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RESEARCH

Response of direct seeded rice to increasing rates of nitrogen, phosphorus, and potassium in two paddy rice soils

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ABSTRACT

The rice (*Oryza sativa* L.) crop is very important worldwide for its contribution to human nutrition. Rice grain yield depends on several agronomic management factors that must also be adjusted to the cropping system such as permanent inundation (anaerobic conditions) or direct seeding (aerobic and anaerobic conditions) mainly in response to the application of nutrients such as N. In Chile, the cropping system with direct seeding has limited agronomic and scientific development. The objective was to determine the effect of increasing N (0, 40, 80, 120, and 160 kg ha^{-1}), P (0, 30, 60, and 120 kg P_2O_5 ha^{-1}), and K (0, 30, 60, and 120 kg K_2O ha^{-1}) rates on grain yield and N agronomic efficiency (NAE) (kg grain produced per kg N applied) in two paddy rice soils for two consecutive seasons. Grain yield had a positive response to increasing N rates in the two evaluated soils (grain yield increased from 6.7 to 8.9 Mg ha^{-1} in the Vertisol and from 7.4 to 11.0 Mg ha^{-1} in the Alfisol) and a low response to P rates in the Vertisol. The Alfisol showed no response to increasing P rates, and both soils had no response to K application. The N rates that obtained the highest rice grain yield were 120 and 160 kg ha^{-1} for Alfisol and Vertisol, respectively. The P rate that obtained the highest rice yield in the Vertisol was 30 kg ha^{-1} P_2O_5. In addition, NAE values associated to those N rates were 74 and 61, respectively. In conclusion, direct seeding in rice cropping had a response to high rates of applied N, low response to P, and no response to K.

Key words: Direct seeding, fertilization, grain yield, *Oryza sativa*.

INTRODUCTION

Rice (*Oryza sativa* L.) is one of the most important cereal crops worldwide that is part of the human diet (FAO-IFA, 2004) because of its nutritional characteristics (Juliano, 1993) and low cost. Among seeding systems, the most used is permanent inundation, but direct seeding is also used (Chauhan et al., 2012; Mahajan et al., 2013). Zhang et al. (2012) have reported that direct seeded rice accounted for 90% of the total rice planting area in the Americas. However, agronomic management in direct seeding compared with permanent inundation can differ such as for seeding date, water requirements during the earlier crop stages, weed management and control, lower amount of greenhouse gas emissions, and N fertilization rates (Khan et al., 2012; Mahajan et al., 2013; Tao et al., 2016).

Nitrogen is the main nutrient associated with yield in the rice crop, but N rates respond differently to rice type (*indica* or *japonica*), cultivar, geographic zone, and other crop practices (Bouman et al., 2007; De-Xi et al., 2007; Huang et al., 2008; Jing et al., 2008; Hirzel et al., 2011a).

To adjust the N rate in rice, it is important to know how much N was supplied by soil mineralization (Angus et al., 1994); it is highly variable over time, difficult to estimate, and represents only a very small fraction of total soil N (Scott et al., 2005; Wienhold, 2007). Several laboratory methods have been developed with different coefficient adjustments for

N crop response, N extraction, or grain yield (Angus et al., 1994; Scott et al., 2005; Sahrawat, 2006; Bushong et al., 2007; Hirzel et al., 2011b). These methods have generated local recommendations that cannot be easily applied to all cultivars, crop management, and regions of the world.

Unfortunately, N management in direct seeded rice has received very little attention and management is usually similar to cropping with permanent inundation (Chen et al., 2018). Studies reported by Mahajan et al. (2011) indicate that the N requirement for direct seeded rice differs from the permanent inundation system. The main differences in N management are the relationships with specific soil saturation, crop growth patterns, root system, and seed rates (Mahajan et al., 2011; 2012). Liu et al. (2015) reported a significant increase in N use efficiency for grain production (NUEg) (N uptake by fertilized treatment – N uptake by control without fertilization)/Rate of N applied in fertilized treatment) between 10.9% and 47.9% for three consecutive seasons with direct seeded rice compared with the permanent inundation system. In contrast, Tao et al. (2016) found no differences in NUEg between both seeding systems at the same N rate. As for optimal water management, the value of NUE was > 80% with direct seeded rice (Wilson et al., 2000), while the value reported for NUE fluctuated between 30% and 40% with permanent inundation (Zheng et al., 2007).

