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Soil solution and rice nutrition under liming and water management in a soil from Amazonian natural fields

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ABSTRACT: Soils of natural grasslands in the Amazon region play an essential role in local food production and preservation of the Amazon rainforest. However, in general, these soils have high acidity, which limits irrigated rice production. The objective of this study was to evaluate the effect of liming and irrigation management on the dynamics of soil reduction, nutrients in the soil solution, nutrition, and aboveground plant biomass in natural fields soil in southern Amazonia, Brazil. The experiment evaluated the correction factors for soil acidity and irrigation management, flooded and saturated soil. The experiment was carried in pots in a greenhouse. Liming reduced the Eh of the soil and had a higher influence than the soil irrigation condition. Liming also had a higher influence on soil pH than irrigation conditions. Liming and saturated soil had the lowest Fe content in the soil solution. Higher Ca and Mg contents were observed in the soil solution under liming and flood irrigation. Thus, liming is an essential strategy to improve chemical conditions for plant development in the soil of natural Amazonian grasslands and can be used in conjunction with saturated irrigation, which is more efficient in using water and reduces the effects of iron toxicity.

Keywords: paddy field, iron reduction, redox reactions, soil acidity, Gleysol.

INTRODUCTION

The Amazon is one of the biomes with the greatest biodiversity of plant and animal species on the planet (IBGE, 2019). Its total area is 6.9 million km^2, of which approximately 60 % is in Brazil (IBGE, 2019). It is an ecological heritage of humanity and its integral preservation is essential for the full functioning of ecosystems. Also, major climate changes in various regions of the world have been reported as resulting from changes in this tropical forest (Arias et al., 2020). In this sense, the areas of natural fields that occur adjacent to the forest can be used to produce food for local populations and, thus, minimize human interventions in the Amazon forest.

Natural grasslands in the Amazon cover about 342 thousand ha (0.05 % of the Amazon forest) and present two well-defined climatic seasons, a rainy season from October to May and a dry season from June to September (Silva et al., 2018). The main crops produced in this region are rice, corn and soybeans. Cultivation of irrigated rice is favored in the natural fields of the Amazon, due to the proximity of the groundwater to the surface, which keeps the soil with high moisture. However, there are differences in water management depending on the season of the year. In rainy seasons, the large availability of water reduces the need for irrigation for irrigated rice production, and the soil is normally kept only saturated with water. In the dry season, there is a need for a higher supply of water via irrigation, with the establishment of a continuous flood irrigation system and a water depth on the ground, which makes the redox conditions more reduced.

Soil redox potential interferes with iron reduction and other oxidized compounds and is conditioned by the activity of anaerobic microorganisms, which is affected by water management (Tanner et al., 2018; Carlos et al., 2022a). Continuous flooding increases anaerobic conditions and favors the reduction of oxidized compounds (Tanner et al., 2018). In saturated soil, there is an alternation in the oxidation-reduction state of the soil, decreasing the anaerobic conditions (Rothenberg et al., 2016; Maneepitak et al., 2019) and, consequently, the reduction of oxidized compounds (Borin et al., 2016; Carlos et al., 2021).

Under these conditions, the iron contents in the soil solution are possibly lower, and the K, Ca and Mg contents displaced into the solution are also lower (Borin et al., 2016; Tanner et al., 2018; Carlos et al., 2020). Soils present in this region of tropical natural grasslands are intensely weathered and have high acidity and aluminum saturation (Al^{3+}), low nutrient content and CEC, which makes the lime application important to neutralize acidity and provide Ca^{2+} and Mg^{2+} in addition to chemical fertilizers to meet the nutritional needs of plants (Carlos et al., 2020).

Rice cultivation in a continuous flooding system can favor plant nutrition, as this system changes soil oxidation-reduction conditions and improves fertility, mainly by increasing the pH (Veçozzi et al., 2018; Maneepitak et al., 2019; Carlos et al., 2022b) and the availability of nutrients (Suriyagoda et al., 2017). On the other hand, in soils rich in iron oxide, the anaerobic environment caused by flooding can cause nutritional iron toxicity in rice plants (Suriyagoda et al., 2017). The toxic effect of iron can be reduced by soil liming and intermittent irrigation, which decrease iron content in the soil solution and increase Ca^{2+} and Mg^{2+} (Schmidt et al., 2013; Carmona et al., 2021).

Due to the particularities, no previous studies evaluated the soils of the Amazon's natural fields to understand the effects of irrigation and liming management on soil solution properties, nutrition and the development of rice plants. The objective of this study was to evaluate the effect of liming and water management on the dynamics of soil reduction, nutritional status and plant production of irrigated rice in a soil from natural fields in the southern region of the state of Amazonas.

MATERIALS AND METHODS

Site description

Soil was collected in the agricultural area of Brasília Farm, located at BR 319 km 15, with geographic coordinates 7° 40’ 2.74” S and 63° 9’ 28.09” W, in the municipality of Humaitá in the state of Amazonas (Figure 1). Soil sampling was carried out in a single location of the superficial layer (0.00-0.20 m) of a *Gleissolo Háplico Alítico típico* (Campos et al., 2012), which corresponds to a Gleysol (IUSS Working Group WRB, 2015), in an area of native natural field that has never been cultivated. The experiment was conducted in a greenhouse.

Experimental design

The experiment was conducted in a completely randomized design with four replications in a 2 × 2 factorial scheme. Factor A, liming, was composed of two levels, with and without liming; factor B, water management, was composed of flooded soil and saturated soil.

