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Fertilization strategies and liming in no-till integrated crop-livestock systems: effects on phosphorus and potassium use efficiency

Lucas Aquino Alves[(1,2)], Luiz Gustavo de Oliveira Denardin[(1)], Gustavo Duarte Farias[(3)], João Pedro Moro Flores[(1)], Dionata Filippi[(1)], Carolina Bremm[(3)], Paulo César de Faccio Carvalho[(3)], Amanda Posselt Martins[(1)], Luciano Colpo Gatiboni[(4)] and Tales Tiecher[(1)*]

(1) Universidade Federal do Rio Grande do Sul, Departamento de Solos, Porto Alegre, Rio Grande do Sul, Brasil.
(2) Universidade Regional Integrada, Departamento de Ciências Agrárias, Frederico Westphalen, Rio Grande do Sul, Brasil.
(3) Universidade Federal do Rio Grande do Sul, Departamento de Plantas Forrageiras e Agrometeorologia, Porto Alegre, Rio Grande do Sul, Brasil.
(4) Universidade do Estado da Carolina do Norte, Departamento de Culturas e Ciência do Solo, Carolina do Norte, Raleigh, Estados Unidos.

*** Corresponding author:**
E-mail: tales.tiecher@ufrgs.br

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ABSTRACT: In an integrated crop-livestock system (ICLS), system fertilization exploits the nutrient cycling imposed by animal grazing and increases the system efficiency. An increasingly popular approach to fertilization in southern Brazil is anticipating P and K requirements for soybeans into the pasture phase. This can increase the use efficiency of these nutrients in ICLS based on meat production in winter and soybean in summer. This study aimed to evaluate the effect of fertilization strategy, grazing and soil acidity correction on herbage and animal production, soybean yield, P and K contents in soil and plant tissue, and P and K use and economic efficiency. In 2017, a field experiment was established on an Acrisol (*Argissolo Vermelho distrófico*) double-cropped with soybean and Italian ryegrass under no-tillage. Herbage and animal production, soybean yield, available P and K contents, and P and K plant tissue status were determined. Available P and K in the soil were unaffected by grazing and fertilization strategy. Conversely, system fertilization and liming increased the P and K contents of aboveground Italian ryegrass biomass. Additionally, the available K budget in the soil was 2.7 times smaller in the integrated system with system fertilization than in the specialized system with conventional fertilization, possibly due to K fixation in non-exchangeable forms. By contrast, the available P budget in the soil was not affected by treatments and was positive with all systems. The use of ICLS increased economic return, and P and K use efficiency for protein production. System fertilization did not affect soybean yield, but it increased the total herbage production of Italian ryegrass. Despite this, sheep live weight did not increase. Using ICLS in combination with system fertilization provides an effective nutrient management strategy with a higher potential for sustainable food production when compared with conventional fertilization.

Keywords: soybean yield, sheep grazing, animal production, nutrient management.

INTRODUCTION

In weathered tropical and subtropical soils, phosphorus (P) and potassium (K) contents are typically low, resulting in a strong dependency on nonrenewable nutrient inputs (Stewart et al., 2005; CQFS-RS/SC, 2016; Dhillon et al., 2019). Despite being one of the world's largest food, fiber, and biofuel producers, Brazil is heavily dependent on fertilizer imports. In 2018 Brazil used approximately 35.5 million tons of fertilizers, 27.5 million (77 %) of which were imported, P mainly from Middle East countries and K from Canada (ANDA, 2019). For that reason, soil fertility management needs to be better planned to increase these nutrients' efficiency use.

Soil fertility management in tropical and subtropical areas, in general, aims to maintain adequate levels of available nutrients by building up soil P and K contents above thresholds values necessary for effective crop development (CQFS-RS/SC, 2016), which usually requires using large amounts of fertilizers. A subsequent fertilization process, which maintains the soil's nutrient status, usually requires less fertilizer input (usually the amounts needed to replenish nutrients removed for grain, fiber, or meat production in addition to losses by erosion, runoff and/or leaching) (CQFS-RS/SC, 2016; Pauletti and Motta, 2019).

Increasing P and K use efficiency entails neutralizing soil acidity (Scanlan et al., 2017). An appropriate soil pH reduces P adsorption by Fe and Al oxides, and increases P availability to plants as a result, and also promote better root growth, increasing water use efficiency, and allowing plants to uptake nutrients from deeper soil layers, increasing nutrient efficiency (Gustafsson et al., 2012; Bai et al., 2017; Penn and Camberato, 2019; Alves et al., 2021; Bossolani et al., 2021). Amending soil acidity by liming also increases the cation exchange capacity (CEC) (Huang et al., 2020), mainly through deprotonation of surface functional groups present in organic matter —which is especially important in sandy soils to avoid K losses by leaching. Soil P and K availability are not only affected by acidity amendments, but also by factors like the animal component in integrated crop–livestock systems (ICLS).

Globally, ICLS is used to obtain more food per unit of land (Moraes et al., 2014), improve P and K cycling (Assmann et al., 2017), and increase the availability of these two nutrients in the soil (Ferreira et al., 2011; Deiss et al., 2016). Nevertheless, P and K efficiency can be further improved in ILCS, particularly if fertilizers are applied at the optimum time. Integrated crop–livestock systems typically alternates between a grain production phase with a higher nutrient exportation and a meat production phase with lower exportation. A long-term (14 years) study in Southern Brazil has shown that grain crops such as corn and soybean grown in the summer season may export up to 95 % of P and K from the soil, and sheep meat produced in winter pasture can export only 5 % (Alves et al., 2019). Thus, new fertilization strategies, which exploit nutrient cycling, transfers between organic and mineral phase, and increased soil biological activity in ICLS, are being envisioned with system fertilization (Ferreira et al., 2011; Deiss et al., 2016; Farias et al., 2020; Sekaran et al., 2021).

With conventional fertilization, P and K are supplied when the grain crops are sown as they require and export larger amounts of nutrients than the winter pasture (CQFS-RS/SC, 2016). Applying P and K to the soil at this time rapidly increase their availability and uptake by soybean plants. Following soybean harvest, the soil may return to a state of decreased availability of P and K, so the winter crop may not benefit from the fertilizer initially applied. By contrast, fertilization during the winter pasture phase can increase the soil's available P and K levels throughout the growth period. As P and K exports through meat are minimal, it is expected that the nutrient availability in the soil will be sufficient for soybean production after the grazing period. Therefore, this system-focused strategy based on periods of high and low nutrient exports may increase P and K use efficiency.

Some studies have shown that soybean yields are unlikely to respond to fertilization in soils with high P and K availability (Boring et al., 2018). By contrast, anticipation fertilization can boost herbage production, especially if pasture is grazed (Farias et al., 2020). In fact, grazing in pastures with well-managed fertilization increases net aboveground primary production and root production (Souza et al., 2008; López-Mársico et al., 2015). Thus, because it boosts growth through multiple defoliation cycles, grazing can increase nutrient uptake from pasture relative to annual crops (Ruess et al., 1983; Chapin and McNaughton, 1989).