Regarding the use of other nutrients, there are differences between geographic areas and countries. In USA, for example, P, K, Zn, and S are applied as basal fertilizer; N is applied in two splits at pre-flooding and midseason between panicle initiation and differentiation, in three splits as basal fertilizer, or at seeding, pre-flooding, and midseason. In Sri Lanka, P is applied as basal fertilizer, K is applied either as basal fertilizer or in two splits (basal and panicle stage), and N is applied in three or four splits. In Malaysia, P, K, and 2/3 N are applied 15 d after seeding and the remaining N is applied at the panicle initiation stage (Kumar and Ladha, 2011).

In Chile, the area cropped with rice has fluctuated between 25 000 and 40 000 ha yr^{-1}, and approximately 15% corresponds to the direct seeding method. Research with different N, P, and K rates was conducted at two representative locations of the Chilean rice area for two seasons. The objective of this study was to determine the effect of increasing N, P, and K rates on grain yield and optimize the rate of nutrient use in the new rice cultivar Digua-CL (Clearfield) that has great potential in Chile.

MATERIALS AND METHODS

The study was conducted in south-central Chile in two types of rice soils with monocrop and rotation during the 2016-2017 and 2017-2018 seasons. This study included Alfisol and Vertisol: clay loam (fine, mixed, active, thermic Aquic Haploxeralfs) in Parral, Maule Region, and Quella clay loam (fine, smectitic, thermic Aquic Durixererts) in San Carlos, Ñuble Region (CIREN, 1997). The climate is Mediterranean, characterized by high temperatures and low rainfall in summer and low temperatures and high rainfall in winter. Minimum and maximum temperatures (Table 1), precipitation, and evaporation (Table 2) were measured in the three growing seasons and two evaluated locations.

Table 1. Minimum (Tm) and maximum (TM) temperatures at both locations during 2016, 2017, and 2018.

	Alfisol (San Carlos)						Vertisol (Parral)					
	2016		2017		2018		2016		2017		2018	
Month	Tm	TM	Tm	TM	Tm	TM	Tm	TM	Tm	TM	Tm	TM
	°C						°C					
January	13.0	29.8	12.5	30.7	11.8	28.8	12.4	30.2	13.8	33.6	11.6	31.0
February	11.2	29.5	12.5	29.3	11.7	30.0	11.4	31.8	12.6	31.3	11.9	32.4
March	9.3	27.8	9.1	24.9	8.7	25.3	9.1	30.4	9.3	27.6	8.3	27.8
April	7.2	18.6	7.3	21.0	5.7	19.3	6.3	20.3	6.3	23.8	5.1	22.4
May	7.8	16.2	4.1	13.8	5.4	14.9	7.3	18.1	3.9	16.2	4.3	18.2
June	1.6	11.3	4.3	11.9	2.1	10.9	0.9	14.0	3.6	13.7	1.3	14.0
July	4.0	11.6	2.6	12.2	2.3	12.2	2.7	13.2	1.8	14.5	1.9	14.3
August	4.6	14.4	3.9	12.7	2.9	13.8	3.5	16.9	3.2	14.3	1.9	16.5
September	5.5	19.6	4.4	16.3	6.1	17.1	3.7	22.1	3.4	18.1	5.6	19.1
October	7.2	20.1	6.4	18.0	6.5	18.4	6.5	22.5	6.0	19.8	5.6	20.2
November	9.0	25.3	9.0	22.9	9.1	23.1	8.3	27.3	8.5	25.1	8.0	25.9
December	10.4	26.6	10.7	27.6	10.5	27.2	10.0	28.0	10.7	29.7	9.6	29.4
Mean	7.6	20.9	7.2	20.1	6.9	20.1	6.8	22.9	6.9	22.3	6.3	22.6

Table 2. Precipitation (pp) and evapotranspiration (ET_0) of both locations during 2016, 2017, and 2018 seasons.

	Alfisol (San Carlos)						Vertisol (Parral)					
	2016		2017		2018		2016		2017		2018	
Month	pp	ET_0	pp	ET_0	pp	ET_0	pp	ET_0	pp	ET_0	pp	ET_0
January	6.3	188.8	2.2	237.1	1.5	188.3	0.9	180.9	0.3	202.9	0.0	181.7
February	0.0	178.7	23.4	156.2	0.1	157.5	0.0	174.3	0.3	134.2	4.5	146.8
March	2.8	139.1	19.2	121.7	3.9	137.3	0.1	130.2	10.4	105.3	16.8	128.8
April	78.8	59.9	62.4	73.6	64.4	61.7	61.0	54.2	18.0	69.5	16.7	56.9
May	56.8	31.3	96.2	32.4	89.3	29.7	56.1	27.9	68.2	30.1	36.2	26.1
June	14.2	22.5	201.4	39.1	94.2	19.9	8.7	20.8	59.5	23.5	45.2	19.6
July	147.2	24.5	92.2	29.9	96.0	27.5	85.8	22.6	100.6	28.4	108.9	26.7
August	46.0	46.9	231.0	38.6	81.0	40.9	14.5	45.6	154.7	38.7	43.0	41.3
September	11.9	84.4	74.7	69.5	109.4	70.8	7.1	86.1	47.9	70.6	61.2	72.6
October	66.7	103.5	68.3	95.6	77.2	91.2	49.9	106.9	38.6	98.4	46.6	92.9
November	11.6	160.4	45.0	136.9	65.2	132.8	5.4	152.7	22.2	140.9	17.3	131.3
December	16.9	174.9	8.9	180.3	14.8	176.5	9.2	164.0	2.3	183.1	1.6	157.0
Total accumulation	459.2	1214.9	924.9	1210.9	729.0	1134.1	298.7	1166.2	523.0	1125.6	398.0	1081.7