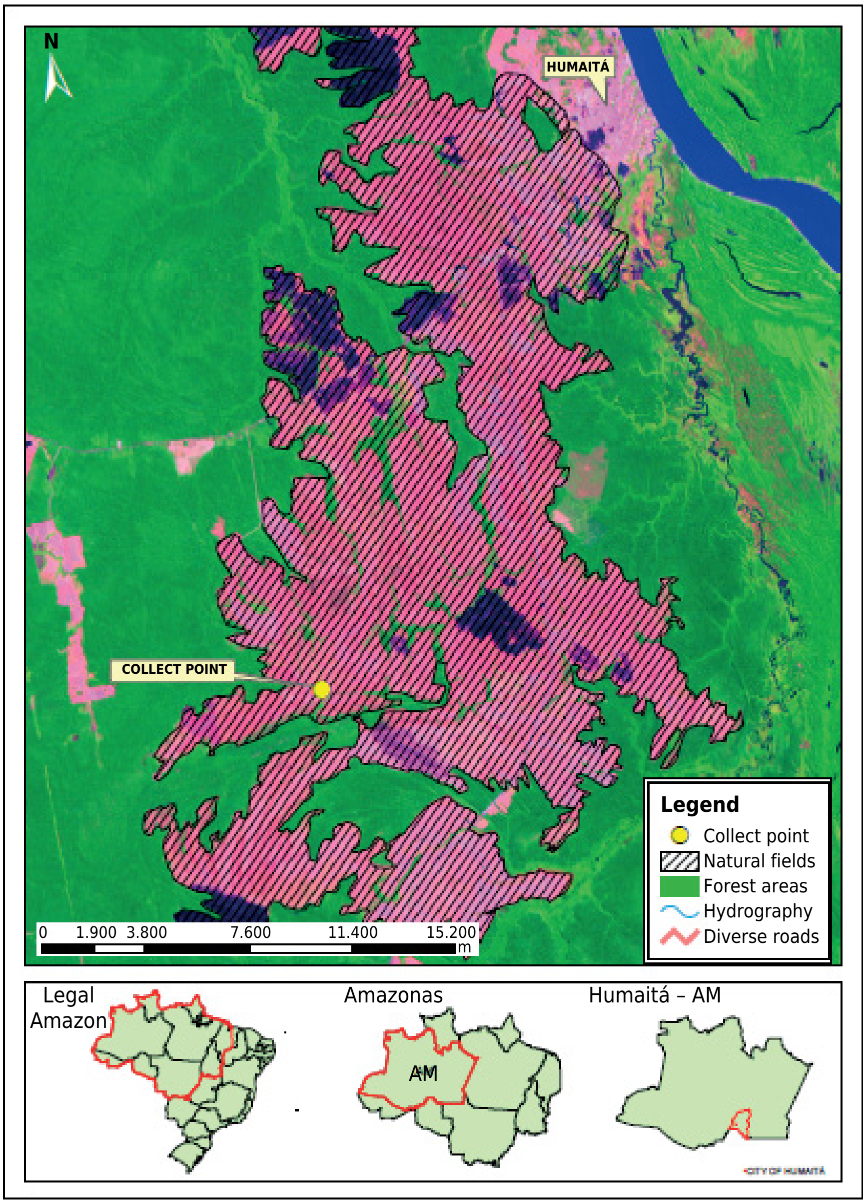

Figure 1. Area of natural fields, in the southern Amazon, with irrigated rice, where the soil collection was performed to conduct the experiment.

Table 1. Soil chemical properties in the 0.00-0.20 m layer before the beginning of the experiment

pH	P	K^+	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	T[(1)]	V[(2)]	m[(3)]	MO	Fe_o	Zn	Mn	Cu
H_2O	mg kg^{-1}	cmol$_c$ kg^{-1}						%		g kg^{-1}	mg kg^{-1}			
4.55	0.59	0.06	0.3	0.1	2.3	7.53	8.0	6	83	23	2846	0.8	4.2	1.2

(1)T: CTC at pH 7; (2) V: base saturation; (3) m: aluminum saturation.

Soil samples were air-dried, soil lumps were broken, and passed through a sieve with a 10 mm mesh opening and placed in 8-liter plastic pots, in an amount equivalent to 6.5 kg of dry soil. Soil samples were subjected to chemical analyses according to the procedures described in Tedesco et al. (1995). Determination of pH in water (1:1); exchangeable cations (Ca, Mg, Mn and Al) extracted with KCl 1 mol L^{-1}; P, K and Na extracted by the Mehlich-1; Zn and Cu extracted with HCl 0.1mol L^{-1}; and ammonium oxalate extractable iron (Feo) 0.2 mol L^{-1} pH 3.0 (Table 1).

Limestone and fertilizer doses were calculated based on soil analysis and fertilization recommendations (Sousa and Lobato, 2004). The acidity corrector was composed of a mixture of calcium oxide and pure magnesium (3:1 ratio) at a dose of 2.25 Mg ha^{-1} with PRNT of 192 %, raising the base saturation to 60 %, corresponding to 1,125 mg kg^{-1} of the mixture per kg of soil. The corrective was applied individually to each pot, mixing it evenly into the 6.5 kg soil. The soils underwent 21 days of incubation, allowing the reactions between soil and limestone to be processed. Eleven days after the start of incubation, the average soil pH was 6.26.

Applied doses of phosphorus and potassium corresponded to twice the fertilization recommendation based on Sousa and Lobato (2004) (90 mg kg^{-1} of P_2O_5 and 45 mg kg^{-1} of K_2O). The sources of P and K used were simple superphosphate and potassium chloride, respectively. For the correction of zinc and copper, 3.4 mg kg^{-1} of Zn, in the form of zinc sulfate and 2.5 mg kg^{-1} of Cu, in the form of copper sulfate, were applied, respectively. Fertilization was carried out by mixing the fertilizers with the soil of each pot, two days before rice sowing. Twelve seeds of cultivar BRS Pelota were sown manually in each pot. The soil was kept at 18 % gravimetric moisture for seven days, when water management related to treatments began.

In the flooded soil treatments, water was applied until a 0.05 m thick layer was formed on the soil surface, which was kept constant until the end of the experiment through daily irrigations with distilled water. In the saturated soil treatment, irrigation was carried out in sufficient quantity to keep the soil saturated, and this was carried out until the beginning of the formation of a thin (3 mm) layer of water on the soil surface. Fifteen days after the starting water management (DAM), the plants were thinned, keeping four rice plants until the end of the experiment. The nitrogen doses used were 100 mg kg^{-1} in the form of urea and potassium at a dose of 90 mg of K_2O kg^{-1} in the form of potassium chloride. Nitrogen dose was fractionated, being applied 50 % at phenological stage V3 and the remainder at the end of the vegetative period, phenological stage V8 (Counce et al., 2000; Marques Neto et al., 2023).

Soil and plant sampling

To evaluate the soil solution, soil solution extractors, similar to those developed by Sousa et al. (2002), were placed at a depth of 0.10 m as the soil samples were placed in the pots. Soil solution collections were carried out every seven days after the beginning of soil flooding up to the end of the experiment. Rice was cultivated for 60 days until reaching the phenological stage of panicle differentiation R0 (Counce et al., 2000). During this period, all the shoots were cut close to the ground, being dried in an oven at a temperature of 60 °C, until constant weight.

Analyses

The pH and Eh analyses of the soil solution were performed with a specific combined electrode, connected to a potentiometer and previously installed in an electrometric cell, built in glass, similar to the one used by Sousa et al. (2002). As the cell remained full of solution during the readings, it was possible to minimize its contact with molecular oxygen, reducing the risk of altering its electrochemical characteristics. After pH and Eh determinations, the samples were filtered through a 0.45 µm millipore filter, transferring approximately 30 mL of solution to glass vials containing 1 mL of HCl 3 mol L^{-1}, resulting in the final concentration of HCl in the sample around 0.1 mol L^{-1}, which enabled, in this way, the analysis of the chemical composition of the samples in the laboratory. In the soil solution samples, the levels of iron, manganese, zinc, phosphorus, potassium, calcium and magnesium were also evaluated, according to the method described in Sousa et al. (2002).