This study aimed to assess the effects of different P and K fertilization strategies, performed at different times: at summer soybean crop sowing – conventional fertilization, or at Italian ryegrass establishment in winter – system fertilization. These fertilization strategies were combined with grazing/ungrazed pasture and lime/control. Then, we evaluate the effect of these factors on herbage and animal production, soybean yield, soil available P and K budgets, plant nutrient uptake and use, and economic efficiency after three years, in a no-tilled Acrisol in a subtropical Brazilian region.

MATERIALS AND METHODS

Experimental area and site

The field experiment started in April 2017, and it was set up at the Experimental Agronomic Station of the Federal University of Rio Grande do Sul (EEA-UFRGS) in Eldorado do Sul, Rio Grande do Sul State, Brazil (30° 05’ S, 51° 39’ W, 46 m above sea level).

The climate in the region is classified as subtropical humid (Cfa) according to Köppen’s system (Alvares et al., 2013). Mean precipitation, air temperature and soil moisture during the experimental period (April 2017 to March 2020), obtained from the EEA-UFRGS mobile automatic station (Weather Watch 2000, Campbell Scientific, Inc.), are presented in figure 1. The soil in the study site is *Argissolo Vermelho distrófico* (Santos et al., 2013), which corresponds to Acrisol (IUSS Working Group WRB, 2015); its main chemical and physical properties are summarized in table 1.

The experimental area has been managed under no-tillage and ICLS since 2003. In the winter season (April to September), Italian ryegrass (*Lolium multiflorum* Lam.) pasture is grazed by sheep; the soil is cropped with soybean (*Glycine max*) in the summer (October to March).

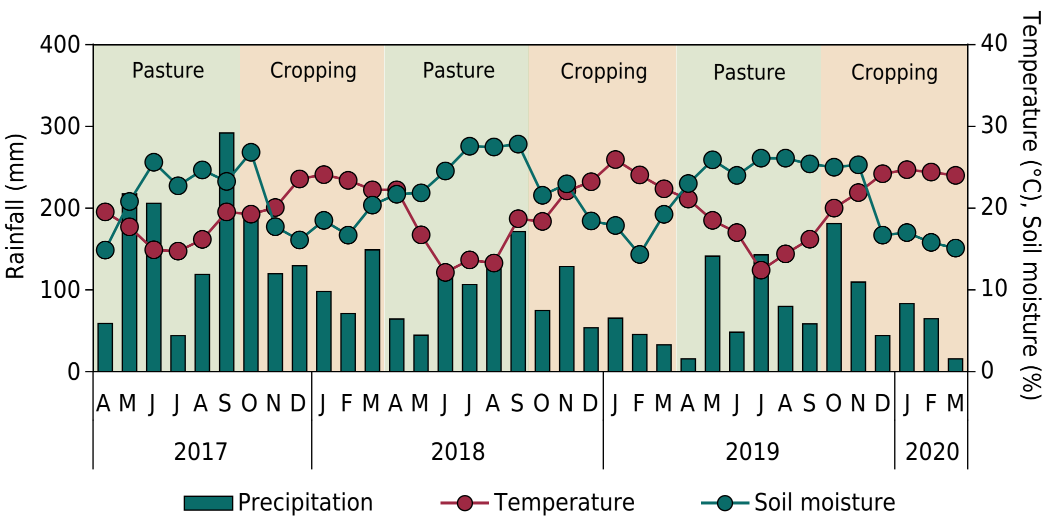

Figure 1. Rainfall, mean air temperature and soil moisture over the three pasture (2017, 2018, and 2019) and cropping cycles (2017/2018, 2018/2019, and 2019/2020) in the ICLS evaluated in Southern Brazil.

Table 1. Soil chemical and physical properties before the beginning of the field experiment (July 2017) in an Acrisol under no-tillage in Eldorado do Sul (Rio Grande do Sul State, southern Brazil)

Soil properties	Soil layer (m)		Interpretation by CQFS-RS/SC (2016) for 0.00–0.10 m soil layer	Reference
	0.00-0.10	0.10-0.20		
$pH(H_2O)$[(1)]	3.9	4.0	Below reference value	Soil pH below the reference value for no-tillage (pH ≥6.0)
Available P ($mg\ dm^{-3}$)[(2)]	94.2	45.8	Very high	Available P very high for a soil containing ≤200 g kg^{-1} of clay (30 mg dm^{-3})
Available K ($mg\ dm^{-3}$)[(2)]	96.6	68.5	High	Available K high for a $CECpH_{7.0}$ value of 7.6–15.0 $cmol_c\ dm^{-3}$ (90 mg dm^{-3})
Ca^{2+} ($cmol_c\ dm^{-3}$)[(3)]	1.1	0.9	Below reference value	Ca^{2+} below the adequate threshold (4.0 $cmol_c\ dm^{-3}$)
Mg^{2+} ($cmol_c\ dm^{-3}$)[(3)]	0.5	0.4	Below reference value	Mg^{2+} below the adequate threshold (1.0 $cmol_c\ dm^{-3}$)
Al^{3+} ($cmol_c\ dm^{-3}$)[(3)]	1.6	1.6	–	–
$CECpH_7$ ($cmol_c\ dm^{-3}$)[(4)]	12.4	11.8	–	–
Cation saturation (%)[(5)]	14.9	14.5	Below reference value	Cation saturation below the reference value (≥65 %)
Al saturation (%)[(5)]	48.5	53.1	Above reference value	Al saturation above the reference value (≤10 %).
Soil organic carbon (g kg^{-1})	16.8	8.1	Medium	Medium soil organic carbon content (14.4–29.0 g kg^{-1})
Clay (g kg^{-1})[(6)]	134	149	Class 4	Textural class 4 (≤200 g clay kg^{-1})
Silt (g kg^{-1})[(6)]	239	234	–	–
Sand (g kg^{-1})[(6)]	627	618	–	–

[(1)] In (1:1, v/v) water suspension. [(2)] Available P and K extracted by Mehlich-1. [(3)] Al^{3+}, Ca^{2+}, and Mg^{2+} extracted by KCl 1.0 mol L^{-1} (1:10; v/v). [(4)] Cation exchange capacity at pH 7.0 as calculated by combining H^+, Al^{3+}, Ca^{2+}, Mg^{2+} and K^+. [(5)] Cation saturation = $(Ca^{2+} + Mg^{2+} + K^+)/(CEC_{pH7}) \times 100$, and Al saturation = $Al^{3+}/(CEC_{effective}) \times 100$. [(6)] Particle size distribution in clay <0.002 mm, silt 0.002–0.05 mm and sand >0.05 mm.