To determine soil chemical and physical properties, soil samples were collected in cores at the 0-20 cm depth before crop establishment (Table 3). Soil anaerobic incubation was used to determine $N\text{-}NH_4^+$ availability through mineralization under anaerobic conditions; 5 g soil and 12.5 mL distilled water were placed in a test tube and incubated without shaking at 20 ºC for 21 d (Hirzel and Stolpe, 2014). Soil ammonium extracts were obtained by adding 12.5 mL 2 M KCl to the soil tubes and the mixture was shaken for 1 h, filtered, and $N\text{-}NH_4^+$ measured with a Skalar autoanalyzer (segmented flux spectrophotometer) (Skalar San^{++}, SkalarAnalytical, Breda, The Netherlands).

The procedures to analyze soil characteristics were carried out in the laboratory of the Instituto de Investigaciones Agropecuarias (INIA), Chile (Sadzawka et al., 2006). All samples were air-dried, ground, and put through a 2 mm sieve. Soil pH was determined in 1:2.5 soil:water extracts with a pH meter. Electrical conductivity was measured with a conductivity cell (1:5 soil:water) and organic C and total N with a total elemental analyzer (Vario MAX CNS, Elementar, Hanau, Germany). Soil extractable P was determined in 0.5 M $NaHCO_3$ (Olsen P) by the molybdate/ascorbic acid method. Soil available K, Ca, Mg, and Na were extracted with 1 M NH_4OAc and determined by flame emission spectrometry (K and Na) and atomic absorption (Ca and Mg). Soil extractable $S\text{-}SO_4$ was determined with 0.01 M calcium phosphate and by turbidimetry.

Table 3. Soil physical and chemical properties (0-20 cm depth) prior to beginning the experiment (2016).

Parameters	Alfisol	Vertisol
Clay, %	31.4	34.4
Silt, %	31.6	41.3
Sand, %	37.0	24.3
Bulk density, g cm^{-3}	1.67	1.78
Total porosity, %	37.0	32.8
$pH_{(soil:water\ 1:5)}$	6.44	6.30
Organic matter, %	3.11	2.11
Available N, mg kg^{-1}	3.0	4.4
Olsen P, mg kg^{-1}	37.3	3.9
Exchangeable K, $cmol_c$ kg^{-1}	0.22	0.13
Exchangeable Ca, $cmol_c$ kg^{-1}	11.04	9.29
Exchangeable Mg, $cmol_c$ kg^{-1}	2.42	5.11
Exchangeable Na, $cmol_c$ kg^{-1}	0.29	0.30
Exchangeable Al, $cmol_c$ kg^{-1}	0.02	0.03
Available S, mg kg^{-1}	9.53	1.00
Available Fe, mg kg^{-1}	123.11	95.28
Available Mn, mg kg^{-1}	51.59	81.86
Available Zn, mg kg^{-1}	0.63	0.29
Available Cu, mg kg^{-1}	2.22	2.78
Available B, mg kg^{-1}	0.38	0.03

Soil micronutrient and trace element concentrations were extracted in DTPA (diethylentriaminepentaacetic acid) by atomic absorption spectrometry. The B concentration was determined by extraction in hot water with azomethine H.

To optimize crop growth, plots were cultivated with conventional tilling equipment to form seedbed in accordance with standard agronomic practices for rice crops in central Chile. The direct seeding system was used for sowing. The recommendation for water use for rice sown under dry soil conditions consisted of flooding 15-25 d after emergency when rice plants were in the V3 or V5 stages (3-5 leaves) (Counce et al., 2000) and maintaining a 5 to 10 cm water height up to 20 d before harvest or until physiological maturity (Carracelas et al., 2019).