Total number of leaves with iron toxicity symptoms was determined (dead, discolored and tanned leaves), from which the total percentage of leaves with symptoms of iron toxicity in relation to the total of leaves in each pot was calculated. In relation to plant growth, shoot dry matter was determined by means of the weight of plant tissue dried in an oven at 60 °C to constant weight. Later, the tissue was ground (2 mm), subjected to acid digestion and the contents of N, P, K, Ca, Mg, Fe, Mn, Cu and Zn were determined according to the methodology described in Tedesco et al. (1995).

Statistical analyses

The results were analyzed using the Shapiro Wilk test. When the assumptions of normality were obeyed, they were subjected to analysis of variance ($p \leq 0.05$). The results of the soil solution collected over time were analyzed using a scatter plot and with 95 % confidence band intervals to assess the statistical difference between treatments. After ANOVA, the rice tissue results were subjected to the Tukey test ($p \leq 0.05$). Statistical analysis calculations were performed using the SAS software.

Pearson correlation was performed to assess the degree of relationship between the chemical properties of the soil solution. A principal component analysis was also performed to assess the overall effect of liming and water management on the chemical properties of the soil solution. For scatter plot synthesis, Pearson's correlation and PCA (Principal Component Analysis), the statistical software R was used.

RESULTS

Redox potential (Eh) and soil solution pH

The Eh decreased and pH increased during the irrigation period in all treatments. Liming promoted the lowest Eh values and the highest pH values in both managements. The pH values were similar between the water management. Eh values did not differ between water management levels throughout the period in treatments without liming, but in treatments with liming, Eh was higher in saturated soil between 25 and 46 days, not differing at other times (Figure 2).

Manganese, iron and zinc in soil solution

Manganese contents in the soil solution were very low in all treatments (Figure 3) and decreased over time. The lowest levels of Mn were observed when there was liming with flooded soil at 39 DAM. The highest Mn contents were observed at 25, 32 and 46 DAM at the level plus liming compared to minus liming, while in saturated soil, the level plus liming was higher than the level minus liming only at 25 DAM. Regarding water management, it was observed that the Mn content was higher at the flooded level compared to the

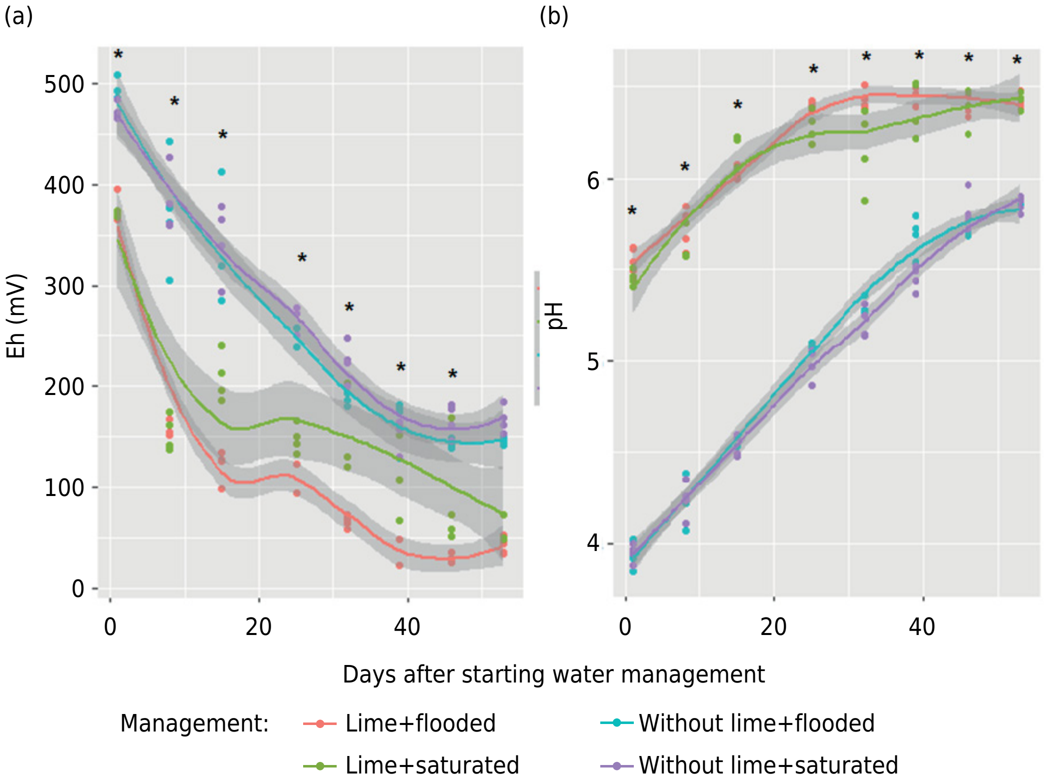

Figure 2. Eh (a) and pH (b) values of the soil solution with and without liming during the saturation and flooding period. *: significant at the 0.05 level.

saturated level in the presence of liming at 32 and 46 DAM (Figure 3). In the absence of liming, there was no difference between water management levels.

Iron contents in the soil solution (Figure 3) increased over time in all treatments, except for the combination of liming and saturated soil, in which the Fe contents increased only up to 25 DAM, then decreasing until 32 DAM tending to stability after this period. Up to 15 DAM, no statistical difference between treatments was detected. In the treatments without liming, there was no difference in the Fe content in the soil solution between the water management treatments up to 39 days, but from 46 days onwards, the flooded water showed higher Fe contents in the solution than the saturated management.

Zinc contents in the soil solution were affected by liming, but there was no effect of water management on this parameter (Figure 3). In the treatment without liming, the average levels of Zn in the soil solution were 0.9 mg L^{-1} at the beginning of flooding, decreasing to values below 0.1 mg L^{-1} after 39 days. Zinc concentration in the soil solution in the treatments minus liming was higher than those observed in the treatments plus liming up to 25 days of flooding, and after this time, there was no significant difference between the treatments for the contents of this element in the soil solution.

Calcium and magnesium in soil solution

The highest levels of calcium (Ca) and magnesium (Mg) were observed in soils plus liming (Figure 4), compared to treatments without liming in most of the evaluation period. The combination of flooded soil plus liming provided the highest values of Ca and Mg in the soil solution, reaching an average of 410 mg L^{-1} of Ca at 39 days and 189 mg L^{-1} of Mg at 53 days. Calcium contents in the treatment with liming and flooded soil increased between 15 and 39 DAM and later decreased to 53 DAM. In the soil with lime and saturated, there was a small increase in Ca contents up to 25 DAM, then decreasing to 32 DAM and then tended to stabilize.

