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Productive characteristics of integrated agricultural systems with or without winter grazing and different fertilization strategies

Características produtivas de sistemas agrícolas integrados com ou sem pastejo no inverno e diferentes estratégias de adubação

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This study aimed to evaluate of productive characteristics in integrated livestock-crop systems with or without winter grazing and fertilization strategies. The experimental design used was a randomized complete block design with split plots (3 replications per treatment). Treatments were composed of four fertilization strategies (COMB = combination of fertilization for both soybeans and winter pasture applied during the pasture phase; FSBP = fertilization for soybeans applied during the pasture phase; REC = recommended fertilizations for pasture and soybean applied in their respective phases and TRAD = traditional recommendation, with N fertilization applied during the pasture phase and P and K fertilizers applied during soybean phase) and two managements of black oat/ryegrass pasture (with or without grazing cattle). Forty crossbred beef cattle were used in an intermittent stocking. Black oat/ryegrass forage production was greater in the presence of grazing animals. When grazed, the winter pasture production was greater under COMP and FSBP fertilization strategies compared to the REC and TRAD. The number of pods per plant and number of grains per pod were higher in grazed areas. The soybean grain productivity was not affected when grazing animals were included into the system. The COMB strategy resulted in the highest soybean productivity. The application of fertilization for soybean crops in the winter pasture increased soybeans productivity regardless of the addition of grazing animals into the system.
Key-words: inverted fertilization, soybean productivity, system fertilization.

O objetivo deste estudo foi avaliar as características produtivas em sistemas de integração lavoura-pecuária com ou sem estratégias de pastejo e adubação de inverno. O delineamento experimental utilizado foi o de blocos completos casualizados com parcelas subdivididas (3 repetições por tratamento). Os tratamentos foram compostos por quatro estratégias de adubação (COMB = combinação de adubação para soja e pastagem de inverno aplicada na fase de pastagem; ASP = adubação para soja aplicada na fase de pastagem; REC = adubações recomendadas para pastagem e soja aplicadas em suas respectivas fases e TRAD = recomendação tradicional, com adubação de N aplicada na fase de pastagem e adubações de P e K aplicadas na fase de soja) e dois manejos de pastagem de aveia preta/azevém (com ou sem pastejo de bovinos). Quarenta bovinos mestiços foram utilizados em lotação intermitente. A produção de forragem de aveia preta/azevém foi maior na presença de animais em pastoreio. Quando em pastoreio, a produção de forragem no inverno foi maior nas estratégias de fertilização COMP e ASP, em comparação com REC e TRAD. O número de vagens por planta e o número de grãos por vagem foram maiores nas áreas pastejadas. A produtividade de grãos de soja não foi afetada quando animais em pastejo foram incluídos no sistema. A estratégia COMB resultou na maior produtividade de soja. A aplicação de adubação para a cultura da soja na pastagem de inverno aumentou a produtividade da soja independentemente da adição de animais em pastejo no sistema.
Palavras-chave: inversão de adubação, produtividade de soja, adubação de sistema.

1. INTRODUCTION

Integrated crop-livestock systems (ICLS) have gained global significance over the past decade [1] as they represent a sustainable approach to intensifying food production while preserving the environment [2]. ICLS are characterized by combining agricultural activities such as grain crops with livestock and/or forestry within the same area, using succession and rotation regimens, or a combination thereof, to promote synergies among the integrated components and compartments (soil, plants, animals, and atmosphere) [3]. The interactions between these components within ICLS often yield positive socioeconomic and environmental impacts [4]. Moreover, these integrated systems can increase food production without the need for expanding agriculture into native areas [5].

