield, and soil water tension in the vegetative (SWTv) and reproductive (SWTr) rice developmental stages, adjusted by the multiple linear regression model for 2011 (A) and 2012 (B) growing seasons.

Table 1
Multiple linear regression models for estimating sprinkler irrigated rice plant height and stalks per meter as a function of soil water tension in the vegetative (SWTv) and reproductive (SWTr) stages.

Model	R^2	P value
^{1} PH = 90.659 - 0.166 (SWTv**) - 0.235 (SWTr***)	0.59	< 0.001
^{2} PH = 82.541 - 0.182 (SWTv*) - 0.205 (SWTr***)	0.42	< 0.001
^{1} SM = 74.901 + 0.059 (SWTv^{NS}) - 0.479 (SWTr^{NS})	0.13	0.138
^{2} SM = 91.832 - 1.555 (SWTv^{NS}) - 0.303 (SWTr^{NS})	0.14	0.172

^{1}2011; ^{2}2012 PH = plant height (cm); SM = stalks per meter; SWTv = soil water tension on vegetative phase (kPa); SWTr = soil water tension on reproductive phase (kPa). *P < 0.05; **P < 0.01; ***P < 0.001; ^{NS}P > 0.05.

Table 2
Multiple linear regression models for estimating sprinkler irrigated rice yield components as a function of soil water tension in vegetative (SWTv) and reproductive (SWTr) stages.

Model	r^2	P value
^{1} WGP = 125.800 - 0.630 (SWTv***) - 0.418 (SWTr**)	0.54	< 0.001
^{2} WGP = 137.784 - 1.054 (SWTv***) - 0.701 (SWTr**)	0.44	< 0.001
^{1} 1000-GW = 24.289 - 0.0014 (SWTv^{NS}) + 0.0575 (SWTr^{NS})	0.04	0.546
^{2} 1000-GW = 24.263 + 0.0110 (SWTv^{NS}) - 0.0491 (SWTr^{NS})	0.25	0.154
^{1} ST = 15.775 + 0.00480 (SWTv^{NS}) + 0.0937 (SWTr^{NS})	0.17	0.071
^{2} ST = 11.338 - 0.00146 (SWTv^{NS}) + 0.123 (SWTr^{NS})	0.11	0.159

^{1}2011; ^{2}2012. SWTv = soil water tension on vegetative phase (kPa); SWTr = soil water tension on reproductive phase (kPa); 1000-GW = 1000-grain weight (g); WGP = whole grains per panicle; ST = sterile (%). ***Significant parameter at 0,1 %; *P < 0.05; **P < 0.01; ***P < 0.001; NSP > 0.05.

In the first growing season the increase in soil density resulted in a better development and yield of rice plants, having a positive correlation between soil density and PH, SM, WGP, and yield. However, in the second crop, the correlation between soil density and PH, WGP, and yield was negative (Table 3).

The chemical attributes pH, Ca, Mg, CEC, and V were positively correlated with plant height, the number of stems per meter and yield. P and K contents in the soil were positively correlated only with yield and limited to the second crop. Increasing the percentage of aluminum in

Table 3

Pearson correlation values between soil physical-chemical attributes and parameters of rice development and yield under sprinkler irrigation.