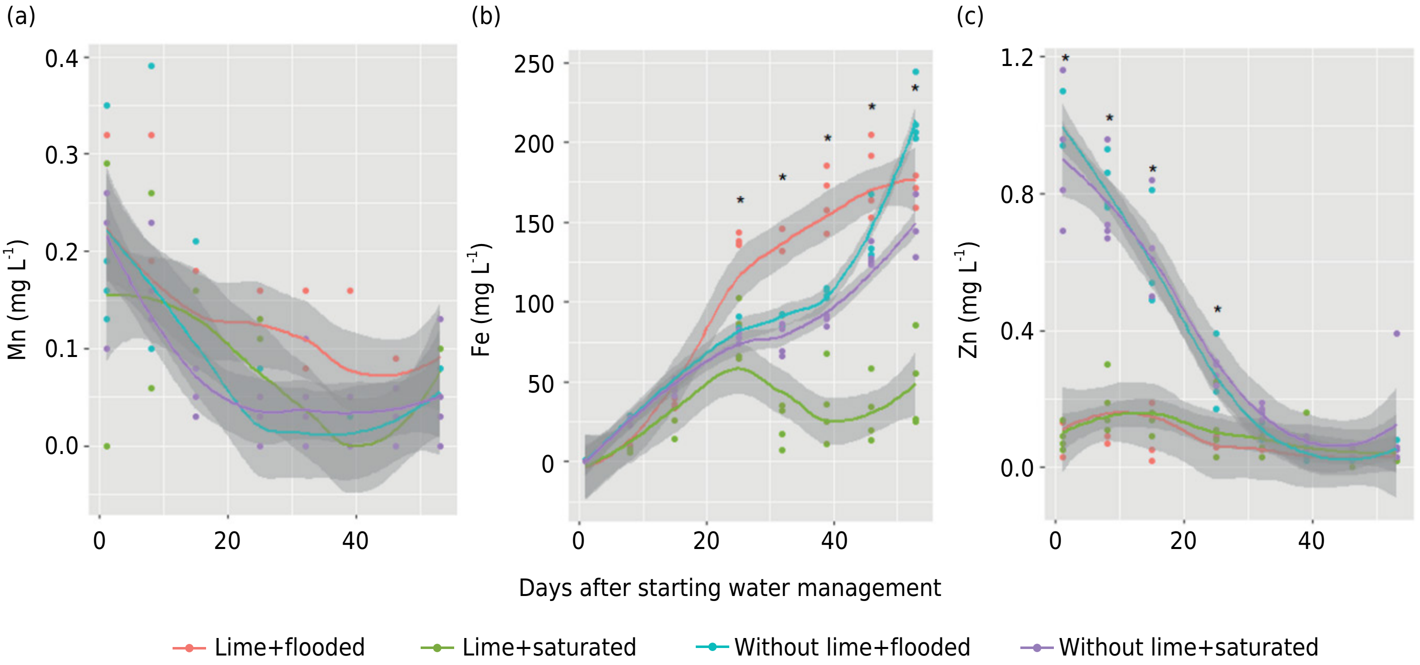

Figure 3. Values of Mn (a), Fe (b) and Zn (c) in the soil solution with and without liming during the saturation and flooding period. *: significant at the 0.05 level.

The Mg contents in the soil solution with limestone and flooded increased until the end of the experiment, while in the soil with limestone and saturated the increase occurred only up to 25 DAM, then decreasing until 39 days. Magnesium increased to 25 DAM, followed by a sharp decrease to 32 DAM, after which it slowly increased again. Treatments minus liming at both management levels had higher Ca content at the beginning, decreased and stabilized. In the absence of liming, there was no significant difference in Ca and Mg contents between the flooded and saturated levels.

Phosphorus and potassium in the soil solution

The P contents in the soil solution were very low (Figure 5) regarding the contents normally observed in flooded soils and presented high variability turning it not possible to infer about the effects of the treatments. The levels of K in the soil solution decreased in treatments without liming throughout the evaluation period, while in treatments with liming, the decrease occurred up to 32 days, tending to stabilization. This behavior was not influenced by water management, as they were similar to each other at each liming level (Figure 5). The K contents in the treatments without liming were higher than those observed in treatments with liming, both in flooded and saturated soil (Figure 5).

Principal Component Analysis and Pearson's Correlation

The PCA confirms results already presented for the soil solution variables (Figures 2, 3, 4 and 5). The plan generated with the two main components corresponds to 68.10 % of the information contained in the original data: 48.00 % in main component 1 (PC1) and 20.10 % in main component 2 (PC2). It is observed that there was the formation of two groups in the plan for the liming factor and two groups in the plan for the water management factor (Figures 6a and 6b), thus characterizing that the variables with each other presented a possible degree of similarity. The results reveal that there was a greater grouping of the effect of liming than of water management (Figures 6a and 6b). Within the liming effect grouping (Figure 6a), the group formed plus liming presents a direct association with the variables Mn, P, Ca, Mg, pH, Fe and time. The group formed minus liming has a direct association with the Eh and Zn variables. Within the grouping of the water management effect (Figure 6b), the flooded and saturated soil groups both

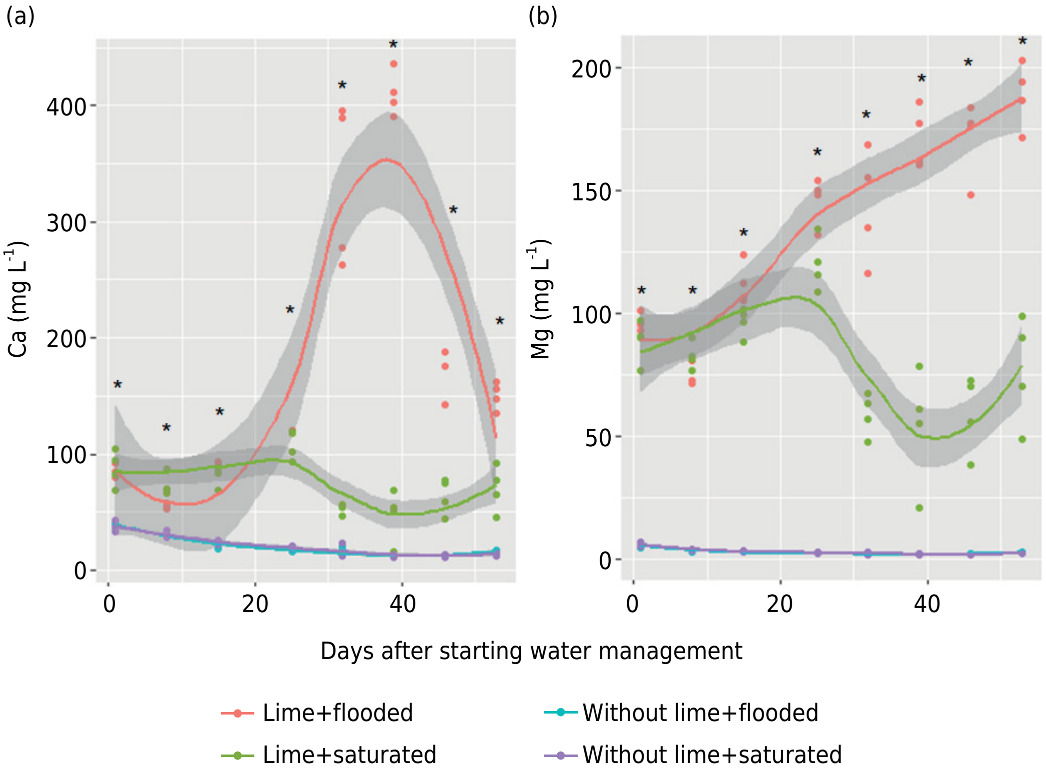

Figure 4. Calcium (a) and Mg (b) concentration in the soil solution with and without liming during the saturation and flooding period. *: significant at the 0.05 level.