In Southern Brazil, integrated systems often involve a combination of cattle grazing during the autumn and winter with the cultivation of grain crops such as corn and soybeans during the summer. Soybean, a legume, is a globally significant oilseed crop and a cornerstone commodity of Brazilian agribusiness [6]. Brazil ranks as the world's top soybean producer, yielding 154.6 million tons [7], with the Southern region contributing approximately 25% of the national soybean production. Livestock is present throughout the entire national territory, and in recent years, it has emerged as a significant ally in the intensification of agriculture, fostering sustainable development in rural areas [8]. The development of beef cattle production has solidified Brazil's position as the world's leading beef exporter. In 2022, the Brazilian beef herd was estimated at 202.8 million head, with a beef meat production totaling 10.8 mi tons carcass equivalent, accounting for 14.3% of world's production [9]. Recently, public policies have been implemented in Brazil to boost agriculture and livestock production through the adoption of sustainable technologies, including ICLS [8]. In these systems, the presence of grazing animals triggers a series of complex interactions within the agroecosystem. Animals play a major role as catalysts of biological processes, introducing new nutrient fluxes and accelerating their cycling [10]. The interactions occur in a direct and immediate manner by the grazing activity concomitant with manure deposition and stepping [11].

System fertilization is another technology that has been gaining notoriety. This technology involves the planning and application of nutrients considering all crops used in the system (e.g., pasture and oilseeds), as well as the transfer of nutrients between phases and system components. Therefore, this approach requires an understanding of the biological cycles of the entire soil-plant-animal-atmosphere interface and an intelligent and responsible exploitation of its synergistic relationships [12, 13]. The system fertilization is a strategy that envisions the total or partial application of recommended doses of fertilizer for summer crops at the seeding of winter crop, whether incorporated into or applied on the soil surface. Also known as inverted fertilization, the agroecosystem fertilization involves the total or partial application of major macronutrients (nitrogen (N), phosphorus (F), and potassium (K)) in the pasture preceding the grain crops [14]. This practice is based on the lower exportation of nutrients by grazing animals compared to the nutrient exportation of grain crops [15]. In addition, the system fertilization can increase vegetative biomass production and reduce nutrient losses [16]. The presence of grazing animals in the system promotes intense nutrient cycling and a residual fertilization effect that can be available for subsequent crops. This strategy aims to mitigate nutrient losses and achieve maximum efficiency of nutrient utilization, thereby maximizing performance of integrated systems [13, 17].

There is evidence in literature demonstrating that inverted fertilization (either total or partial) in ICLS with soybeans can improve total biomass production [16, 18]. However, given the diverse range of soils, managements, and climates, further studies evaluating inverted fertilization in ICLS are warranted. In addition, the official recommendations for fertilization are crop-specific, failing to consider the preceding or subsequent crops and the timing of application. As a result, researchers have posed several questions. For instance, which recommendation should a farmer adopt: the recommendation of fertilization for the main summer crop (grains) and apply it on winter crop (pasture or cover crop)? Alternatively, should the farmer combine the fertilization recommendations for both crops and apply them during the winter? Or should the farmer invert the fertilization recommendations for P and K for soybeans and follow the fertilization recommendation for N for the winter grass? Given the uncertainties outlined, the hypothesis of this study was that it is possible to apply the fertilization recommendations (K and P) for soybean crop over the pasture of oat and ryegrass (the winter crop preceding soybean crop) without impairing soybeans productivity. The aim of this study was to evaluate different fertilization strategies for K and P in an ICLS composed of winter pasture (a mixture of black oat and ryegrass) with or without grazing animals, and their effects on forage mass and soybean grains productivity.

2. MATERIAL AND METHODS

2.1 Local and agricultural year

This study was carried out during the agricultural year from April 2022 to April 2023 on a commercial farm (Fazenda Silveira) in the municipality of Coronel Vivida, Southwestern Paraná - Brazil (6°04'S and 52°25' W, 845 m altitude). The region climate is defined as Cfa, humid subtropical mesothermal, according to Köppen's classification. Climate conditions during the experimental period are shown in Figure 1. Climatological data were collected from the National Aeronautics and Space Administration/Prediction of Worldwide Energy Resources-NASA/POWER platform [19].