Three fertilization experiments were conducted in each soil and season, that is, five increasing N rates (0, 40, 80, 120, and 160 kg N ha^{-1}), four increasing P rates (0, 30, 60, and 120 kg P_2O_5 ha^{-1}), and four increasing K rates (0, 30, 60, and 120 kg K_2O ha^{-1}).

For the experiment with increasing N rates, 60 kg P_2O_5 and 60 kg K_2O as triple superphosphate and potassium chloride (KCl), respectively, were applied at seeding. Nitrogen was applied at three different times: 33% the day prior to seeding, 33% at tillering, and 34% at initial panicle (Hirzel et al., 2011a). For the experiment with increasing P rates, 120 kg N and 60 kg K_2O as urea and KCl, respectively, were applied. For the experiment with increasing K rates, 120 kg N and 60 kg P_2O_5 as urea and KCl, respectively, were applied. Both P and K were applied at seeding.

'Digua-Clearfield', from the Clearfield experimental rice line, is the first Chilean Clearfield variety of the temperate *japonica* type and was direct seeded (Paredes et al., 2019). It reduced herbicide use to a single product and provided adequate weed control. The seeding rate was 160 kg ha^{-1} at the two experimental locations and sowing occurred on 14 October 2016 and 15 October 2017. Weed control after emergence consisted of a herbicide combination: Penoxsulam (2-(2,2-difluoroethoxy)-*N*-(5,8-dimethoxy-[1,2,4]triazolo[1,5-c]pyrimidin-2-yl)-6-(trifluoromethyl)benzenesulfonamide; 240 g L^{-1}; Ricer Dow AgroSciences, Indianapolis, Indiana, USA), MCPA (2-(4-chloro-2-methylphenoxy)acetic acid; 750 g L^{-1}; MCPA 750 SL, A.H. Marks and Company, Bradford, UK), and bentazone (2,2-dioxo-3-propan-2-yl-1*H*-2lambda6,1,3-benzothiadiazin-4-one; 480 g L^{-1}; Basagran, BASF, Ludwigshafen, Germany) at rates of 0.03, 0.19, and 0.72 kg ai ha^{-1}, respectively. The crop was harvested at grain maturity with 18% grain moisture content at the end of March in both 2016 and 2017. The evaluated parameters were paddy grain yield and N agronomic efficiency (NAE) (kg grain produced per kg N applied). Yield was evaluated from a 1 × 2 m sample from each plot. Grain moisture content was measured with a moisture meter (Satake model SS-5, Sharma Agrico Industries, West Bengal, India) and grain yield was calculated at 14.5% moisture content (Hirzel et al., 2011a).

A split-split plot experimental design was used for each experiment with increasing N, P, or K rates in which the main plot was the soil, the split plot was the season, and the N, P, and K rates were the split-split plot. Three replicates were used for each experimental unit. Results were analyzed with ANOVA and Tukey's test ($p = 0.05$) by the SAS general model procedure (SAS Institute, Cary, North Carolina, USA). In addition, some contrasts were defined to quantify the effects because the experimental design did not allow for independent assessments of the effect of soils, season, and N, P, and K rates (interactions between sources of variation) (Hirzel et al., 2011a).

RESULTS AND DISCUSSION

Soil properties prior to the experiment

The physical and chemical properties of each soil prior to the experiments exhibited few limitations for rice cultivation. Some important properties include a low K concentration in both soils and low available P, S, Zn, and B in the Vertisol (Table 3). High organic matter (OM) content and available Fe in the Alfisol, which are associated with the soil N supply capacity (Sahrawat, 2006; Lima et al., 2008; Hirzel and Stolpe, 2014), should be highlighted (Table 3) when compared with the mean value of Chilean paddy rice soil (Hirzel et al., 2011a).

Increasing N rates

For the experiment with increasing N rates, grain yield was significantly affected by soil, season, and N rate ($p < 0.01$) (Table 4). There was a significant interaction between soil and N rate ($p < 0.01$). The NAE was also significantly affected by soil, season, and N rate ($p < 0.01$). When comparing the two soils as the mean of seasons and N rates (Table 4), the highest grain yield and NAE were obtained in the Alfisol ($p < 0.05$) with increases of 1.55 Mg ha^{-1} and 18.9, respectively, as compared with the Vertisol. When comparing the mean of soils and N rate between seasons (Table 5), the highest grain yield and NAE occurred in the 2017-2018 season ($p < 0.05$) with increases of 0.51 Mg ha^{-1} and 8.6, respectively, compared with the 2016-2017 season.