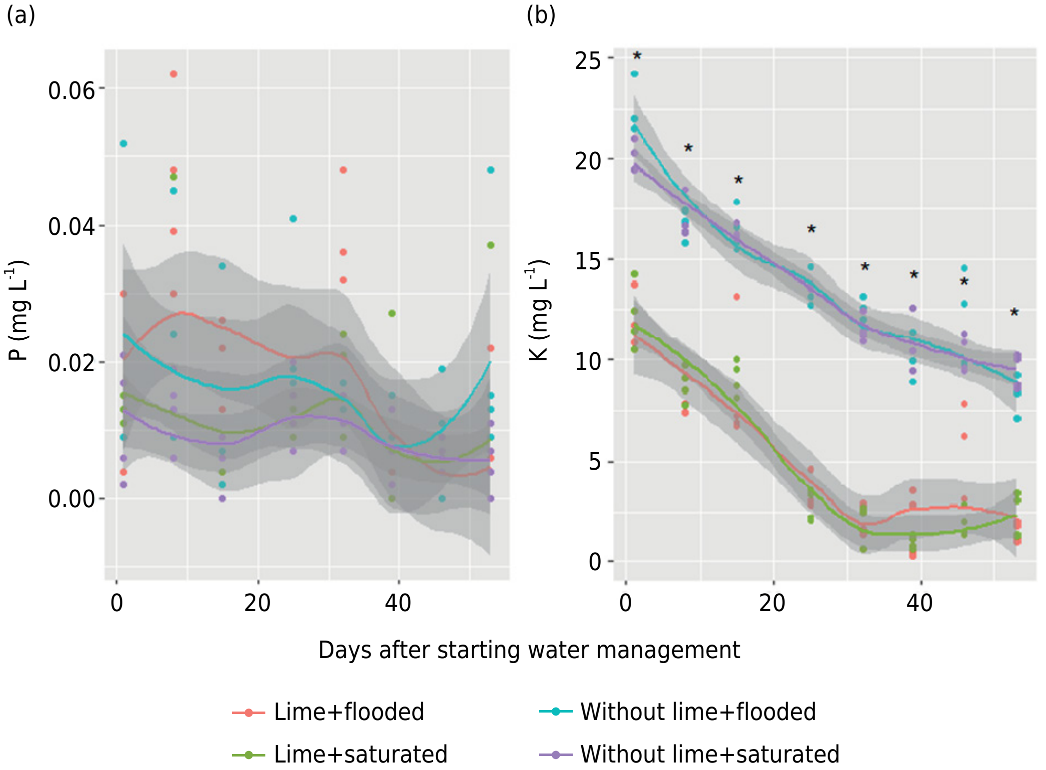

Figure 5. Concentration of P (a) and K (b) in the soil solution with and without liming during the saturation and flooding period. *: significant at the 0.05 level.

