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Soybean Yield Does Not Rely on Mineral Fertilizer in Rotation with Flooded Rice under a No-Till Integrated Crop-Livestock System

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Abstract: In subtropical lowlands, the introduction of soybean and livestock in rotation are an alternative to rice monoculture. Due to the nutrient cycling process improved by animal grazing in winter fertilized pastures, soybean may not respond to mineral fertilization under a no-till integrated crop–livestock system (ICLS). Thus, the objectives of this study were to evaluate (i) the soybean yield response to different fertilization levels of phosphorus (P) and potassium (K) and (ii) the relationship between soybean yield and soil chemical properties sampled in different soil layers, in a no-till ICLS in subtropical lowlands. Two field studies were conducted in a system that included a soybean-flooded rice rotation integrated with cattle grazing during the winter season. During the 2015/2016 cropping season, five levels of P and K fertilization were applied to the soil. During the 2017/2018 cropping season, the relationships between soybean yield and soil chemical properties were evaluated under no fertilization treatment. Soybean yield under an ICLS did not respond to P and K fertilization, even when the soil P level was below the critical threshold. The associations between soybean yield and soil chemical properties were greatest in the 10–20 cm soil layer as compared with the 0–10 cm soil layer, especially for available P, followed by pH and soil organic matter (SOM). The crop rotation and ICLS adoption under no-till reduced the soybean reliance for mineral fertilization prior to cropping. Results of this study inform producers of possible fertilization adjustments, in which supplementing mineral fertilizer for soybean may not be necessary.

Keywords: paddy fields; *Glycine max*; lowland; cattle grazing; soil chemical properties

1. Introduction

Soybean (*Glycine max* (L.) Merrill) can be grown in a range of environments including uplands and lowlands. Brazil is the largest rice (*Oryza sativa* L.) producing country outside Asia, with Rio Grande do Sul (RS) state alone being responsible for 65% of the country production. In RS state, rice is mostly grown in lowland flooded paddy fields in monoculture [1]. Rice monoculture can present issues with soil degradation, increasing pest and disease pressure, while consequently reducing yields. One option to diversify this system is via the inclusion of soybean, ultimately improving soil conditions and breaking pest, disease, and weed cycles [2].

Paddy-upland rotation is an important system for sustainable agriculture [3]. This system can alter either soil physical or chemical properties, or improve soil quality and fertility, and optimize rice yields [4,5]. The benefits of legumes in rotation are not only caused by biological nitrogen (N) fixation but also by increased nutrient availability through higher microbial carbon use efficiency from legume residues that increase the soil organic matter content, which could help to sustain the long-term productivity of cereal-based cropping systems [6,7]. In addition, both rice and soybean benefit in this environment, which can be achieved under an integrated crop–livestock system (ICLS) [8,9]. These systems enhance the nutrient cycling process and increase both soil phosphorus (P) and potassium (K) supplies [10]. Under a no-till ICLS, the flooded rice efficiently utilizes N, P, and K; therefore, the flooded rice under a no-till ICLS does not respond to P and K fertilization [8].

Soybean is considered to be a highly responsive crop to P fertilization and nutrient application rates have increased grain yield in subtropical soils, especially under available P content below the appropriate thresholds and no-till conditions [11–13]. In addition, rainfed crops, such as soybean, following flooded rice in rotation often require P fertilization. The cultivation of upland crops in the first year after flooded rice is often characterized by poor growth and low yield, due to the lower soil P availability after long flooding periods [14]. In addition, soybean often responds to K application, because this is one of the most demanded nutrients by this crop. According to Bharati et al. [13], soybean responded significantly to K application even when the soil test levels were considered to be medium to high under a no-till condition. However, we hypothesized that, due to the nutrient cycling process improved by winter grazing, soybean yield response could be smaller than expected to P and K fertilization under a no-till ICLS, even in rotation with flooded rice. The evaluation of this hypothesis is necessary to improve the soybean fertilization management in lowlands, since knowledge on this issue is still scarce.