The decrease in grain yield in the 2016-2017 season was probably due to high temperatures during the reproductive stage (panicle initiation), and the maximum temperature was 39 and 44 °C at the San Carlos and Parral locations, respectively (data not shown). High temperatures (> 35 °C) during the reproductive stage can cause spikelet sterility and low grain yield (Wang et al., 2019). High temperatures during panicle initiation (> 38 °C) induce spikelet degeneration (Jagadish et al., 2013; Wang et al., 2015; Wu et al., 2017), cell damage from increased peroxide radical production (Fu et al., 2015), reduced number of spikelets, and inhibition of anther filling (Wang et al., 2016). In general, grain yield and NAE values were normal for the geographic zone in which the experiments were conducted (Artacho et al., 2009; Hirzel et al., 2011b; Hirzel and Rodríguez, 2017).

The higher yield obtained in the Alfisol can be associated with its higher OM and available Fe content (Table 3); these soil parameters are associated with potentially mineralizable N in the soil (Sahrawat, 2006; Lima et al., 2008; Hirzel and Rodríguez, 2017). The higher concentration of available S, Zn, and B in the Alfisol (Table 3) should also be mentioned because it can increase yield potential compared with the Vertisol.

The effect of the Soil × N rate interaction on grain yield (Figures 1a and 1b) indicated a significant response to increasing N rates ($p < 0.05$). The highest yield in the Alfisol was obtained with 120 kg N ha^{-1} ($p < 0.05$) (Figure 1a). Meanwhile, the highest yield in the Vertisol was obtained with 160 kg N ha^{-1}, which was only higher than the N-free control and 40 kg N treatment ($p < 0.05$) (Figure 1b). The Vertisol showed an increased yield response (Figure 1b) of 3.6 Mg ha^{-1} compared with the N-free control, while the increase in the Alfisol was only 2.2 Mg ha^{-1} compared with the N-free control (Figure 1a). The different response in these soils is associated with the lower N mineralization capacity of the Vertisol (more dependent on N fertilization) given its lower OM and available Fe content (Table 3), as discussed above (Sahrawat, 2006; Lima et al., 2008; Hirzel and Rodríguez, 2017). The response to the increasing N rate for the direct seeding system in the study area was greater than findings reported by some authors for traditional seeding systems (Ortega, 2007; Hirzel et al., 2011b; Hirzel and Rodríguez, 2017). Artacho et al. (2009) reported grain yield response to an N rate between 160 and 200 kg ha^{-1} for a traditional rice sowing system in the same study area, although they did not indicate the number of split plots used.

Table 4. Statistical analysis of rice grain yield for the experiments with increasing N, P, and K rates and N agronomic efficiency (NAE) in the treatment fertilized with N.

Parameters	Soil (S)	Season (Y)	N rate (N)	Interaction S × Y	Interaction S × N	Interaction Y × N	Interaction S × Y × N
Grain yield	**	**	**	NS	**	NS	NS
NAE	**	**	**	NS	NS	NS	NS
	Soil (S)	Season (Y)	P rate (P)	Interaction S × Y	Interaction S × P	Interaction Y × P	Interaction S × Y × P
Grain yield	*	**	**	**	NS	**	NS
	Soil (S)	Season (Y)	K rate (K)	Interaction S × Y	Interaction S × K	Interaction Y × K	Interaction S × Y × K
Grain yield	NS	NS	NS	NS	NS	NS	NS

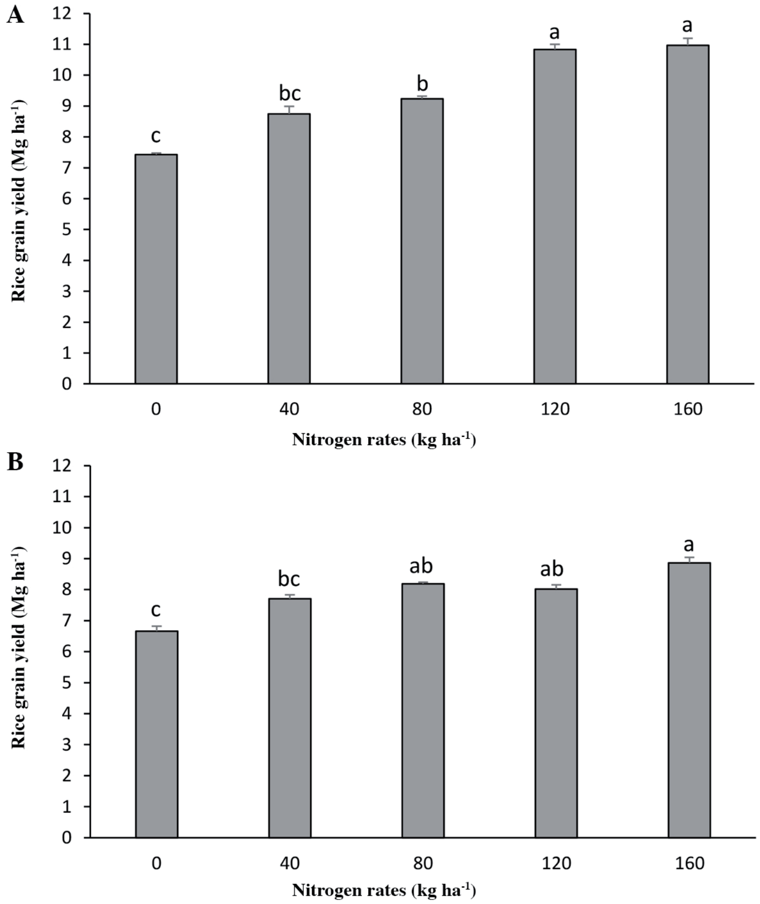
*Significant at $p < 0.05$; **Significant at $p < 0.01$; NS: nonsignificant.