Experimental design and soil management history

The experiment was established in 4.8 ha, split into 16 paddocks 0.23–0.41 ha in size. The experimental design was a completely randomized block with 4 replications in a 2 × 2 factorial system and split-plots. The first factor was animal grazing, that is, whether the land was grazed (integrated system) or ungrazed (specialized system). The second factor was P and K fertilization strategy, which involved supplying the soil with fertilizer in the soybean cropping phase (conventional fertilization) or winter pasture (Italian ryegrass) phase (system fertilization). The split-plot was the effect of acidity amendment (i.e., whether or not the soil was limed).

The effect of acidity neutralization (i.e., liming or no liming) was examined in all plots by excluding an area of 32 m^2 (4 × 8 m) from limestone application to maintain the original acidity conditions (subplot). Table 1 summarizes the chemical properties of the soil at that point. Soil acidity was amended by applying limestone in the amount needed to raise the pH (H_2O) to 6.0, as recommended by the local Soil Fertility Committee (CQFS-RS/SC, 2016). The soil was limed with 7.5 Mg ha^{-1} of dolomitic limestone [$CaMg(CO_3)_2$] with an effective neutralizing power of 72 %. Liming was performed in July 2017 on the soil surface without incorporation.

Grazing started in June or July of 2017, 2018, and 2019, and finished in October each year (Table 2). Italian ryegrass was established by sowing viable seeds at a rate of 25 kg ha^{-1} with a centrifugal distributor in May of each year. Urea (45 % N) was applied at a rate of 150 kg ha^{-1} of N to all paddocks at the ryegrass V_3 stage (3 totally expanded leaves). All treatments received N fertilization. Table 2 shows detailed information about the sheep. The stocking rate was adjusted by put-and-take method (Mott and Lucas, 1952) and it was used to maintain the average sward canopy height (SCH) at 0.15 m, which provides the optimum plant structure for maximizing animal production (Carvalho, 2013). The SCH was monitored at 7-day intervals using a sward stick (Barthram, 1985) to measure 150 randomly chosen points per experimental unit monthly. Immediately, at the end of the pasture phase, residual ryegrass was desiccated with glyphosate herbicide before soybean was sown.

The P and K fertilization rates were calculated from the amounts of P and K removed by soybean grains at an expected yield of 4.0 Mg ha^{-1}. In the soybean crops of 2017/2018 and 2018/2019 were applied 30 kg ha^{-1} of P and 58 kg ha^{-1} of K, and in 2019/2020 crop season a rate of 25 kg ha^{-1} of P and 67 kg ha^{-1} of K was used (Table 2). Fertilization rates were calculated according to CQFS-RS/SC (2016). The application of P and K fertilizer was performed on the soil surface, both in the conventional fertilization treatment, coupled with soybean sowing, and in the system fertilization, at the establishment of the Italian ryegrass. As can be seen in table 1, soil available P and K levels at the beginning of the experiment exceeded the critical thresholds. Table 2 shows the cultivars, sowing method, harvesting date, and sowing density for the 2017/2018, 2018/2019, and 2019/2020 seasons. Soybean was sown in rows 45 cm apart in all cropping seasons.

Assessment of soil acidity, soil available P and K, and P and K contents in plant tissue

Phosphorus and K content in soil and plant were determined at four different sampling times from 2017 to 2019. In the winter pasture phase, soil and plant samples were collected after 100 days of grazing to determine soil pH, and Ca^{2+}, Mg^{2+}, and Al^{3+} in

Table 2. Summary of the pasture and cropping phases in the three years of the experiment

Pasture phase	Season		
	2017	2018	2019
Stocking period			
Start of stocking period	June 13	June 5	July 5
End of stocking period	October 15	October 5	October 26
Grazing days	124	122	113
Italian ryegrass variety	BRS Ponteio	BRS Ponteio	BRS Ponteio
Sowing rate (kg ha^{-1})	25	25	25
Nitrogen fertilization rate (kg ha^{-1} of N)	150	150	150
Animal information			
Breed group	Corriedale	Corriedale	Corriedale
Age (months)	11	11	10
Initial live weight (kg)	25	30	31
Cropping phase	**Cropping period**		
	2017/2018	**2018/2019**	**2019/2020**
Sowing	November 20	October 23	November 28
Harvest	April 27	April 23	April 13
Crop days	158	182	137
Soybean cultivar	DM 5958RSF IPRO	ND 5909	TMG 7063 IPRO
Sowing rate (seeds ha^{-1})	255 000	255 000	255 000
Phosphorus fertilization rate (kg ha^{-1} of P)	30	30	25
Potassium fertilization rate (kg ha^{-1} of K)	58	58	67

September 2017 and 2018. In the cropping phase (January), samples were collected at the R_1 soybean stage in the 2017/2018 and 2018/2019 cropping seasons (Fehr and Caviness, 1977). The soil was sampled with an auger in the 0.00-0.20 m layer. Samples were dried in a forced-air oven at 45 °C, the larger lumps being crumbled, ground, and sieved (Ø = 2.0 mm). Soil pH was measured in aqueous suspensions (1:1 ratio, v/v). Available P and K were extracted with Mehlich-1, and Al^{3+}, Ca^{2+}, and Mg^{2+} with KCl 1.0 mol L^{-1} (Tedesco et al., 1995). Cation and Al saturation were calculated according to CQFS-RS/SC (2016).

Italian ryegrass tissue was sampled after 100 days of grazing, six sub-samples from each paddock being combined into a composite sample. Each sample was obtained by clipping at ground level the blades inside a 0.25 m² (0.5 × 0.5 m) quadrat. Soybean tissue was obtained at the R_1 stage by cutting whole plants near ground level. Four sub-samples per paddock of 2 linear meters (2.0 × 0.45 m) were combined to obtain a composite sample. Both pasture and soybean samples were dried in a forced-air oven at 65 °C, weighed on an analytical balance, milled, and sieved (Ø = 0.5 mm). The P and K contents of plant tissue were determined after chemical digestion with H_2O_2 + H_2SO_4 according to Tedesco et al. (1995).

Soybean, pasture, and animal production

Soybean yield, total herbage production, and live weight gain (LWG) per hectare were evaluated over three seasons. Soybean yield (kg ha^{-1}) was determined in five random sub-samples (2.0 × 0.45 m) from each plot (total area 4.5 m^2). Samples were collected at physiological maturity, threshed to determine grain moisture, and yield was calculated adjusting the moisture level to 130 g kg^{-1}.

Total herbage production as dry matter (kg DM ha^{-1}) was calculated as the daily herbage accumulation rate (kg DM day^{-1}) for each stocking period multiplied by the number of days of the period and that of stocking periods, the result being added to the initial herbage mass as determined one day before the start of the stocking period. Residual herbage mass at the end of the stocking cycle was estimated identically with herbage mass. The daily herbage accumulation rate was determined by using 4 grazing exclusion cages per experimental unit, the herbage mass inside each cage being clipped at ground level at 28-day intervals. On the other hand, the daily herbage accumulation rate was obtained as the difference between herbage mass in the grazing exclusion cage and pasture mass at the beginning of each stocking period divided by the number of days of the period.