The adoption of no-till often causes a gradient of nutrient (especially P and K) concentrations in the soil profile, due to the lack of soil disturbance. The local official recommendation system of fertilization indicates that soil sampling under no-till adoption should focus on the 0–10 cm instead of 0–20 cm soil layer for upland fields [11]. Since flooded rice is mostly cultivated under soil disturbance, the recommendation is to sample the soil at 0–20 cm [11]. In addition, many researchers have proven the importance of evaluating other soil chemical properties than available P and K contents for soybean yield [9,13].

Limited data exist studying soybean response to P and K fertilization in rotation with flooded rice in no-till paddy fields under an ICLS. In addition, the relationship between soybean yield and soil chemical properties, sampled in different layers, is also poorly explored. Thus, the objectives of this study were to evaluate (i) the soybean response to different P and K fertilization levels and (ii) the relationship between soybean yield and soil chemical properties sampled in different soil layers, in a no-till ICLS, in subtropical lowlands.

2. Materials and Methods

2.1. Site Description and Historical Characterization of the Experimental Area

Field studies were conducted as an on-farm experiment during the 2015/2016 and 2017/2018 soybean cropping seasons at Corticeiras Farm, located in Cristal County, RS State, Brazil (31°37′13″ S, 52°35′20″ W, 28 m a.s.l.). The regional climate is a warm humid summer climate, classified as Cfa, according to Koeppen. The local annual average temperature is 18.3 °C, and the annual cumulative rainfall is 1522 mm (Supplementary Figure S1). The soil is poorly drained and classified as Albaqualf [15], with a sandy clay loam texture (24, 23, and 53% of clay, silt, and sand, respectively).

The experimental area had been cultivated with flooded rice followed by fallow since the 1960s. The last rice cropping season was in 2009, followed by a fallow period until March 2013, when soil samples were collected for chemical characterization. In April 2013, soil acidity was corrected through lime incorporation (three heavy disks) at a rate of 4.5 Mg ha^{-1} (total neutralization relative power of 70%), determined according to CQFS-RS/SC [11], to increase the 0–20 cm soil layer to pH 6.0.

After soil correction, five production systems involving the cultivation of flooded rice were established in an area of 18 hectares, in a randomized complete block design with three replications. One of five potential fields was selected for the experiment based on its historically high rate of soybean cultivation under an ICLS and no-tillage with soybean/flooded rice crop rotation during the summer season and annual ryegrass (*Lolium multiflorum* Lam.) under beef cattle grazing during the winter season. The three ICLS plots were blocked by soil chemical properties. Since the experiment was initiated, flooded rice was cultivated during the 2014/2015 and 2016/2017 cropping seasons and soybean was cultivated during the 2013/2014, 2015/2016, and 2017/2018 cropping seasons, with pasture grazing in all winter seasons. Soybean was sown (single disk opener planter type) with a plant density of 31 plants per m^2, with a 45 cm row spacing. The soybean sowing and harvest occurred in November and April, respectively, and the same cultivar was sown, TEC IRGA 6070 RR, during all cropping seasons. The IRGA 424 rice cultivar was used during both cropping seasons, seeded at a density of 100 kg ha^{-1}, with a 17 cm row spacing. The rice sowing (single disk opener planter type) and harvest occurred in October and April, respectively, during both cropping seasons.

Angus steers (*Bos taurus taurus*) with initial body weight of 200 kg and seven months of age were used for grazing in 2013, 2014, 2015, 2016, and 2017 winter seasons. Average pasture height was 15 cm and average stocking was 831 ± 114 kg live weight ha^{-1}, simulating a cattle fattening or finishing system during 62 ± 15 days of grazing. The cattle's feeding was forage-based with only mineral salt provided. A continuous stocking was adopted (with a minimum of three test steers) and put-and-take animals were used to maintain targeted sward height. Annual ryegrass was re-sowed at a density of 30 kg ha^{-1} using BRS Ponteio cultivar.