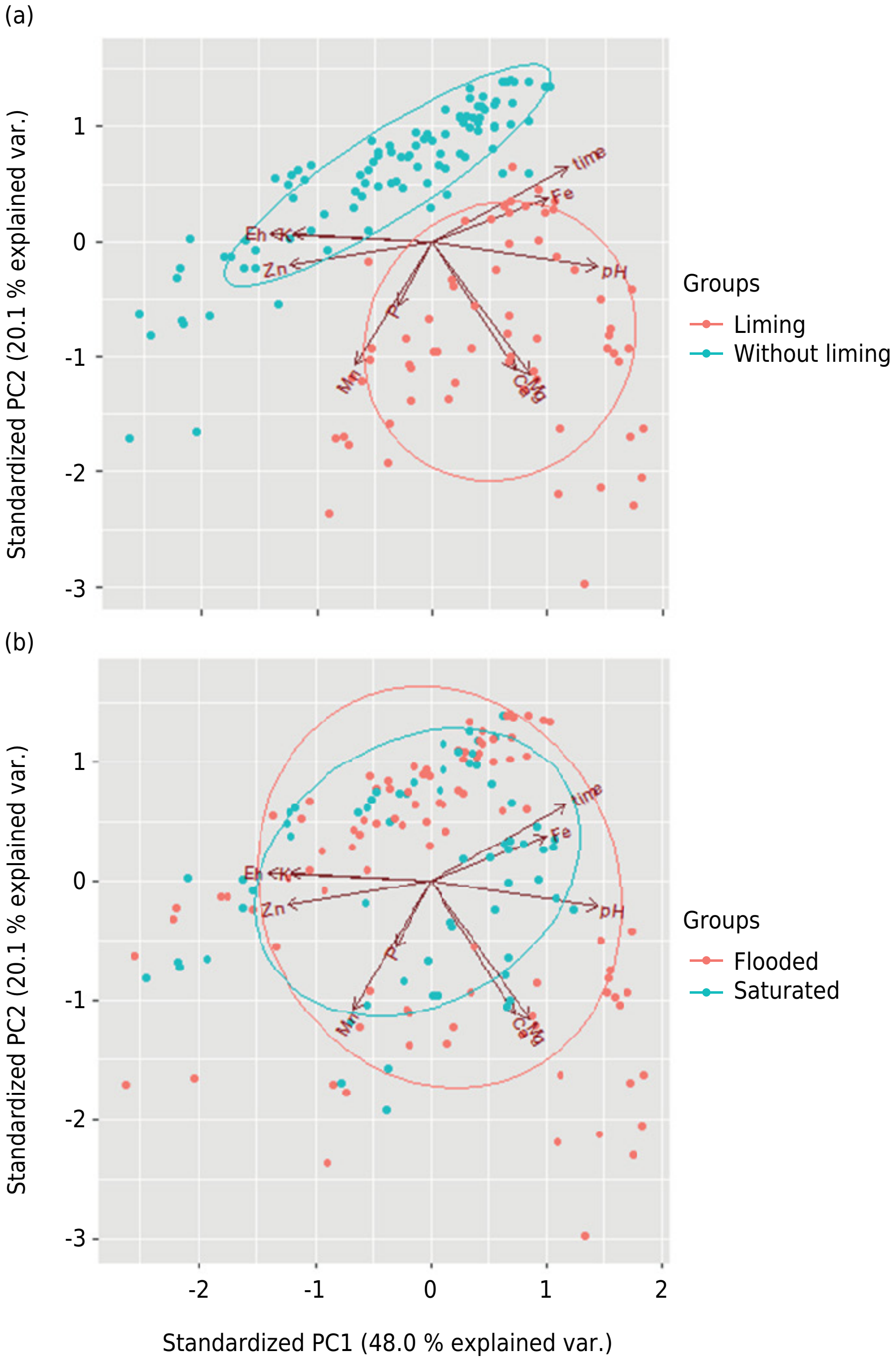

Figure 6. Biplot plot of the first and second main components of the principal component analysis (PCA) containing the variables of soil solution and liming factors (with liming and without liming) (a) and water management (flooded and saturated) (b). Eh: redox potential; Zn: zinc; Mn: manganese; P: phosphorus; Ca: Calcium; Mg: magnesium; pH: pH of the soil solution; Fe: iron.

present an association with the soil solution variables, as the effects of both are similar on some of the studied variables.

Pearson's correlation reinforces the results already presented. The moderate negative correlation between Eh and Fe (-0.62) occurs as Eh decreases and Fe contents increase. The negative correlation between Eh and pH (-0.88) is strong because as Eh decreases, pH increases. The moderate positive correlation between pH and Fe (0.47) occurs as the pH increases, the Fe content in solution increases. Strong negative correlation (-0.80) was found between pH and Zn, because as the pH increases, the Zn contents

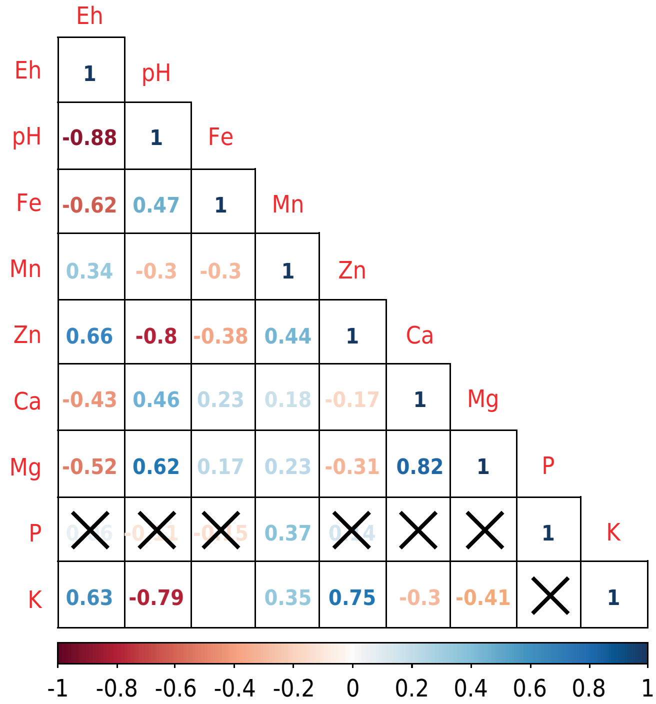

Figure 7. Pearson correlation between chemical properties of soil solution under liming and water management. (X) indicates no statistical difference at the 5% level.

decrease. There was a strong negative correlation between pH and K (-0.79), when the pH increases, the K contents decrease (Figure 7).

Tillers, symptoms of iron toxicity, shoot and leaf macronutrient contents

Analysis of variance revealed that there was an interaction effect of the factors liming and water management for the variables number of tillers, total percentage of leaves with iron toxicity, shoot dry matter (DM) and N, P, K and Mg contents in rice tissue. For the variable Ca content in the aerial part of rice, there was no effect of the interaction of the evaluated factors (Table 2).

The saturated management in the soil plus liming provided the highest number of tillers, lower total percentage of leaves with iron toxicity, and higher dry matter of the aerial part in relation to the flooded management. The treatments minus liming greatly limited the growth of rice plants in the two water managements, showing the lowest number of tillers, the highest percentage of total leaves with iron toxicity, and the lowest dry matter of the aerial part (Table 2).

Nutrient contents in the aboveground part of rice (Tables 2 and 3) depended on the accumulation of dry matter and the phenological phase of the plant. In the treatments without liming, the production of DM was much lower than that observed in the treatments with liming (Table 2), causing the plants to present higher levels of N, P, K, Fe, Mn, Zn and Cu.

In the treatments with liming, the flooded water management provided higher levels of N and K and lower levels of Ca and Mg in the aerial part of the rice, compared to the saturated management. In relation to P contents, there was no significant effect of water management in the soil plus liming (Table 2).

Leaf contents of Fe, Mn, Zn and Cu

There was an interaction effect between liming and water management factors for the Fe and Mn variables. For the contents of Zn and Cu in the rice shoot there was no effect

Table 2. Number of tillers and total percentage of leaves with iron toxicity evaluated at 45 DAM, shoot dry matter (DM) and tissue N, P, K, Ca and Mg contents in rice plants of the cultivar BRS Pelota under liming and water management

Liming	Water management		Average
	Flooded	Saturated	
	Tillers (n° pot^{-1})		
Lime	24 b A(1)	38 a A	31
No lime	16 a B	14 a B	15
Average	20	26	
CV (%)	13.1		
	Total leafs with iron toxicity (%)		
Lime	72.5 a B	29.7 b B	51.1
No lime	87.3 a A	88.2 a A	87.8
Average	79.9	58.9	
CV (%)	4.0		
	Shoot dry matter (g pot^{-1})		
Lime	20.4 b A	31.3 a A	25.9
No lime	1.3 a B	1.7 a B	1.5
Average	10.9	16.5	
CV (%)	12.6		
	N (g kg^{-1})		
Lime	24.9 a A	17.4 b B	21.1
No lime	27.3 a A	27.7 a A	27.5
Average	26.1	22.5	
CV (%)	7.9		
	P (g kg^{-1})		
Lime	0.8 a B	0.7 a B	0.7
No lime	1.1 b A	1.3 a A	1.2
Average	0.9	1.0	
CV (%)	13.0		
	K (g kg^{-1})		
Lime	27.3 a A	16.5 b B	21.9
No lime	26.4 b A	34.0 a A	30.2
Average	26.8	25.3	
CV (%)	9.7		
	Ca (g kg^{-1})		
Lime	4.7	4.8	4.8 A
No lime	2.6	3.1	2.9 B
Average	3.7 b	4.0 a	
CV (%)	7.8		
	Mg (g kg^{-1})		
Lime	1.7 b A	2.7 a A	2.2
No lime	0.2 a B	0.2 a B	0.2
Average	1.0	1.4	
CV (%)	15.7		

(1) Means followed by distinct letters, lowercase in the row and uppercase in the column, differ from each other by the Tukey test at 5 % probability. CV: coefficient of variation.