Soil/Plant	PH	SM	1000-GW	WGP	ST	Yield
[1]Soil bulk density	0.42*	0.39*	−0.20^{NS}	0.55**	−0.51**	0.52**
[2]Soil bulk density	−0.88***	0.18^{NS}	0.19 ^{NS}	−0.47**	0.46**	−0.39**
[1]Macroporosity	−0.42*	−0.41*	0.21^{NS}	−0.30^{NS}	0.11^{NS}	−0.36 ^{NS}
[2]Macroporosity	−0.23^{NS}	−0.18^{NS}	0.05^{NS}	−0.22^{NS}	0.28 ^{NS}	−0.18^{NS}
[1]Microporosity	−0.01^{NS}	−0.01^{NS}	−0.18^{NS}	0.08^{NS}	−0.04^{NS}	−0.09^{NS}
[2]Microporosity	0.13^{NS}	0.13 ^{NS}	−0.16^{NS}	0.39*	−0.35*	0.24^{NS}
[1]Total porosity	−0.34^{NS}	−0.17^{NS}	0.02 ^{NS}	−0.27^{NS}	0.14^{NS}	−0.25^{NS}
[2]Total porosity	−0.11 ^{NS}	−0.06 ^{NS}	−0.09 ^{NS}	0.14 ^{NS}	−0.04 ^{NS}	0.04^{NS}
[1]pH (H_2O)	−0.06^{NS}	−0.08^{NS}	−0.20 ^{NS}	0.17^{NS}	−0.44*	0.04^{NS}
[2]pH (H_2O)	0.32*	0.32*	0.09 ^{NS}	0.15 ^{NS}	−0.13 ^{NS}	0.47**
[1]Ca	0.40*	0.01^{NS}	−0.19 ^{NS}	0.32^{NS}	−0.39*	0.30^{NS}
[2]Ca	0.40**	0.36*	−0.01 ^{NS}	0.41**	−0.35*	0.47**
[1]Mg	0.08^{NS}	0.03^{NS}	−0.44*	0.43*	−0.41*	0.10^{NS}
[2]Mg	0.46**	0.50**	0.04 ^{NS}	0.42**	−0.33*	0.59***
[1]P	−0.31^{NS}	−0.15^{NS}	−0.15 ^{NS}	−0.01^{NS}	−0.08^{NS}	−0.14^{NS}
[2]P	−0.12^{NS}	−0.19^{NS}	−0.14^{NS}	0.17^{NS}	−0.20 ^{NS}	0.29*
[1]K	0.06^{NS}	0.04^{NS}	0.05 ^{NS}	0.30^{NS}	0.24^{NS}	0.14^{NS}
[2]K	−0.37*	0.05^{NS}	−0.14 ^{NS}	0.03 ^{NS}	0.05 ^{NS}	0.27*
[1]CEC	0.01 ^{NS}	−0.08^{NS}	−0.08 ^{NS}	0.40*	−0.39*	0.02^{NS}
[2]CEC	0.31*	0.32*	−0.14 ^{NS}	0.56**	−0.54**	0.31*
[1]V (%)	0.39*	−0.03^{NS}	−0.03 ^{NS}	0.16^{NS}	−0.27^{NS}	0.21^{NS}
[2]V (%)	0.45**	0.38*	0.11 ^{NS}	0.17 ^{NS}	−0.08 ^{NS}	0.46**
[1]m (%)	−0.43*	−0.26^{NS}	0.01 ^{NS}	−0.25^{NS}	0.22^{NS}	−0.42*
[2]m (%)	−0.48**	−0.53*	0.07 ^{NS}	−0.20 ^{NS}	0.17 ^{NS}	−0.48**

[1]2011; [2]2012 PH = plant height (cm); SM = stalks per meter; 1000-GW = 1000-grain weight (g); WGP = whole grains per panicle; ST = sterile (%); CEC = cation exchange capacity at pH 7.0; V = base-saturation percentage; m = Al saturation percentage. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; $^{NS}P > 0.05$.

the soil (m) resulted in lower PH, SM, and yield. There was a positive correlation between WGP with microporosity, Ca, and Mg levels and CEC, and a negative correlation with sterile (ST) for these same soil attributes (Table 3).

3.4. *Water use*

The total irrigation and rainfall depths in the vegetative and reproductive stages of the rice crop are presented in Table 4. Total rainfall was found to be 385 and 401 mm in the 2011 and 2012 growing seasons, respectively. Independent of the year, the highest rainfall occurred during the reproductive period.

In this study, the highest irrigation depth applied was 534 mm in 10 kPa management. According to SOSBAI (2018), in order to supply the rice water need in the flooded system, an estimated mean water volume of 600–1200 mm for an average period of irrigation of 80–100 days is required. Considering that irrigated rice crops in the state of Rio Grande do Sul consume on average 900 mm, use of a sprinkler irrigation management system with SWT of 10 kPa would mean a reduction of water usage by 40 %.

Table 4

Total irrigation depths and rainfall at each period of the rice crop cycle for different irrigation management based on soil water tension in the 2011 and 2012 growing seasons.

Growing season	Management	Vegetative stage		Reproductive stage	
		Irrigation (mm)	Rainfall (mm)	Irrigation (mm)	Rainfall (mm)
2011	20 kPa	108	102	183	283
	40/20 kPa	81	102	192	283
	40 kPa	72	102	159	283
2012	10 kPa	138	170	396	231
	20 kPa	63	170	252	231
	40 kPa	30	170	156	231
	40/10 kPa	30	170	369	231

4. Discussion

4.1. *Rice vegetative development*

Water deficit conditions usually lead to a decrease in the growth rate of plants. In the present study, a decrease in plant height was observed. According to Jones (1992), water deficit affects photosynthesis and ion absorption, reflected as a reduction in the plant growth rate, and understood to be an adaptive characteristic for plant survival.