The ryegrass fertilization was according to CQFS RS/SC [11] recommendation averaging 126-119–112 kg ha^{-1} of N-P_2O_5-K_2O annually from the 2013 to 2017 winter seasons. In the 2013/2014 summer season, the soybean fertilization was according to CQFS RS/SC [11] representing 20-110-120 kg ha^{-1} of N-P_2O_5-K_2O. The rice fertilization in the summer seasons was according to CQFS RS/SC [11] recommendation, representing 150-70-120 kg ha^{-1} of N-P_2O_5-K_2O, during the 2014/2015 and 2016/2017 cropping seasons.

2.2. Initial Soil Fertility Characterization and Soybean Studies

The initial soil fertility characterization of the experiment was conducted by sampling 5 to 6 points per block in October 2015, prior to the installation of the first soybean cropping season. Each point represented a composite sample from six subsamples randomly collected around the point and separated into the following two soil layers: 0–10 and 10–20 cm. Composite samples were mixed before the soil analyses.

During the 2015/2016 cropping season, a homogeneous area of 25 × 25 m within each block was selected, split into five 5 × 5 m plots that were, then, randomly assigned to different fertilizer treatments. Fertilizer treatments were applied in October 2015, with levels based on soybean yield expectation, according to CQFS-RS/SC [11]. Fertilizer treatment corresponded to different P and K fertilizer rates (in kg ha^{-1} of N-P_2O_5-K_2O) as follows: (a) no fertilizer application (0-0-0), (b) expected yield of 2 Mg ha^{-1} (0-15-20), (c) expected yield of 3 Mg ha^{-1} (0-30-45), (d) expected yield of 4 Mg ha^{-1} (0-45-70), and (e) expected yield of 5 Mg ha^{-1} (0-60-95). Fertilizer sources used were single superphosphate (18% P_2O_5) and potassium chloride (60% K_2O). The P and K fertilizer rates were manually applied after soybean sowing.

Due to the results obtained in the first soybean experiment (2015/2016 cropping season), another experiment was carried out during the 2017/2018 cropping season. Thus, soybean was not fertilized during the 2017/2018 cropping season, and the relationship between yield and soil chemical properties, sampled in 0–10 and 0–20 cm soil layers, was evaluated at the block level.

For the evaluation of the relationship between soybean yield and soil chemical properties, five samples were collected per each plot at the crop sowing stage, totaling 15 soil samples (samples were composed of three subsamples) for each layer (0–10 and 0–20 cm). The sampling point was identified for subsequent soybean harvesting and yield analysis.

2.3. Soil and Plant Analyses

Soil samples were stored in plastic bags and transported to the Federal University of Rio Grande do Sul Soil Fertility Research Laboratory. The samples were dried in a forced-air circulation oven at 50 °C, ground, sieved through 2 mm mesh, and analyzed. The soil chemical properties used for the soil fertility evaluation were pH in water, SOM content (Walkley-Black method), available P and K (extracted by Mehlich-1), exchangeable calcium (Ca) and magnesium (Mg) (extracted by 1.0 mol L^{-1} KCl), cation exchange capacity at pH 7.0 ($CEC_{pH\ 7.0}$), and base and aluminum (Al) saturation.

Exchangeable Al was determined by titration with 0.0125 mol L^{-1} NaOH solution, Ca and Mg by atomic absorption spectrometry, K by flame photometry, and P by colorimetry. Potential acidity (H + Al) was calculated through the SMP (Shoemaker, MacLean, and Pratt) index. The sum of bases was obtained by the sum of Ca, Mg, and K. The $CEC_{pH7.0}$ was calculated by sum of bases + (H + Al); base saturation (V%) was calculated using the relation, V% = 100 × sum of bases/$CEC_{pH7.0}$; and Al saturation (m%) was calculated using the relation, m% = 100 × Al/(sum of bases + Al) [11].

During both soybean cropping seasons (2015/2016 and 2017/2018), harvests were performed by hand from 4.5 m^2 per plot. Samples were threshed, cleaned, and weighed. Grain moisture was determined and adjusted to 130 g kg^{-1}.