Animals were weighed at the beginning and end of each grazing period (28 ± 3 days) to adjust stocking rates and monitor animal performance. The total LWG per hectare (kg ha^{-1}) was calculated as the difference between the final and initial weight of tester sheep multiplied by the number of animals per hectare and divided by the paddock area (ha).

Available soil P and K budgets

All P and K inputs via fertilizer and outputs through soybean grains and sheep meat were considered in the total budget. Phosphorus and K removal by soybean grains were calculated using the mean values adopted by CQFS-RS/SC (2016), namely: 6.1 kg P Mg^{-1} of grain and 16.6 kg K Mg^{-1} of grain. The nutrient contents of sheep meat (LWG) were calculated according to Williams (2007) (i.e., on the assumption that the sheep removed 0.194 g kg^{-1} of P and 0.344 g kg^{-1} of K).

Soil available P and K budgets were calculated with provision for the initial and final available P and K contents in the 0.00-0.20 m soil layer, and all inputs (fertilizer) and outputs (LWG and grain biomass) (Alves et al., 2019):

$$SB = (FS - IS) - (IF - OGM) \quad \text{Eq. 1}$$

in which: SB denotes soil budget; FS denotes final soil content (January 2019); IS denotes initial soil content (July 2017); IF means inputs via fertilizer; and OGM means outputs via grain and meat. All units have been converted to kg ha^{-1}.

Economic and use efficiency of P and K fertilization

Use efficiency (UE) for protein production per P and K fertilizer unit applied was calculated as 5.71 times (Merrill and Watt, 1973) the N content of soybean (CQFS-RS/SC, 2016). For live weight gain, carcass yield in Corriedale lambs was assumed to be 44.1 % (Carvalho et al., 2006) and protein content 20.4 % (Kremer et al., 2004). The P and K use efficiency were calculated according to equation 2.

$$UE = Prot_{total}/Nutr_{applied} \quad \text{Eq. 2}$$

in which: $Prot_{total}$ denotes the total amount of protein produced in soybean grains and sheep live weight over 3 years, and $Nutr_{aplied}$ denotes the total amount of nutrient (P or K) applied via fertilizer in the same period.

Economic efficiency (EE) per fertilizer P and K unit applied was calculated from the economic return of soybean and meat production of sheep in US dollars (USD), using the average price for the previous three years (CEPEA, 2020):

$$EE = USD_{total}/Nutr_{applied} \quad \text{Eq. 3}$$

in which: USD_{total} is the total economic return from soybean grains and sheep LWG for the three-year period; and $Nutr_{aplied}$ is the total amount of nutrient supplied via fertilizer in the same period.

Statistical analyses

Statistical analyses were performed with the software SAS® 9.4 (SAS, 2015). The results were checked for normality with the Shapiro–Wilk test and variance homoscedasticity with the Levene test, both at a significance level of 5 %, prior to analysis of variance (ANOVA, $p<0.05$). When significant, differences between treatment means were evaluated with Tukey’s test, also at the 5 % significance level.

The effects included in the statistical model were fertilization strategy (conventional or system fertilization), grazing (specialized or integrated system), and liming (with or without). Fertilization strategy (F), grazing (G), liming (L), and the interactions F*G, F*L, G*L and F*G*L, were used as fixed effects, and block and its interactions as random effects. We use the PROC MIXED procedure and RANDON effect in SAS® 9.4 (SAS, 2015). The models for available P and K in soil, total herbage production, LWG per area and soybean yield included the fixed effect of year (Y) and its interactions with other factors.

RESULTS

Soil acidity, and P and K contents of soil and plants

Soil acidity was affected by neither grazing nor fertilization (Table 3). Liming increased soil pH (4.3 to 5.0), Ca^{2+} (1.7 to 2.4 $cmol_c$ dm^{-3}), Mg^{2+} (1.2 to 1.9 $cmol_c$ dm^{-3}) and cation saturation (26.1 to 37.3 %), and decreased Al^{3+} (1.0 to 0.7 $cmol_c$ dm^{-3}) and Al saturation (25.7 to 17.3 %), in the 0.00-0.20 m soil layer after 18 months (Table 3).

Available P and K in the 0.00-0.20 m soil layer was affected by neither grazing nor fertilization strategy at any time during the sampling period (Figure 2a). Soil available P was lower in the cropping phase of the 2018/2019 season (53 mg dm^{-3}) than it was in the pasture phases of 2017 (91 mg dm^{-3}) and 2018 (83 mg dm^{-3}), and in the cropping phase of 2017/2018 (90 mg dm^{-3}) (Figure 2a). Liming had no effect on soil available P (mean of 77 mg dm^{-3}; Figure 2b). Available K was lower in the 2017/2018 cropping phase (76 mg dm^{-3}) than it was in the 2017 and 2018 pasture phases (111 and 122 mg dm^{-3}, respectively), and in the 2017/2018 cropping phase (100 mg dm^{-3}) (Figure 2c). Also, it was lower with liming (102 mg dm^{-3}) than without it (90 mg dm^{-3}) (Figure 3c).

Phosphorus and K contents of aboveground pasture biomass were affected by grazing, fertilization strategy and liming (Figure 3). Thus, P contents in the 2017 and 2018

Table 3. Acidity-related chemical properties of the soil in the 0.00-0.20 m layer 18 months after surface liming in the ICLS

Soil property	Without liming	With liming
pH(H_2O)	4.3 ± 0.3 B	5.0 ± 0.3 A
Cation saturation (%)	26.1 ± 4.2 B	37.3 ± 5.4 A
Al saturation (%)	25.7 ± 3.9 A	17.3 ± 2.8 B
Exchangeable Ca (cmol$_c$ dm^{-3})	1.7 ± 0.4 B	2.4 ± 0.5 A
Exchangeable Mg (cmol$_c$ dm^{-3})	1.2 ± 0.2 B	1.9 ± 0.2 A
Exchangeable Al (cmol$_c$ dm^{-3})	1.0 ± 0.1 A	0.7 ± 0.1 B

Different letters in each row denote significant differences as per Tukey's test (p<0.05).