Soil water tension did not influence rice tillering. However based on the models, in both years the average number of stalks per meter was found to be less than 100. Considering that there was only one panicle per stem, this is quite a small value. According to SOSBAI (2018) for a maximum expression of productive potential of flooded rice cultivars, more than 120 panicles per meter are needed. The small number of stalks may indicate the need for a higher sowing density for sprinkler irrigated rice compared to paddies.

4.2. *Rice yield and its components*

Several agronomic factors can interfere with crop productivity, such as soil fertility, pests, diseases, weed control, seed quality and sowing season, among others. However, based on the multiple linear regression models, in this study, around 70 % of the crop yield may be lost due to inadequate soil water tension management, making the proper monitoring of adequate soil water tension and irrigation scheduling essential for sprinkler irrigated rice.

The variation in SWT of 0–40 kPa showed that rice plants have a considerable sensitivity to water deficiency. Kar et al. (2018) also observed that as the threshold for irrigation increased from no stress to 40 kPa, rice grain yield declined. Therefore in sprinkler irrigation, as in the case of flooded rice systems, the demand for water has to be adequately supplied to avoid grain yield losses. In two years of evaluation, Crusciol et al. (2003) observed linear increases in rice grain yield due to an increase in water availability.

Soil water tension should be kept as close to saturation as possible, provided that no runoff losses occur during irrigation. The high water availability of saturated soil results in high leaf water potential, which in turn favors the photosynthetic rate and as a consequence, mass accumulation. The highest yields that were obtained when soil water tension was close to soil water saturation can be also explained by the cultivar used in this study. The BRS Pampa was developed for cultivation with flood irrigation; thus, the closer to the saturated soil condition, the better the environment is for this cultivar. In Malaysia, Zain et al. (2014) conducted a study comparing the performance of a rice cultivar developed for flood irrigation, in flooded, saturated, and aerobic systems, and observed that productivity was the same in flood irrigation treatments and saturated soil conditions.

Although SWTv and SWTr affected rice yield, the effect of the soil water deficit was more adverse during the reproductive stage. According to Pinheiro (1999), when water deficiency occurs in the vegetative phase of rice, no severe reduction in crop yield is observed. However, in the reproductive phase, this effect causes a significant reduction in productivity, especially if the occurrence is during the period of pollen meiosis and flowering.

In regards to yield components, only the number of grains per panicle was sensitive to water deficiency. It could be because both nutrient uptake and maintenance of plant photosynthetic rates are impaired by water stress, resulting in decreased grain formation and filling. Patel et al. (2010) evaluated yield components of rice grown under aerobic and flood conditions in India, and found that the number of spikelets per panicle was lower in aerobic conditions and was the greatest factor contributing to the difference of rice grain yields under aerobic and flooded conditions. Kumar et al. (2018) also observed an adverse effect of the water deficit on the number of whole grains per panicle in sprinkler irrigated rice.

The soil water tension did not have an influence on the 1000-grain weight. This variable is characteristic of the genetic improvement of the cultivar, highly correlated to varietal character, quite stable and little influenced by environmental conditions (Yoshida, 1981).

No effect of soil water tension on spikelets sterility was observed. In a study carried out in Thailand, Ginigaddara and Ranamukhaarachchi (2009), evaluated rice yield components under different water management systems: flooded; two weeks with irrigation and two weeks without irrigation; one week with irrigation and three weeks without irrigation. Similar to the current study, the authors did not observe an effect of water stress on the 1000-grain weight or the sterility of spikelets. According to Kato and Katsura (2014), providing irrigation before the soil water tension decreased below 30 kPa, could eliminate the risk of spikelet sterility in the aerobic rice crop.

The highest productivity obtained in this study was 8811 kg ha^{-1} (SWTv = 7.8 kPa, SWTr = 5.6 kPa), obtained in 2011. Given that the expected productivity of the cultivar BRS Pampa with flood irrigation was 10.2 t ha^{-1}, the productivity of the sprinkler irrigated crop was around 87 % of the maximum productivity obtained with flood irrigation. In drip irrigated rice in China, Adekoya et al. (2014) utilized a total irrigation depth of 3000 m^3 ha^{-1}, while in the conventional method of irrigation by flooding 11,250 m^3 ha^{-1} was used. Comparisons of rice productivity under drip irrigation in their study varied between 76 and 95 % of the productivity obtained under flood irrigation.