2.4. Statistical Analyses

Analyses were performed using the SAS statistical package® v.9.4 (Statistical Analysis System Institute, Cary, North Carolina). A linear mixed-effect analysis of variance (ANOVA) model was used to assess the response of soybean yield to different P and K fertilizer rates, with fertilizer treatment (fixed) and block (random) as the explanatory variables. Model residual assumptions were checked with the Shapiro–Wilk normality test and Levene's homogeneity of variance test. Fertilizer treatment means were compared using Tukey's test. All tests were performed at a significance level of alpha = 0.05.

Mixed-effect linear regression models were used to explore the relationships between soybean yield and individual soil chemical properties in the 0–10 cm and 0–20 cm soil layers, during the 2017/2018 cropping season, using the lme function from the nlme package in R [16,17]. Regression models were fit using all data (n = 15) and subsamples within the plots were properly identified and modeled, with Kenward–Roger degrees of freedom approximation method. Due to the low number of observations, models were assessed using both statistical significance and coefficient of determination (R^2).

3. Results and Discussion

3.1. Soil Fertility Characterization and Soybean Yield Response to P and K Fertilization

In October 2015, before the first soybean cropping season experiment installation, the experimental area presented an available P and K, exchangeable Ca and Mg, and base saturation levels in 0–10 cm soil layer of 28.1 and 135.5 mg kg^{-1}, 5.6 and 2.8 $cmol_c$ kg^{-1}, and 70.9%, respectively (Table 1). The soil nutrient levels under a no-till ICLS were classified as medium for P content (20–30 mg kg^{-1}) and high for K content (91–180 mg kg^{-1}) in the 0–10 cm soil layer, according to fertilizer recommendation system for soybean in Brazilian subtropical soils.

Table 1. Soil fertility variables (0–10 and 10–20 cm layer), for October 2015, in a soybean-flooded rice rotation under no-till integrated crop–livestock system in paddy fields of a Brazilian subtropical region.

Soil Layer	SOM (1)	pH (2)	P (3)	K (3)	Ca (4)	Mg (4)	CEC (5)	m (6)	V (7)	Clay
cm	%		mg kg^{-1}			cmol$_c$ kg^{-1}			%	
0–10	2.3 ± 0.2	5.4 ± 0.1	28.1 ± 5.6	135.4 ± 12.3	5.6 ± 0.5	2.8 ± 0.2	12.2 ± 0.9	0.7 ± 0.4	70.9 ± 2.5	17.7 ± 0.5
10–20	1.5 ± 0.2	5.4 ± 0.1	10.7 ± 2.4	78.0 ± 9.0	4.5 ± 0.3	2.5 ± 0.2	11.3 ± 0.7	1.5 ± 0.3	62.8 ± 2.6	22.7 ± 0.7
Average	1.9	5.4	19.4	106.7	5.0	2.7	11.7	1.1	66.8	20.7

(1), soil organic matter (Walkley–Black method); (2), pH in water, 1:1 ratio; (3), Available phosphorus (P) and potassium (K) (Mehlich 1 method); (4), Exchangeable calcium (Ca) and magnesium (Mg) (KCl 1 mol L^{-1} method); (5), cation exchange capacity at pH 7.0; (6), Al saturation; (7), base saturation. The values are expressed as arithmetic mean ± standard error of the mean.

Usually, rainfed crops following flooded rice respond to P fertilization [18]. However, during the 2015/2016 cropping season, soybean yield did not respond to P and K fertilization with average yield across treatments of ~4.5 Mg ha^{-1} (Figure 1). The lack of soybean yield response could be related to the greater cycling of P and K under an ICLS, favored by fertilized pasture residues and cattle manure [8,10]. The high pasture fertilization rates could have led to an accumulation of nutrients in the soil, contributing to a reduction in the response to mineral fertilizer in soybean. In addition, livestock manure has an overall greater bioavailability of nutrients in the soil than the crop residue [18]. According to Ning et al. [19], due to the higher P use efficiency of the manure relative to P fertilizer, the addition of manure could reduce the requirement of P fertilizer. Regarding the K fertilization, in addition to the K cycling from animal and pasture residues, soil K was high (Table 1), justifying the lack of soybean yield response.