Table 3. Iron, Mn, Cu and Zn contents in the shoot tissue of rice plants of the cultivar BRS Pelota under liming and water management

Calagem	Water management		Average
	Flooded	Saturated	
	Fe (mg kg^{-1})		
Lime	216 a B[1]	107 b B	161
No lime	1296 a A	290 b A	793
Average	756	199	
CV (%)	68.0		
	Mn (mg kg^{-1})		
Lime	9 b B	38 a B	24
No lime	50 b A	65 a A	57
Average	29	51	
CV (%)	13.4		
	Cu (mg kg^{-1})		
Lime	6	7	6 B
No lime	20	20	20 A
Average	13 $^{\text{ns}}$	13	
CV (%)	38.2		
	Zn (mg kg^{-1})		
Lime	47	43	45 B
No lime	88	89	88 A
Average	67 $^{\text{ns}}$	66	
CV (%)	10.2		

(1) Averages followed by distinct letters, lowercase in the row and uppercase in the column, differ by the Tukey test of means at 5 % probability of error.

of the interaction of the evaluated factors, with significant differences occurring only for the main effect of liming (Table 3). Iron contents in the tissue were higher in the flooded level, compared to the saturated level, while for Mn, the highest contents in the fabric were observed in the saturated water management treatment (Table 3). The contents of Zn and Cu in rice tissue were higher in treatments minus liming, regardless of water management.

DISCUSSION

Redox potential (Eh) and pH

The decrease in Eh values was observed in all treatments (Figure 2) and was attributed to the reduction of oxidized compounds by anaerobic microorganisms (Ponnamperuma, 1972; Veçozzi et al., 2018; Gu et al., 2019), characteristic of flooded or saturated soils. The lowest Eh values observed in the treatment with liming, for both water managements, were due to greater microbial activity provided by liming, since the soil without liming presented restrictive chemical conditions, mainly related to the limited supply of Mg (Figure 4) (Madigan et al., 2010), high aluminum saturation (Jia et al., 2015) and low pH (Figure 2) (Lauber et al., 2009; Madigan et al., 2010; Griffiths et al., 2011). The combination of liming and saturated soil levels, presented Eh values higher in some periods than in the limed and flooded soil. Saturated soil allows the diffusion of small amounts of oxygen from the air in contact with the saturated soil surface, which raises the Eh. Saturated soil and intermittent irrigation are practices used to reoxidize the soil for a few moments, increasing the Eh (Schmidt et al., 2013;

Borin et al., 2016), when extremely low conditions can cause nutritional toxicity to rice, such as by iron or H_2S.

Oxidation-reduction reactions of the flooded soil occur with the consumption of H^+ ions, causing the pH to increase (Figure 2), a phenomenon known as “self-liming” (Ponnamperuma, 1972). The increase in pH was enhanced by liming because the dissolution of calcium and magnesium oxides added to the soil releases bicarbonate and OH^- ions into the soil solution, neutralizing the H^+ ions and increasing the pH. In flooded soil, two antagonistic effects act on pH (Vahl and Sousa, 2004): oxidation-reduction reactions occur with the consumption of H^+ ions, which increases the pH; on the other hand, the accumulation of CO_2 acts on the production of carbonic acid which, when dissociated, releases H^+ which tends to lower the pH. The balance between these two antagonistic effects determines the flooded soil’s pH value (Ponnamperuma, 1972).

Manganese, iron and zinc in soil solution

Low levels of Mn (<0.3 mg L^{-1}) in all conditions in the soil solution were due to the low levels of manganese oxides in the soil. The decrease in Mn contents observed over time was due to higher absorption due to the higher demand caused by plant growth. The opposite has been observed (Rinklebe et al., 2016), where the Mn contents in seven soils increased over time (0.06 to 10.77 mg L^{-1}). The higher Mn content in the flooded level compared to the saturated level in the presence of liming is explained by the greater reduction of manganese oxides due to the more intense anaerobic microbial activity in flooded soil, favored by liming. Norton et al. (2017) found no difference between flooded and intermittent management. The same was observed in the treatment without liming, which showed no difference in Mn content between water management levels.

The variation and lower Fe contents in the liming treatment in saturated soil can be explained by the alternation of oxidation and reduction conditions due to oxygen diffusion in the saturated soil, as discussed in relation to Eh. This behavior of Fe is characteristic of soil subjected to intermittence in the water layer and has been observed by other authors (Yang et al., 2019). Variations in Fe content in the treatment with flooded liming followed the behavior of Eh, since as Eh decreased, indicating that more oxidized compounds were reduced, the Fe content in the soil solution increased. Similarities in the behavior of Fe^{2+} in soil solution in continuous flooding were observed in the study by Yang et al. (2019).

The higher Fe contents from 25 DAM possibly occurred due to the greater reduction of ferric oxides by the microbial activity favored by liming. Borges Jr et al. (1998) revealed that liming in certain soils was more efficient in decreasing potential acidity and providing Ca and Mg to plants, than decreasing Fe contents in the soil solution. The same authors point out that iron toxicity is more a question of the balance of nutrients in the soil solution than the result of high levels of reducible Fe in the soil. However, other authors have shown that liming promoted lower Fe content in the soil solution (Dynia and Barbosa Filho, 1993; Silva and Ranno, 2005). The lower Fe content in the saturated soil with liming compared to the level without liming is the result of the sequence of reactions that occurred in the soil, where a lower Eh value indicates a greater reduction in ferric oxides, with a consequent increase in the Fe content in the solution from soil. However, the increase in pH caused by liming precipitated this Fe and decreased its content in the soil solution (Silva and Ranno, 2005).

Calcium and magnesium in soil solution

The highest levels of Ca and Mg over time at the treatment with liming in flooded soil occurred as calcium and magnesium oxides dissolved in the soil, releasing Ca^{2+} and Mg^{2+}, increasing the content of these elements in the soil solution. The increase in the solution content is favored by the displacement provided mainly by Fe^{2+}, which occupies a significant part of the cation exchange capacity (CTC) due to its high concentration (Sousa et al., 2010). The liming treatment in saturated soil had lower Ca^{2+} and Mg^{2+} contents in solution, when compared to flooded soil, as the lower reduction and release of Fe^{2+} in this treatment (Figure 2) decreased the amount of these elements displaced by Fe to the soil solution, as noted by Sousa et al. (2010).

Phosphorus and potassium in the soil solution

The P contents in the soil solution were low in all treatments. With the flooding and the hypoxic condition, there is a reduction of iron oxides (Fe^{3+}) that release phosphorus that was fixed in this mineral. Thus, there is an increase in phosphorus levels in the soil solution (Cardoso et al., 2020). The decreases in K in each combination of liming levels and water management over time were attributed to the increasing amounts of K taken up by the plants as they developed. The lower levels observed in treatments plus liming at both management levels were due to the greater amount of K absorbed by the plants, which showed normal development, compared to treatments that did not receive liming at both management levels, where plant growth was incipient, and as a result, there was less absorption of K.