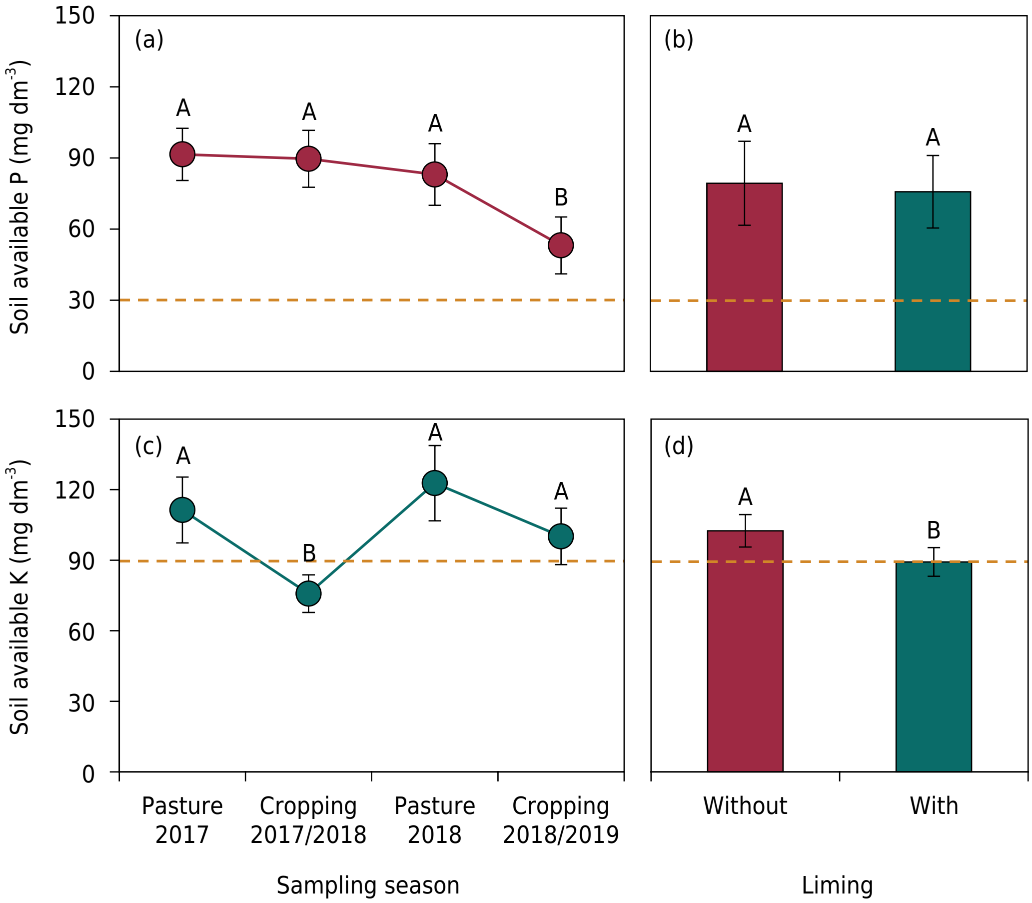

Figure 2. Available phosphorus (P) in the 0.00-0.20 m soil layer as affected by sampling season (a) and liming (b), and available potassium (K) in the soil as affected by sampling season (c) and liming (d) (with or without liming). The orange dotted lines represent the reference values for available P (30 mg dm^{-3}) and available K (90 mg dm^{-3}) in soil containing ≤200 g dm^{-3} clay and having a CEC$_{pH7}$ value of 7.6–15 cmol$_c$ dm^{-3} (CQFS-RS/SC, 2016). Different letters denote significant differences as per Tukey's test (p<0.05).

pasture seasons were higher with system fertilization than with conventional fertilization (3.4 vs 2.6 g kg^{-1} in 2017 and 5.8 vs 4.2 g kg^{-1} in 2018; Figure 3a). Similar results were obtained as regards grazing. Thus, P contents were higher with the integrated system than they were with the specialized system in both pasture seasons (viz., 3.3 vs 2.6 g kg^{-1} in 2017 and 5.6 vs 4.6 g kg^{-1} in 2018; Figure 3c). Potassium contents were higher with system fertilization than with conventional fertilization (viz., 16.5 vs 19.7 g kg^{-1} in 2017 and 31.5 vs 24.9 g kg^{-1} in 2018; Figure 3b); also, they were higher with the integrated system than with specialized system (20.3 vs 15.3 g kg^{-1} in 2017 and 32.3 vs 24.1 g kg^{-1} in 2018; Figure 3d). Finally, P contents in the 2018 pasture season were higher with liming than without it (5.1 vs 4.6 g kg^{-1}; Figure 3e), and so were K contents (29.4 vs 26.9 g kg^{-1}; Figure 3f).

Soybean, pasture, and animal production

Average production of Italian ryegrass herbage in the studied period (2017–2019) was higher with the integrated system than with the specialized system (8616 vs 7795 kg DM ha^{-1}; Figure 4a). Ryegrass production was also greater with system fertilization