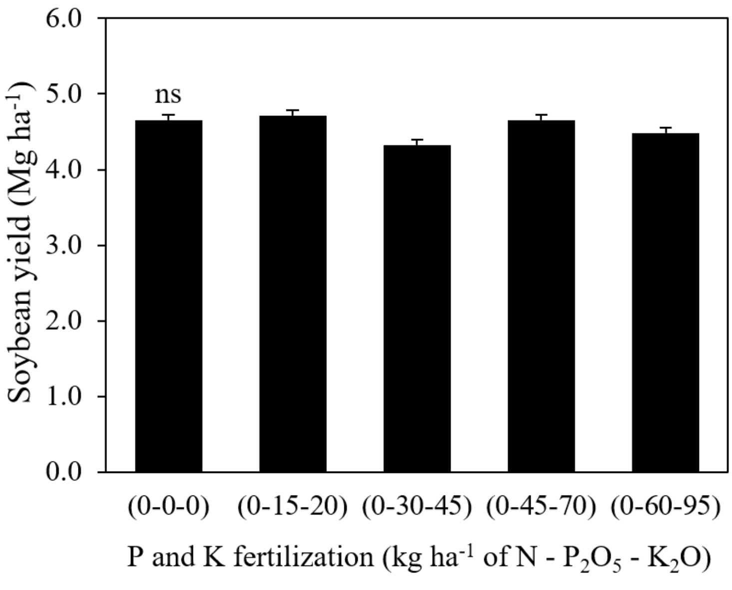

Figure 1. Soybean yield affected by different P and K fertilization rates in an integrated crop–livestock system in the Brazilian subtropical region, during the 2015/2016 cropping season. The fertilization rates were based on different soybean yield expectations, according to CQFS-RS/SC [11], being (as kg ha^{-1} of N-P_2O_5-K_2O) 0-0-0, 0-15-20, 0-30-45, 0-45-70, and 0-60-95 for control, 2, 3, 4, and 5 Mg ha^{-1}, respectively. ns, no significance ($p > 0.05$). Error bars represent standard error of the mean (n = 3).

Denardin et al. [8] found a lack of flooded rice yield response to P and K fertilization under a no-till ICLS. In contrast, under the traditional flooded rice Brazilian system (rice fallow, under soil disturbance), rice continues to respond to P and K fertilization, even though both systems have similar levels of soil P and K supplies [8]. The system with animals exports a minimum amount of nutrients in the meat, with all nutrients applied to the pasture via fertilization released to the following crop in the rotation in the form of plant residues, dung, and urine, not identified by traditional soil chemical analyses [10,20]. Thus, the use of pasture fertilization and cattle grazing during the winter season in lowlands ensures high grain yields and reduces the fertilization requirements of soybean (Figure 1). Therefore, in these systems, the fertilization regimes must be adjusted and probably the supply of mineral fertilizer for soybean is not necessary.

3.2. Relationship Between Soybean Yield and Soil Chemical Properties

Soybean grain yield, during the 2017/2018 cropping season, averaged 3.5 Mg ha^{-1}, ranging from 2.7 to 4.2 Mg ha^{-1}. The soil available P content remained below the critical level (30 mg kg^{-1}) during the 2017/18 cropping season, on average 23 mg kg^{-1} and ranging from 8.6 (very low P content) to 53 mg kg^{-1} (high P content) (Figure 2). The available P content in the subsurface soil layer (5 mg kg^{-1}) was on average 77% lower than the 0–10 cm soil layer and presented a CV of 38%. Soybean yield and soil nutrients at the 0–10 and 10–20 cm soil layers were not correlated. However, a large coefficient of determination (R^2) value (0.69) was observed when relating soybean yield and soil available P content at the 10–20 cm soil layer. This large R^2 in spite of a nonsignificant slope was the result of few observations at the plot level, which decreased statistical power. Therefore, a larger number of samples would be needed to increase statistical power and find significance in regression. Each unit of available P in the 10–20 cm soil layer increased 153 kg ha^{-1} of soybean yield, whereas in the 0–10 cm layer it increased only by 20 kg ha^{-1} (Figure 2). The lower relationship between soybean yield and the available P content in the topsoil (0–10 cm soil layer) ($R^2 = 0.36$) could be due to 80% of the samples presenting P content below the critical level ("very low", "low" or "medium" P content (Figure 2) [11]. The mechanisms of vertical movement of P in the soil profile by diffusion are closely related to soil physical and hydraulic properties [11,21]. Therefore, improvements in soil physical and hydraulic conditions can potentially help with root growth and exploration, bringing water and nutritional benefits to soybean plants [21].