Table 5. Rice grain yield in two soils for two seasons as a mean of different N and P rates and N agronomic efficiency (NAE).

		Soil		Season	
Experiment	Parameters	Alfisol	Vertisol	2016-2017	2017-2018
Increasing N rates	Grain yield, Mg ha^{-1}	9.44a	7.89b	8.41b	8.92a
	NAE	123.20a	104.30b	109.50b	118.10a
Increasing P rates	Grain yield	9.17b	9.54a	9.74a	8.98b

Different letters in the same row indicate significant differences between soils or seasons according to Tukey's test ($p < 0.05$).

Figure 1. Rice grain yield with increasing N rates in two soils, Alfisol (A) and Vertisol (B), as the mean of two seasons (2016-2017 and 2017-2018).



Different letters over the bars indicate significant differences according to Tukey's test ($p < 0.05$).
Lines over the bars indicate standard error.

As expected, there was an inverse relationship between NAE and the N fertilization rate related to NAE as a mean of the two soils and two seasons (Figure 2). There was also a significant decrease in this value ($p < 0.05$) with the increasing N rate. Given that the highest yield in the evaluated soils occurred at rates of 120 and 160 kg ha^{-1} (Alfisol and Vertisol, respectively), the NAE values associated with these yields fluctuated between 74 and 61 kg grain kg^{-1} N for each N rate, respectively. These values were slightly higher than those indicated by Thind et al. (2018) in their rice experiment with direct seeding and N rates between 120 and 180 kg ha^{-1}, which resulted in a maximum yield (6.6 Mg ha^{-1}) that was lower than the values in our experiment.

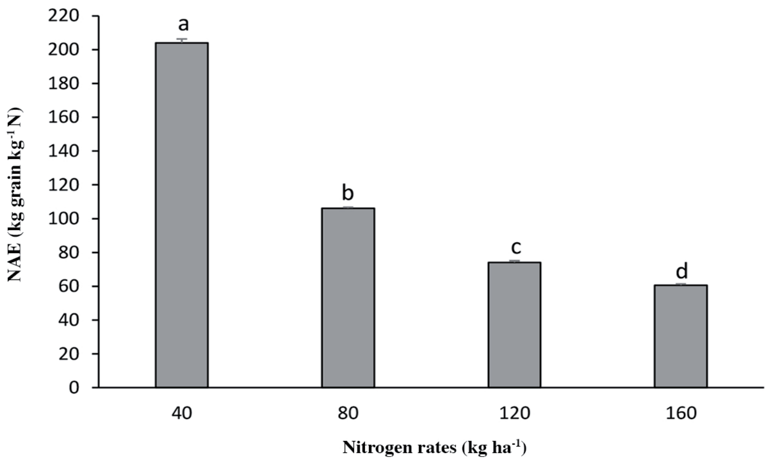
Increasing P rates

The statistical analysis indicated that grain yield was significantly affected by soil ($p < 0.05$), season, and P rate ($p < 0.01$). There was a significant interaction between soil and P rate ($p < 0.01$) and between season and P rate ($p < 0.01$) (Table 4).

When comparing soils as a mean of seasons and P rates (Table 5), the highest grain yield was obtained in the Alfisol ($p < 0.05$) with increases in grain yield of 0.37 Mg ha^{-1} compared with the Vertisol. This was consistent with the results of the experiment with increasing N rates (Table 5).

Meanwhile, the highest grain yield was achieved in the 2016-2017 season ($p < 0.05$) with increases in grain yield of 0.76 Mg ha^{-1} compared with the 2017-2018 season when comparing between seasons as a mean of soils and P rates

Figure 2. Nitrogen agronomic efficiency (NAE) with four increasing N rates as the mean of two soils (Alfisol and Vertisol) and two seasons (2016-2017 and 2017-2018).