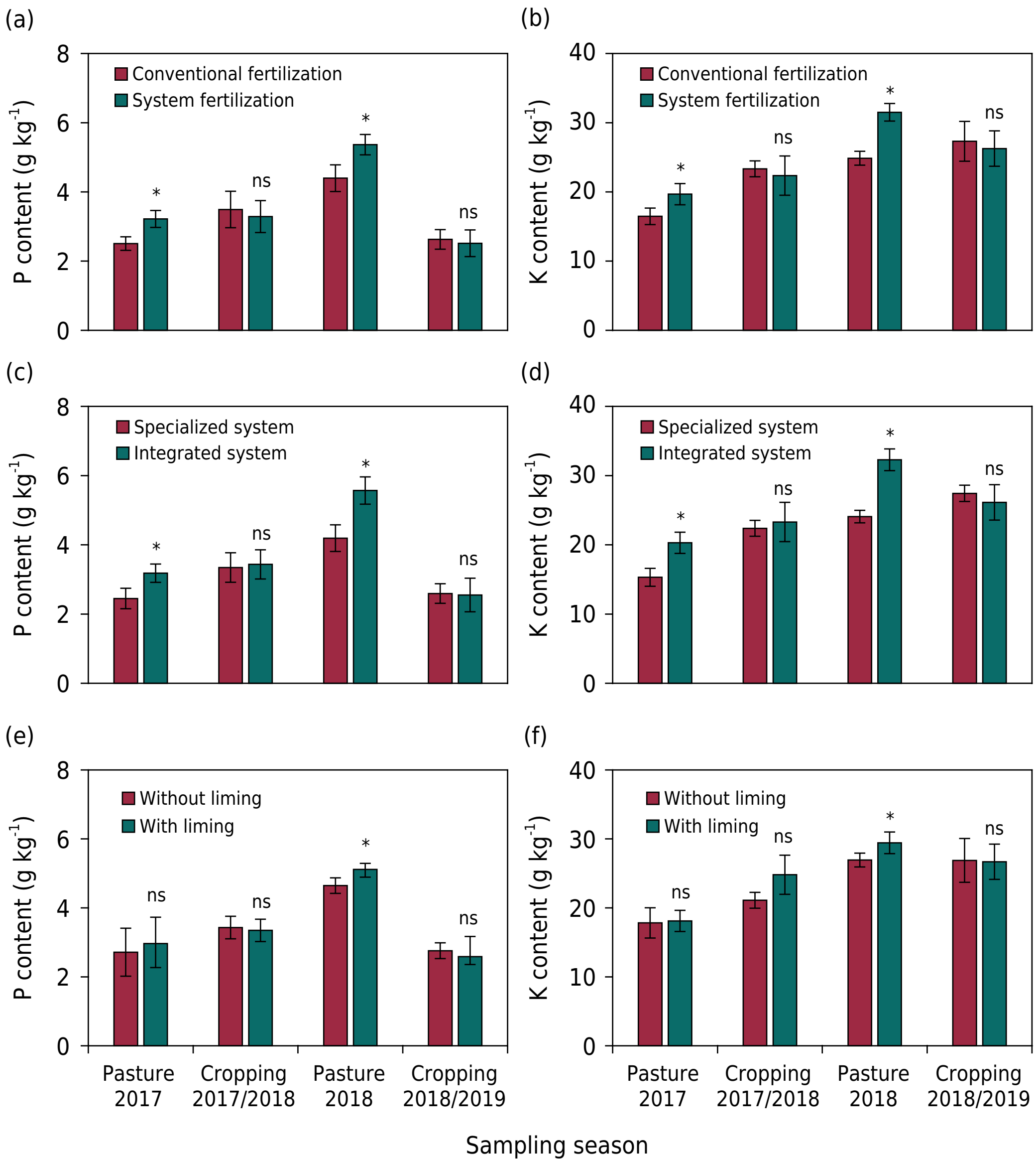

Figure 3. Phosphorus (P) and potassium (K) contents in aboveground biomass as affected by fertilization strategy (conventional or system) (a, b), animal grazing (specialized or integrated) (c, d), and liming (with or without) (e, f). Asterisks denote significant differences as per Tukey's test ($p<0.05$).

than conventional fertilization (8879 vs 7657 kg DM ha^{-1}; Figure 4a). Even so, the sheep LWG per unit area was similar to both fertilization strategies. Also, LWG was higher in the pasture phases of 2017 (300 kg ha^{-1}) and 2018 (325 kg ha^{-1}) than it was in 2019 (213 kg ha^{-1}) (Figure 5a).

Soybean yield exhibited no substantial differences between grazing or fertilization strategies (Figure 5b). Moreover, it decreased over time, from 2.90 Mg ha^{-1} in the 2017/2018 season to 2.64 Mg ha^{-1} in 2018/2019 and 2.51 Mg ha^{-1} in 2019/2020 (Figure 5a). Also, the average soybean yield for the three cropping seasons was higher with liming than without it (2.77 vs 2.59 Mg ha^{-1}; Figure 5c).

Soil P and K budgets

Available P budget in soil was positive and affected by none of the treatments (Table 4). On the other hand, the available K budget was negative with all treatments, but higher with the system fertilization-integrated system combination (-25.6 kg K ha^{-1}) than it was with the conventional fertilization-specialized system, conventional

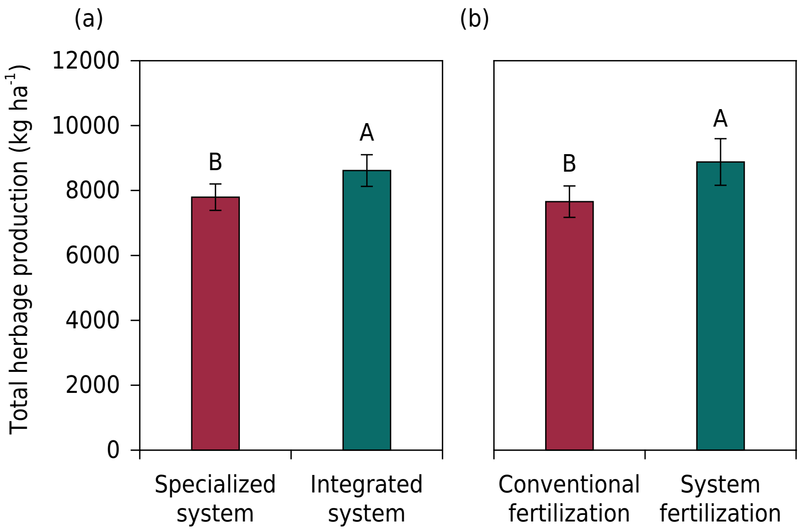

Figure 4. Total herbage production of Italian ryegrass (average of the years 2017, 2018 and 2019) as affected by animal grazing (specialized or integrated) (a) and fertilization strategy (conventional or system) (b). Different letters denote significant differences as per Tukey's test ($p<0.05$).

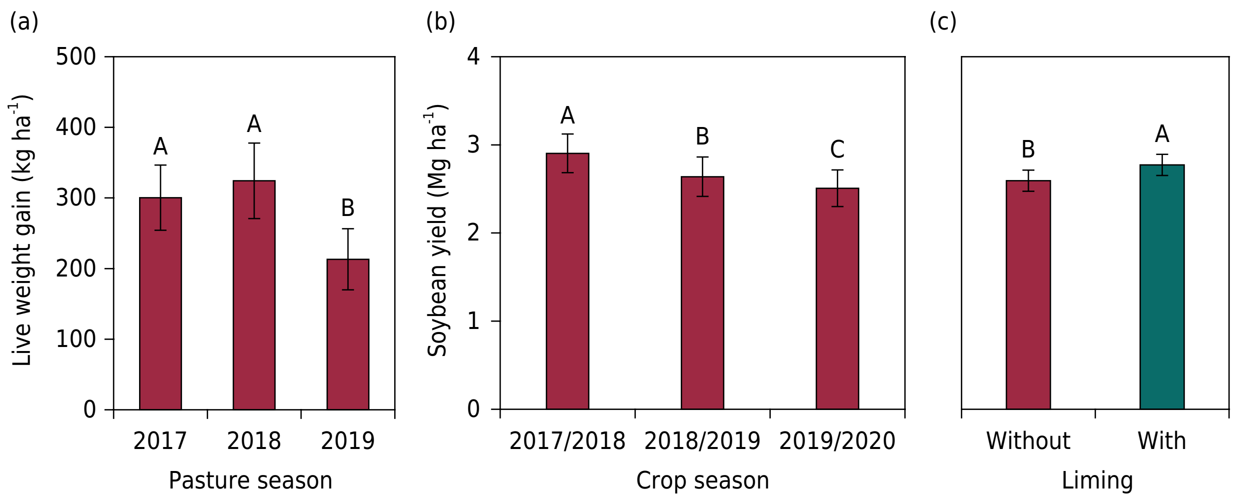

Figure 5. Live weight gain of sheep per unit area in each pasture season (a), and soybean yield as affected by crop season (b) and liming (with or without) (c). Different letters denote significant differences as per Tukey's test ($p<0.05$).

fertilization–integrated system and system fertilization-specialized system combinations (-68.8, -95.3 and -108.9 kg K ha^{-1}, respectively; Table 4). Liming, however, had no effect on the available P and K budgets.

Economic and use efficiency of P and K fertilization

Increased protein production per P and K unit applied via fertilizer resulted in an increased use efficiency with integrated system (35.1 kg P kg^{-1} and 16.4 kg K kg^{-1}) relative to specialized system (29.7 kg P kg^{-1} and 13.9 kg K kg^{-1}) (Figure 6a). Also, the increased economic return, in dollars, from soybean production and sheep LWG per P and K unit applied via fertilizer resulted in increased economic efficiency with the integrated system (49.7 USD kg^{-1} P and 23.3 USD kg^{-1} K) relative to the specialized system (30.9 USD kg^{-1} P and 14.5 USD kg^{-1}) (Figure 6b).