4.3. Soil physico-chemical attributes and rice development and yield

Soil bulk density affects rice development and yield. However, in the first year of the present study an unexpected positive effect was observed. This could be due to the fact that increased soil bulk density results in decreased pore size, and smaller sized pores results in greater soil water retention. Thus, an increase in density would also be an increase in water availability, which, as seen earlier, is critical for rice production. In the second year, soil bulk density had a negative effect, possibly due to soil compaction in the area. Soil compaction causes a decrease in root system development as well as in water and nutrient absorption, and as a consequence, can lead to decreases in plant growth and yield.

Soil pH, Ca and Mg levels, CEC, and V were positively correlated with rice growth and yield, while aluminum saturation (m) was negatively correlated. These relationships showed the importance of soil acidity correction for adequate rice development. Liming increases Ca and Mg levels and in turn CEC and V, as well as neutralizes Al. Liming becomes essential for soil fertility management when rice is sprinkler irrigated, since according to SOSBAI (2018), pH elevation occurs naturally as a consequence of the soil reduction process in flooded soils.

4.4. Water use

Higher rainfall volumes occurred during the reproductive stage; however, irrigation volumes were also higher during this time. A higher water demand during the reproductive stage could be owing to the length of the reproductive stage in comparison to the length of the vegetative stage. In 2011 the vegetative stage lasted for 53 days and the reproductive stage 77 days; in 2012 the stages were 64 and 74 days for vegetative and reproductive stages, respectively. In this phase of the crop cycle the plants are bigger, resulting in higher water consumption. It is also during this this stage that the formation and filling of grains occurs, increasing the photosynthetic rate and the water demand of the plant. Most of the water lost by the plant evaporates as the CO_2 required by photosynthesis is absorbed from the atmosphere (Taiz and Zeiger, 2004).

The reduction of water consumption in sprinkler irrigation is mainly due to rainwater, since the rains that occurred during the crop cycle replaced several irrigations. This represents an economy that, depending on the year, can reach significant values in total water usage. According to Mohammad et al. (2018), a sound irrigation schedule is one that facilitates the efficient use of rainfall in the wet season, and minimizes water application losses. Throughout the crop cycle in the 10 kPa treatment, which had the highest irrigation demand as well as the highest yields, the total irrigation was 534 mm, and the total rainfall was 401 mm. In this way it can be seen that rainfall roughly represented 40 % of the water used by the crop in the experiment.

Although rice yields were found to be slightly less in sprinkler irrigation rather than under flooding conditions, adopting the sprinkling system is expected a efficient use of water in rice fields, attending a global demand to more sustainable agriculture. A further benefit of sprinkler irrigation is that some fertilizers and agrochemicals can be applied through the irrigation machinery. Moreover, the nature of sprinkler irrigation and its implementation with soil conservation practices such as no-tillage and crop rotation is another important factor to consider, as its adoption can benefit the environment. In this way, sprinkler irrigation for rice can be seen as a viable system, especially in areas with undulating relief where the use of flood irrigation would be even more costly.

5. Conclusions

According to the current study, rice development under sprinkler irrigation was impaired by soil water tensions, as evidenced by a reduction in plant heights and yield as soil water tension increased. Therefore, soil water tension of 10 kPa is adequate for sprinkler irrigation management in rice crop, especially during the reproductive period and when using a cultivar developed for the flood irrigation system. Besides soil water tension, rice development and yield were affected by increasing soil acidity; thus, liming becomes essential for soil fertility management when rice is sprinkler irrigated. Finally, it is essential to note that rainwater represented approximately 40 % of the water used by sprinkler irrigated rice during the crop cycle, contributing to the reduction of irrigation water use.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Marília Alves Brito Pinto: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft. **José Maria Barbat Parfitt:** Conceptualization, Methodology, Investigation, Project administration, Resources, Writing - review & editing. **Luís Carlos Timm:** Conceptualization, Methodology, Project administration, Writing - review & editing, Funding acquisition. **Lessandro Coll Faria:** Conceptualization, Validation, Formal analysis, Writing - review & editing. **Germani Concenço:** Validation, Formal analysis, Writing - review & editing. **Lizete Stumpf:** Validation, Formal analysis, Writing - review & editing. **Bernardo Gomes Nörenberg:** Validation, Formal analysis, Writing - review & editing.

Acknowledgments

The authors wish to thank the National Council for Scientific and Technological Development (CNPq) and the Foundation for Research Support of Rio Grande do Sul (Fapergs), program Decit/SCTIE-MS, for financial support; the Coordination for the Improvement of Higher Education Personnel in Brazil (CAPES) for the scholarship and the Valmont and Embrapa Clima Temperado Companies, for the concession of infrastructure to carry out this work.

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