Different letters over the bars indicate significant differences according to Tukey's test ($p < 0.05$).
Lines over the bars indicate standard error.

(Table 5). This result contrasts with our findings in the experiment with increasing N rates (Table 5). However, the same 120 kg N ha^{-1} rate was used in the experiment with increasing P rates, whereas different N rates (mean 80 kg ha^{-1} for treatments) were used in the experiment with increasing N rates; this could have reduced the potential crop yield in the direct seeding system (Mahajan et al., 2011; 2012). As shown in Table 5, the mean yield of soils or seasons are 8.67 and 9.36 Mg ha^{-1} in the experiments with increasing N and P rates, respectively.

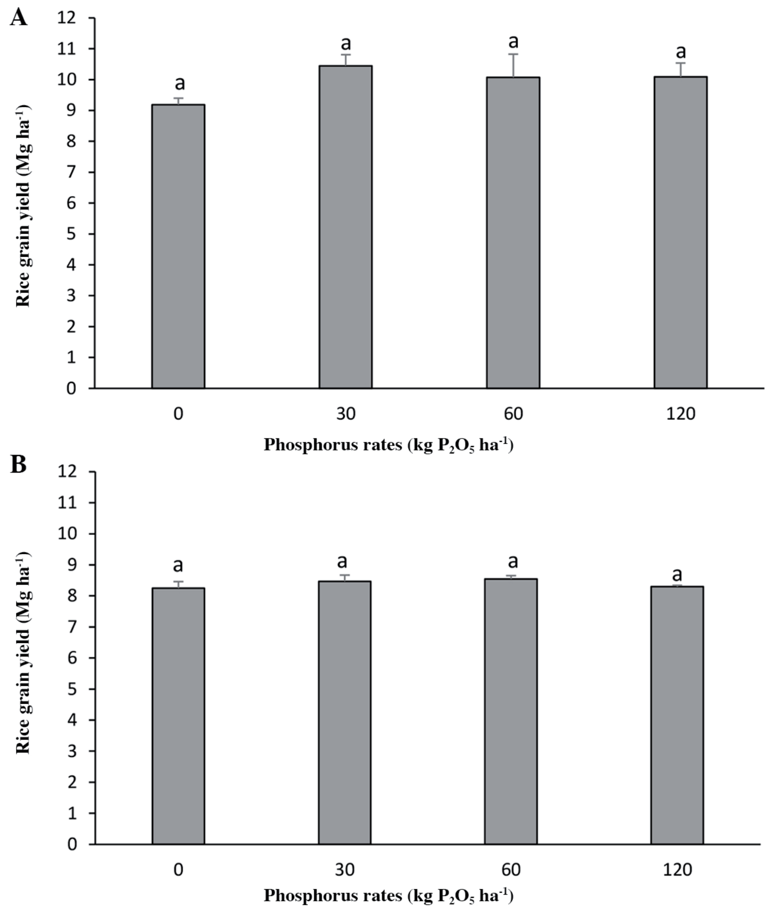
The increasing P rates in the Alfisol for both seasons (Figures 3a and 3b) had nonsignificant effect on grain yield ($p > 0.05$). However, increasing P rates in the Vertisol for both seasons (Figures 4a and 4b) only affected grain yield in the 2016-2017 season ($p < 0.05$). The lowest grain yield was obtained in the P-free control in the Vertisol in the 2016-2017 season ($p < 0.05$), and there was no difference between treatments in which different P rates were applied ($p > 0.05$). The response to P application in the Vertisol in the first season can be associated with the low concentration of this nutrient in the soil (Table 1), while no response to adding P was expected in the Alfisol because of the high concentration of available P in the soil at the beginning of the experiments (Table 3). However, a response to P application in the Vertisol was expected in the second season but no effect was found (Figure 4b), although mean yields in this soil were similar between seasons (9.52 and 9.56 Mg ha^{-1} in the 2016-2017 and 2017-2018 seasons, respectively). Frageria et al. (2011) indicated that the anaerobic soil environment created by flood irrigation of lowland rice generates several chemical changes in the rhizosphere, which decrease the oxidation-reduction or redox potential and improve the concentration and availability of P and other nutrients. Hernández et al. (2013) indicated that P desorption forms clays under flooding conditions, which could explain the lack of response to the P application.