Table 4. Available P and K budgets in the 0.00-0.20 m soil layer as affected by fertilization strategy (conventional or system fertilization) and animal effect (specialized system or integrated system) in the ICLS

Fertilization	Grazing	Soil budget[1]	
		Stock of available P	Stock of available K
		kg ha^{-1}	
Conventional	Specialized system	49.9 ± 10.8	–68.8 ± 13.2 B
	Integrated system	30.3 ± 8.6	–95.3 ± 12.1 BC
System	Specialized system	26.3 ± 7.8	–108.9 ± 19.1 C
	Integrated system	36.9 ± 9.4	–25.6 ± 8.2 A
Mean		35.8^{ns}	-74.6^{*}

[1] Calculated as SB = (FS – IS) – (IF – OGM). SB: soil budget; FS: final soil content; IF: inputs via fertilizer; IS: initial soil content; OGM: outputs via grain and meat. ns: not significant at p<0.05. * Significant at p<0.05. Different letters distinguish the soil K budget under the effect of the interaction between fertilization strategy (conventional or system fertilization) and grazing (specialized system or ICLS) as per Tukey's test (p<0.05).

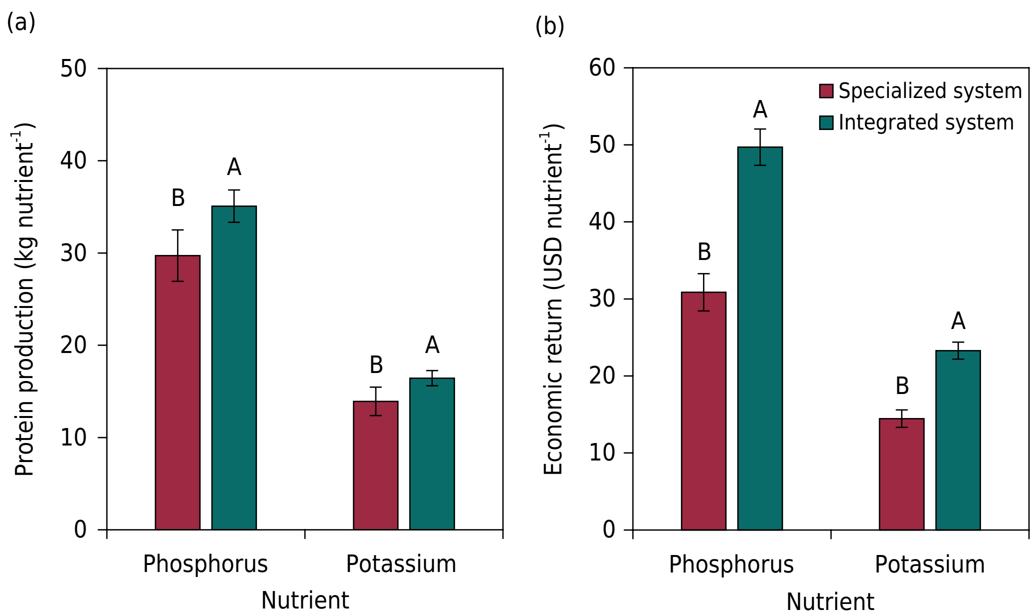

Figure 6. Phosphorus and potassium use efficiency for protein production (a) and economic return (b) as affected by grazing. Different letters denote significant differences as per Tukey's test (p<0.05).

DISCUSSION

Effect of soil acidity amendment by liming

Liming has well-known benefits on plant nutrition, like greater nutrients absorption such as N, P, K, Ca, Mg, and S, which leads to higher crop yields (Goulding, 2016; Holland et al., 2018, 2019; Bossolani et al., 2021). In this study, it increased the P and K contents of Italian ryegrass aboveground biomass in the 2018 pasture season (Figures 3a and 3b). Amending soil acidity by liming boosts root development and shoot growth (Fageria and Nascente, 2014), and increased root growth facilitates the exploration of deeper soil layers, facilitating P and K uptake by plants.

Although the applied lime rate was calculated to raise the pH to 6.0, the soil pH in the 0.00-0.20 m layer only reached 5.0 after 18 months. The limited effect of surface liming in the first few centimeters of soil is recurrent in no-tillage areas (Rheinheimer et al., 2018; Miotto et al., 2019), and proportional to the reaction time after application. Therefore, this result is explained by the short-term effect combined with the low solubility of lime. Moreover, the faster reactivity of the finer particles in the first centimeters raises the soil pH and Ca^{2+} content, resulting in a slow dissolution of the coarser particles of lime, hampering soil acidity correction (Scott et al., 1992). For these reasons, it is recommended that in areas with chemical restriction in-depth (>20-30 % Al saturation) associated with available P content below the critical level, liming with incorporation should be always carried out (CQFS-RS/SC, 2016). As the initial levels of available P in the soil were above the critical level in the experimental area, liming was carried out on the soil surface. Despite not having increased the soil pH to the target value in the 0.00-0.20 m layer (pH 6.0), and although in our study Al^{3+} was not completely neutralized by liming this soil layer, it is still possible to verify the beneficial effect of liming on soybean productivity (Figure 5c) (Holland et al., 2019).

Despite that soybean yield was higher in the liming treatment, the average yield of the treatments in the three harvests (2.7 Mg ha^{-1}) was below the expected 4 Mg ha^{-1} used to calculate the required P and K rates. Therefore, the residual acidity (pH values below 5.5 and Al saturation >10 %) in the liming treatment may be the limiting factor to achieve the target soybean yield (CQFS-RS/SC, 2016). In addition, another factor that has been limiting crop yields in the experimental area is water restriction, as droughts are frequently documented (Alves et al., 2020). Some studies under ICLS previously showed that liming does not affect soybean yield in moderately acidic soils (pH 4.8, cation saturation 56 % and Al saturation 15 % in the 0.00-0.20 m deep layer) (Martins et al., 2014a). These conditions, however, are contrasting from those of our soil, which had an initial pH of 4.0, cation saturation of 15 %, and Al saturation of 50 % in the 0.00-0.20 m layer, all of which led to an increased soybean yield.

Effect of sheep grazing and fertilization strategy

Higher herbage production obtained with the system fertilization results from the higher P and K contents in the aboveground biomass of Italian ryegrass (Figures 3a and 3d). By contrast, P and K content in soybean biomass did not differ between fertilization strategies, resulting in similar grain yields. This result testifies to the high potential of system fertilization for improving nutrient availability and plant nutrition, largely due to P and K fertilizer being applied in the pasture phase. The fact that P and K supply was maintained throughout the pasture phase was a result of the heavy cycling of nutrients caused by grazing and by the sheep returning most of the nutrients ingested through dung and urine (Ferreira et al., 2011; Silva et al., 2014; Deiss et al., 2016; Assmann et al., 2017; Alves et al., 2019).