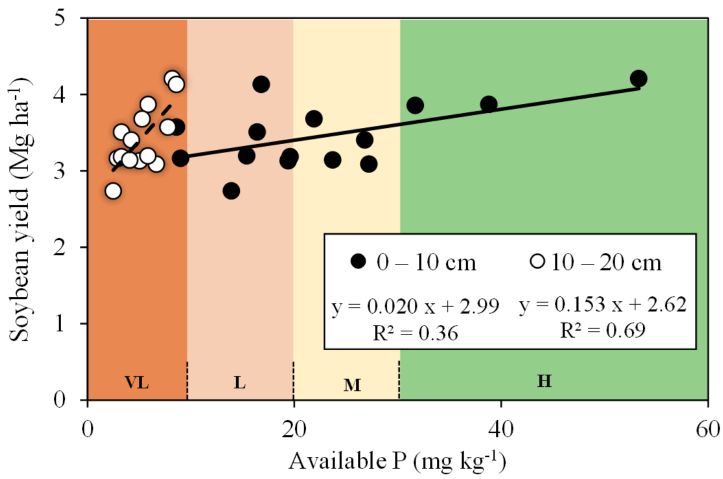

Figure 2. Relationship between soybean grain yield and available phosphorus (P) in 0–10 and 10–20 cm soil layers, in an integrated crop–livestock system in the Brazilian subtropical region, during the 2017/2018 cropping season. The highlighted color ranges corresponds to the bands of interpretation of soil available P content, being very low (VL, ≤10.0 mg kg^{-1}), low (L, 10.1–20.0 mg kg^{-1}), medium (M, 20.1–30.0 mg kg^{-1}), and high (H, 30.1–60.0 mg kg^{-1}), considering the 0–10 cm soil layer and soybean cultivation in a soil with texture class 4 (clay content ≤ 20%) [11].

Similar to P, K also presented high variability (CV of 33%) within the soil surface, ranging from 46 to 138 mg kg^{-1} (Figure 3), and averaging 95 mg kg^{-1} (very high K content). In addition, almost every sample was above the critical K level (60 mg kg^{-1}), explaining the lack of relationship between yield and this nutrient (Figure 3) [11].

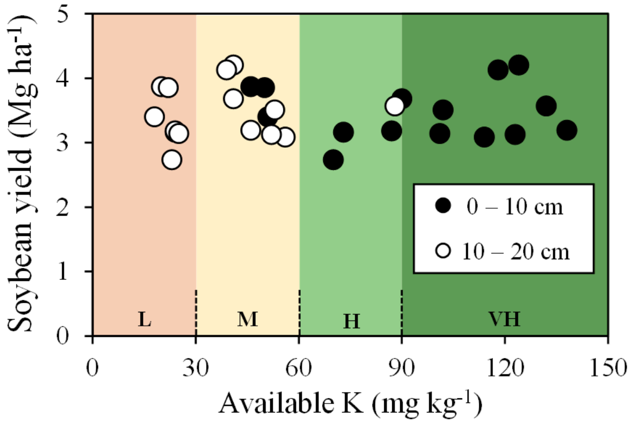

Figure 3. Relationship between soybean grain yield and available potassium (K) in 0–10 and 10–20 cm soil layers, in an integrated crop–livestock system in the Brazilian subtropical region, during the 2017/2018 cropping season. The highlighted color ranges corresponds to the bands of interpretation of soil available P content, being very low (VL, ≤30 mg kg^{-1}), low (L, 31–60 mg kg^{-1}), medium (M, 61–90 mg kg^{-1}), high (H, 91–180 mg kg^{-1}), and very high (VH, >180 mg kg^{-1}), considering the 0–10 cm soil layer and soybean cultivation in a soil with $CTC_{pH7.0}$ content from 7.6–15.0 mg kg^{-1}.