Increasing K rates

The statistical analysis indicated neither significant effects for any of the sources of variation nor for the interaction effects ($p > 0.05$) (Table 4). Grain yield varied between 9.48 and 11.43 Mg ha^{-1} (data not shown). Although the K concentration in the Vertisol was very low (Table 3), there was no response to its application in either of the two evaluated seasons (Table 5). This can be explained by K desorption processes from Vertisol expansive clays (Havlin et al., 1999), which are enhanced in soil flooding processes, generating a larger fraction of K ions that are displaced from the exchange complex into the soil solution (Frageria et al., 2011). The K concentration in the Alfisol was moderate (Table 3); in addition, K desorption processes in non-expansive clays (Havlin et al., 1999) in a flooded soil allow an adequate K supply to the rice crop (Frageria et al., 2011). The release of Fe and Mn ions and ammonium ion production result in the displacement of some K ions from the exchange complex to the soil solution (Patrick and Mikkelsen, 1971). Dobermann and Fairhurst

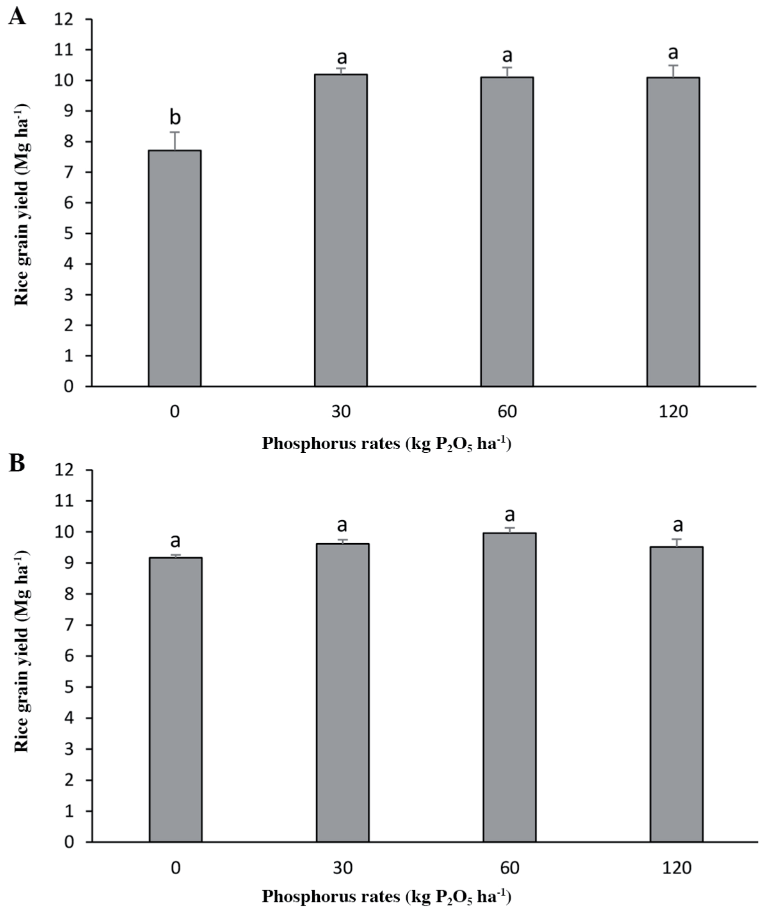
(2000) indicated that the soil K critical level for soils with high clay content is 0.2 cmol kg^{-1}. In addition, these authors showed that this critical level could fluctuate with the type of clay; it can fluctuate between 0.1 and 0.4 cmol K kg^{-1} and is lower in type 1:1 clay soils and higher in type 2:1 clay soils. In our experiment, exchangeable K in the Vertisol was 0.13 cmol kg^{-1} (Table 3) and there was a response to K application.

Figure 3. Rice grain yield with increasing P rates in an Alfisol for the 2016-2017 (A) and 2017-2018 (B) seasons.



Different letters over the bars indicate significant differences according to Tukey's test ($p < 0.05$).
Lines over the bars indicate standard error.

Figure 4. Rice grain yield with increasing P rates in a Vertisol for the 2016-2017 (A) and 2017-2018 (B) seasons.



Different letters over the bars indicate significant differences according to Tukey's test ($p < 0.05$).
Lines over the bars indicate standard error.

CONCLUSIONS

There was a positive grain yield response of direct seeded rice to increasing N rates in the two evaluated soils (Vertisol and Alfisol), and increasing P rates induced a low response in the Vertisol. Direct seeded rice in the Alfisol showed no response to increasing P rates, and both locations showed no response to K application.

The N rates that showed the highest rice grain yield were 120 and 160 kg ha^{-1} for the Alfisol and Vertisol, respectively. In addition, the N agronomic efficiency values associated with those N rates were 74 and 61 kg grain produced per kg^{-1} N applied, respectively.

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