Increased total production of Italian ryegrass is consistent with the increased herbage production previously found by Farias et al. (2020). Nitrogen, P, and K fertilization usually increase total herbage production by providing a greater supply of fodder to sheep, thereby increasing meat production (Ihtisham et al., 2018). Although the increase in total herbage production resulted in no substantial increase in LWG per area here (Figure 5a), gains are expected to become apparent in the long term. However, using pasture residues as inputs is crucial to regulate the soil C stock to maintain soil fertility and nutrient availability and have a positive effect on soybean yield in the long term (Alves et al., 2020).

The fact that soybean yield failed to respond to earlier P and K fertilization may have resulted from the curve of nutrient uptake by grain crops comprising a single cycle. In addition, the soil P and K content were above the critical level, thus the likelihood of crop response is much lower (Oliveira Junior et al., 2016; CQFS-RS/SC, 2016). This result is interesting as it is one of the first field studies demonstrating that system fertilization can be an effective strategy to enhance system production. Unlike grain crops, pasture is continuously stimulated to grow and uptake nutrients from the soil due to defoliation (Gastal and Lemaire, 2015). Grazing can increase photosynthetic and growth rates in plants (Gifford and Marshall, 1973), thereby increasing the requirements for nutrient uptake over several cycles of growth stimulation during grazing (Ruess et al., 1983; Chapin and McNaughton, 1989). This is consistent with the increased ryegrass herbage production observed when P and K were supplied in the pasture phase. This result, however, should only be expected when soil P and K levels exceed a critical threshold (Table 1). Our results cannot be extrapolated to soil conditions where P and K levels are below the critical level. Thus, further studies should be conducted using soils with available P and K contents below the critical level, as well as observing if other nutrients, such as N, could be managed in system fertilization. We emphasize that for a good functioning of the production system and for the system fertilization to be efficient, it is necessary to take into account some prerequisites, such as proper fertilization, soil acidity neutralization, use of the no-till system, and the adoption of ICLS (Anghinoni and Vezzani, 2021).

Once the amount of K exported by grains and meat was lower than the K inputs via fertilizers, the negative soil available K budget obtained with all treatments was possibly a result of excess K accumulating in non-exchangeable and structural forms in the soil - a frequent occurrence in soils containing 2:1 clay minerals (Watson et al., 2002; Berry et al., 2003) as found in previous studies in the same experimental area (Alves et al., 2019). In fact, 2:1 clay minerals can easily fix K in their interlayer spaces (Ernani et al., 2007). Also, applied K can partly migrate to soil layers below 0.20 m. In any case, the soil K budget was 2.7 times greater with the system fertilization–integrated system combination than with the conventional fertilization–specialized system combination. This result testifies the importance of animal grazing when nutrients are applied via fertilizer at an earlier time. In fact, grazing boosts root production (López-Mársico et al., 2015), thereby expanding nutrient uptake volume. In addition, continuous growth stimulation by grazing increases the requirements for nutrient uptake (Ruess et al., 1983; Chapin and McNaughton, 1989), thus hindering potential losses of K through leaching and runoff. By contrast, the soil available P budget was positive and similar to all treatments (Table 3). This was largely the result of the fertilization history in the experimental field (Alves et al., 2019), leading to saturation of the most P-eager sites and reducing the ability of the soil to immobilize P, converting it into less available forms as a result.

Integrated system provides greater economic returns than a specialized system (Franzluebbers, 2007; Sulc and Tracy, 2007; Oliveira et al., 2014). The increased protein production (use efficiency) and economic return (economic efficiency) with the integrated system arise from incorporating animals as a new source of protein and economic return into the production system (Oliveira et al., 2014; Martins et al., 2014b; Costa et al., 2014). The increased protein production of integrated systems is only possible with nutrient cycling by animals; in fact, most of the nutrients ingested by grazing are returned to the soil and made available to crops (Sanderson et al., 2013; Alves et al., 2019). Although system fertilization in ICLS increased total forage production, this did not result in higher animal production, thus not resulting in higher production and economic efficiency in these first three years of the experiment. However, it is expected that the higher total production of Italian ryegrass in the long term will benefit the system as a whole and contribute to higher system efficiency.

CONCLUSION

In this short period of time evaluated, system fertilization did not result in greater efficiency in the use of P and K, although it increased the P and K contents of pasture and total herbage production. Integrated system increases nutrient use efficiency, leading to a less negative available K budget in the soil. Neither soybean yield nor sheep live weight gain per unit was influenced by fertilization strategy, but soybean yield was increased by liming. Integrated system increased the use and economic efficiency of P and K fertilization by increasing food production per fertilizer unit. There is evidence that system fertilization provides an effective choice for promoting better use of nutrients by integrated crop-livestock systems, but future studies should continue this approach to evaluate the long-term effect of this fertilizer strategy on the efficiency of use of P and K.

AUTHOR CONTRIBUTIONS

Conceptualization: Amanda Posselt Martins (equal), Carolina Bremm (equal), Paulo César de Faccio Carvalho (equal), and Tales Tiecher (equal).

Data curation: Amanda Posselt Martins (equal), Carolina Bremm (equal), Dionata Filippi (equal), João Pedro Moro Flores (equal), Gustavo Duarte Farias (equal), and Tales Tiecher (equal).

Formal analysis: Dionata Filippi (equal), João Pedro Moro Flores (equal), Lucas Aquino Alves (equal) and Luiz Gustavo de Oliveira Denardin (equal).

Funding acquisition: Amanda Posselt Martins (equal), Carolina Bremm (equal), and Tales Tiecher (equal).

Investigation: Dionata Filippi (equal), João Pedro Moro Flores (equal), Lucas Aquino Alves (equal), Luiz Gustavo de Oliveira Denardin (equal), Paulo César de Faccio Carvalho (equal), and Tales Tiecher (equal).

Methodology: Amanda Posselt Martins (equal), Dionata Filippi (equal), João Pedro Moro Flores (equal), Gustavo Duarte Farias (equal), Lucas Aquino Alves (equal), Luiz Gustavo de Oliveira Denardin (equal), and Tales Tiecher (equal).

Project administration: Amanda Posselt Martins (equal), Carolina Bremm (equal), Paulo César de Faccio Carvalho (equal), and Tales Tiecher (equal).

Supervision: Amanda Posselt Martins (equal), Carolina Bremm (equal), Luciano Colpo Gatiboni (equal), and Tales Tiecher (equal).

Validation: Gustavo Duarte Farias (equal), Lucas Aquino Alves (equal), and Luciano Colpo Gatiboni (equal).

Writing – original draft: Lucas Aquino Alves (lead) and Tales Tiecher (equal).

Writing – review & editing: Amanda Posselt Martins (equal), Carolina Bremm (equal), Dionata Filippi (equal), Gustavo Duarte Farias (equal), João Pedro Moro Flores (equal), Lucas Aquino Alves (equal), Luciano Colpo Gatiboni (equal), Luiz Gustavo de Oliveira Denardin (equal), Paulo César de Faccio Carvalho (equal), and Tales Tiecher (equal).

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