Native soil P and K supply have a high CV in the soil, with values exceeding 35%. In addition to this variation, the manure (dung and urine) deposition by grazing animals is inconsistent and non-uniform [22]. However, variation of both quantity and quality of plant residues is also important due to a differential release of nutrients. This, combined with the return of nutrients supplied to the pasture via animal manure and plant residues, could explain the lack of response of soybean to P and K fertilization and the lower dependence on the use of fertilizers in soybean (Figure 1).

The relationship between SOM and pH relative to soybean yield was higher considering the 10–20 cm soil layer, with R^2 values of 0.35 for soil pH and 0.27 for SOM (Figure 4a,b). From a pH standpoint, soil acidity directly affects soybean yields, mainly by regulating the availability of many nutrients and the N_2 fixation process [23]. However, the soil pH in the current study averaged 5.7 (medium), which was unlikely to negatively affect soybean under no-till [11]. The SOM content presented an average of 2.6% in 0–10 cm soil layer, during the 2017/2018 cropping season, classified as a medium content (Figure 4b) [11]. Although the SOM content is very related to the N availability, it is believed that in this yield range (up to 4.5 Mg ha^{-1}) soybean obtains most of the N via biological N fixation [24]. Therefore, possibly this correlation of both pH and SOM in subsurface is related to physical and hydric soil properties, such as aggregation, porosity, and water retention [21].

Franzluebbers et al. [25] suggested that pore connectivity could be positively influenced by greater SOM content in grazed systems, in an ICLS. According to Williams and Weil [26], the soybean roots used the root channels left by the decomposition of the roots of previously cultivated cover crops, improving crop productivity. This effect can be enhanced by changing the root structure of pastures, which, under grazing stimulation, invest more energy in developing roots [27]. Our results are supported by Denardin et al. [28], who found an improvement of physical soil properties due to the effect of improvement in SOM (Figure 4b), providing better timing/release of nutrients and enhancing water retention, deeper soybean root development and, consequently, greater soybean yields.

The soil physical properties in lowlands are very important, mainly because they regulate water availability for crops [29]. In this sense, although flooded rice cultivation normally affects soil physical properties negatively, no-till and ICLS adoption have proven beneficial practices for improving these attributes, mainly in deeper layers [24,27,30]. In addition, Tran Ba et al. [30] demonstrated that cropping systems comprised of rice and upland crops such as soybean improved soil physical properties as compared with long-term intensive monoculture of rice.