Principal Component Analysis and Pearson’s Correlation

Principal component analysis reinforces some of the results already discussed in the soil solution nutrient topics. In the group of soils without liming, the Eh and Zn variables are associated (Figure 6a). The Eh values were higher in soils without liming, as the absence of liming did not favor the microbial activity and less oxides were reduced, making the Eh values higher in the soil solution. Zinc contents were higher at lower pH in soils without liming, as opposed to soils with liming, where Zn contents are low.

In the group of soils with liming, the variables Mn, P, Ca, Mg, pH, Fe and time are associated (Figure 6b). Liming was essential to increase the Ca, Mg and pH of the soil solution. As oxidized compounds were reduced, Eh values decreased and pH increased. The Fe content in the liming treatment increased as the Eh decreased, indicating that more oxidized compounds were reduced, mainly ferric oxides, and increasing the Fe content in the soil solution. The moderate negative correlation between Eh and Fe occurred as Eh decreased and Fe contents increased, and the strong negative correlation between Eh and pH occurred as Eh decreased and pH increased.

A moderate positive correlation between pH and Fe occurs because as the pH increased, the Fe content in solution increased. However, at higher pHs, Fe contents tend to decrease. Liming was not enough to reduce Fe contents in the flooded soil. In saturated soil, liming proved be efficient in relation to soil without liming, with lower Fe content. We can state that there was a greater effect of liming to decrease iron contents in saturated soil and less impact in flooded soil compared to soils without liming, and a greater effect of saturated water management compared to flooded soil in liming soil. The strong negative correlation between pH and Zn occurred as the pH increased, the Zn contents decreased, being precipitated. The strong negative correlation between pH and K is explained by the decrease in solution K that plants absorbed while the solution pH increased.

Tillers, iron toxicity, shoot and leaf nutrient contents

Many authors (Bouman et al., 2005; Wang et al., 2016; Norton et al., 2017; Hamoud et al., 2018; Sriphirom et al., 2020) report that rice has higher yield when it is cultivated under continuous flooding, mainly due to the greater availability of water and nutrients. However, in the present study, the Pelota rice cultivar showed symptoms of Fe toxicity, and in this case, the maintenance of the soil only saturated without water layer and liming are important factors to mitigate the effects of toxicity by Fe. The lowest total percentage of leaves with symptoms of toxicity and the highest number of tillers in soil with liming (Table 2) were attributed to the lowest iron content in the saturated management soil solution (Figure 3), which, in turn, presented higher production of shoot dry matter (Table 2).

Other authors also observed a higher number of productive tillers in intermittent management (Chu et al., 2015; Norton et al., 2017), which provided higher rice yield when the plants are under excess Fe stress (Norton et al., 2017). According to Schmidt et al. (2013), Fe toxicity reduces tillering, number of leaves, and DM in rice and, with the use of alternative water management (saturated soil and/or intermittent irrigation), the Fe contents in the soil solution and plant decreased, reducing the negative effects of Fe. In the evaluated soil, liming was essential to ensure the effect of chemical fertilization and provide Ca and Mg for the highest averages of DM in soils plus liming. The deficient content of N in the fabric at the saturated level in soil with liming (Fageria et al., 2014), was due to the higher production of DM at the saturated level, which contributed to a dilution of N in the fabric, decreasing its content (Table 3). Saturated soil, because it is less reduced, favors the denitrification process in which N losses occur, which may have probably contributed to the lower N content in the tissue.

Higher K content in the tissue at the flooded level in the soil with liming can be explained by the higher content of Ca in the soil solution from 32 DAM at the flooded level (Figure 4), as according to Vahl and Lopes (1998), the increased Ca content in the solution practically eliminates the negative effect of iron on K absorption. Norton et al. (2017) did not observe any difference between the flooded and intermittent management. The highest contents of Ca and Mg in the fabric occurred in the combination of saturated and liming levels. Higher contents of Ca and Mg in the tissue were also observed in the intermittent management (Norton et al., 2017).

The higher Fe content in the solution (Figure 3) possibly contributed to the lower absorption of Ca and Mg by plants at the flooded level. Magnesium was the only nutrient with very low contents in the soil without liming at the flooded and saturated levels; possibly, the low contents contributed to the lower development of the plants, associated to Fe toxicity and high aluminum concentration in the soil. In the treatments without liming, the lower DM production caused the plants to have higher levels of N, P, K, Fe, Mn, Zn and Cu (Tables 2 and 3), but this does not mean that they would be better nourished in relation to these nutrients.

Fe, Mn, Zn and Cu contents in the shoot

The highest Fe content in the tissue at the treatment without liming in both managements was attributed to the very reduced development of rice plants, according to the shoot dry matter values (Table 2). In the absence of liming, the plants had their growth limited due to the low Mg contents (Figure 4), high Fe contents in the soil solution (Figure 3) and high aluminum saturation (83 %) in the soil (Table 1). Thus, it resulted in a low production of DM with a high concentration of Fe in the tissue, and any comparison and interpretation of nutrient contents in that treatment should be done carefully.

In the treatments with liming, the waterlogged water management provided the highest Fe content in the plant tissue because in this treatment there was the highest Fe content in the soil solution (Figure 3). The liming did not allow the Fe content in the tissue to reach values capable of causing severe toxicity to rice plants, as it increased the pH of the soil solution, decreasing the Fe solubility. In addition, the high content of Ca in the solution provided by liming contributed to reducing iron absorption, as verified by Vahl and Lopes (1998).

The lower Mn content in the tissue at the flooded level compared to the saturated level in the soil plus liming (Table 3), also observed in the study by (Norton et al., 2017), can be explained by the high levels of iron in the solution, which decreased absorption of Mn by plants. There was no significant effect of water management on the contents of Zn and Cu in the rice tissue (Table 3), which are within a range considered adequate, according to the criteria presented by (Fageria et al., 2014). Thus, these micronutrients did not constitute restrictive factors for plant growth in the experiment.

CONCLUSIONS

Liming associated with flooded water management promotes the highest state of reduction shown by the lowest Eh values of a Gleysol solution. Liming provides the highest pH values in a Gleysol solution, regardless of water management, saturated or flooded. Liming and saturated management promote better nutritional conditions for rice plants, reduce the effects of iron toxicity and provide higher dry matter production of the aerial part of rice grown in a Gleysol of natural fields in the southern region of the state of Amazonas.

Gleysol presents a strong resistance to altering the pH value in the absence of liming, compared to what occurs with most soils cultivated with rice, mainly those in the state of RS, which, associated with high levels of iron, provided intense iron toxicity, making its cultivation unfeasible without liming.

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