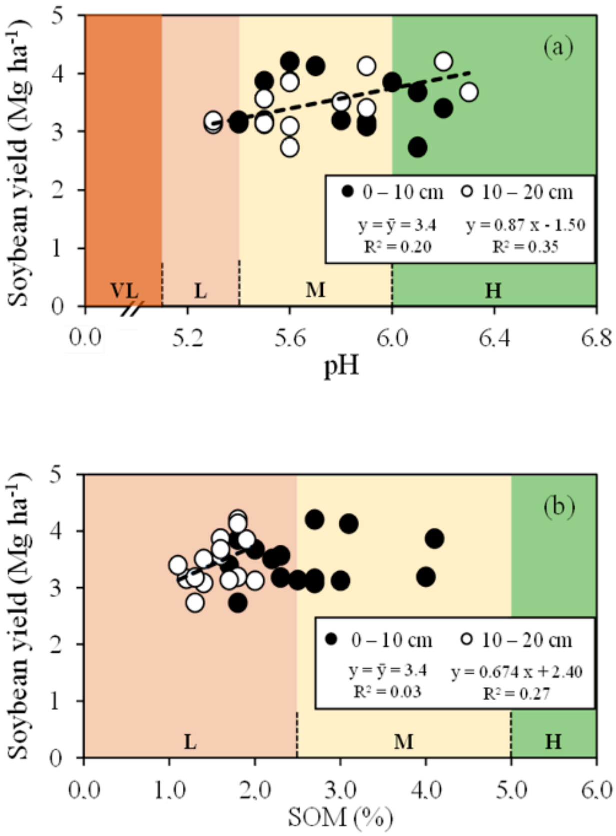

Figure 4. Relationship between soybean grain yield and (**a**) soil pH and (**b**) soil organic matter (SOM) content in 0–10 and 10–20 cm soil layers, in an integrated crop–livestock system in the Brazilian subtropical region, during the 2017/2018 cropping season. The highlighted color ranges correspond to the bands of interpretation of soil chemical properties, according to CQFS-RS/SC [11]. pH: very low (VL, ≤5.0), low (L, 5.1–5.4), medium (M, 5.5–6.0), and high (H, >6.0), considering the 0–10 cm soil layer. SOM: low (L, ≤2.5%), medium (M, 2.6–5.0%), high (H, >5.0%).

In addition to the improvement related to physical and hydric soil properties, SOM and pH are also closely related to soil biological fertility. Soil microorganisms mediate a number of important soil processes related both to the availability of water and nutrients for plants [31]. In this case, the benefit of no-till adoption in paddy fields for improving soil quality through increases in SOM is already known [28]. These benefits can be improved under crop rotations and animal grazing, provided mainly by improving the soil biodiversity and microbial activity [32].

The variation of the other soil chemical properties did not influence the soybean yield, in any soil layers assessed. All samples in the 0–10 cm soil layer presented high exchangeable Ca and Mg content, on average 5.0 and 2.5 $cmol_c$ kg^{-1}, respectively. Even five years after liming, the base saturation and Al saturation are still at adequate levels for soybean growth [11]. The average of base saturation and of Al saturation, found in the 0–10 cm soil layer, were 73.7% and 1.25%, respectively. As verified by Martins et al. [33], an ICLS is more efficient in the use of nutrients such as Ca and Mg, avoiding their losses. This could explain the high soil nutrient levels, the slow soil re-acidification, and the lack of a relationships between soybean yield and these soil chemical properties [33].

4. Conclusions

This study was one of the first attempts to elucidate the role of fertilization, soil characteristics, and depth of soil diagnostic layer in soybean yields under a lowland no-till ICLS. This study contributes information supporting a more sustainable use of the subtropical lowlands, improving their soil fertility and diversifying cash crops, based on a conservation management system, such as no-till and ICLS.

Our results showed that crop rotation and ICLS adoption under no-till reduce the soybean reliance on mineral fertilizer prior to cropping. The supply of P and K fertilizer did not promote a response in soybean yields, even with soil P levels below the critical threshold in the 0–10 cm soil layer. Therefore, the fertilization regimes must be adjusted and probably the supply of mineral fertilizer for soybean is not necessary under a lowland no-till ICLS. Hence, in these systems, the P and K removed in soybean seeds can be replaced during the pasture phase, enhancing forage and animal production.

In addition, there is no relationship between soybean yield and most of the soil chemical properties in the 0–10 cm layer, with a large proportion of the yield accounted for by changes in available P, followed by pH and SOM in subsurface soil (10–20 cm layer). In synthesis, even after five years of no-till adoption, it is important to monitor and to access soil fertility in deeper soil layers (10–20 cm soil layer). New calibration studies need to be conducted in lowland soils used by paddy fields and rainfed crops under no-till to redefine the right soil layer to be sampled for improving the nutrient diagnosing recommendations.

The goal of this study was to evaluate soybean phases under an ICLS rotation, therefore, the different analyses were limited to data from a single growing season. The results reported, herein, are novel and provide direction for soybean nutrient management under an ICLS, yet they should be interpreted within the context of the environment and year of measurements. Future studies should address this gap by conducting similar experiments at a larger number of sites and over more years.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4395/10/9/1371/s1, Figure S1. Monthly cumulative precipitation and average temperature (from August 2015 to July 2016 and from August 2017 to July 2018) in Cristal County/RS State, site of the experimental area of integrated crop-livestock system in southern Brazil. Source: National meteorological institute, Brazil.

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