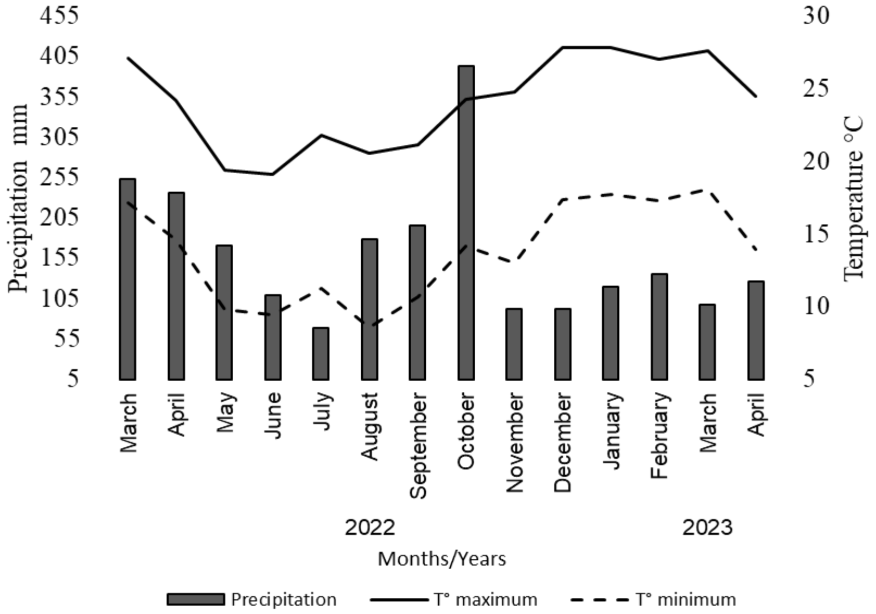

Figure 1: Precipitation (mm) and maximum and minimum temperatures (°C) during the experimental period.

The experimental area consisted of 25.2 ha divided into 24 experimental plots of 1.06 ha each. The soil of the experimental area was considered as typical dystroferric Red Latosol, with clayey texture, containing 64% clay, 18% silt, and 18% sand. Before setting up the experiment, soil samples (0-20, 20-40 cm) were taken from the experimental area to determine the soil's chemical analysis (Table 1).

Table 1. Chemical characteristics of the soil (0-20 cm and 20-40 cm layer) from the experimental area, Coronel Vivida (PR).

	Chemical properties								
Depth	**pH**	**OM**	**CEC**	**Ca^{2+}**	**Mg^{2+}**	**K^{+}**	**Al**	**V**	**P**
	CaCl^2	g dm^{-3}		-------------cmol$_c$ dm^{-3}-------------				%	mg dm^{-3}
0-20 cm	5.51	33.0	19.2	8.74	4.14	0.88	0.0	71.4	18.5
20-40 cm	4.47	14.9	14.0	1.17	3.37	0.14	0.0	35.8	1.33

pH = potential of hydrogen; OM = organic matter; CEC = cation exchange capacity; Ca = calcium; Mg = magnesium; K = potassium; Al = aluminum; V% = base saturation; P = phosphorus.

2.2 Experimental design and experimental area

This study was carried out as a randomized complete block design experiment with split-plots, where four fertilization strategies were considered as the main plots and the pasture managements (with or without grazing) were considered as the subplots. Treatments had three replicates. The strategies of fertilization were: the combination of soybean fertilization (P, K) and pasture fertilization (N, P, K) applied in pasture phase (COMB); soybeans recommended fertilization (P, K) and the N recommendation for pasture applied in the pasture phase (FSBP); recommended fertilizations for pasture (N, P, K) and soybean (P, K) applied in their respective crops (REC); and traditional recommendation, with N fertilization applied during the pasture and P and K fertilizers applied soybeans crop (TRAD). The doses of each nutrient are described in Figure 2. The recommended doses of N, P, and K for pasture and/or for soybeans crop were retrieved from the guidelines of fertilization and liming of Paraná State [20] based on soil analysis. Soybeans have been cultivated during the summer season, while a pasture consisting of black oat and ryegrass in consortium has been grown during the winter months.

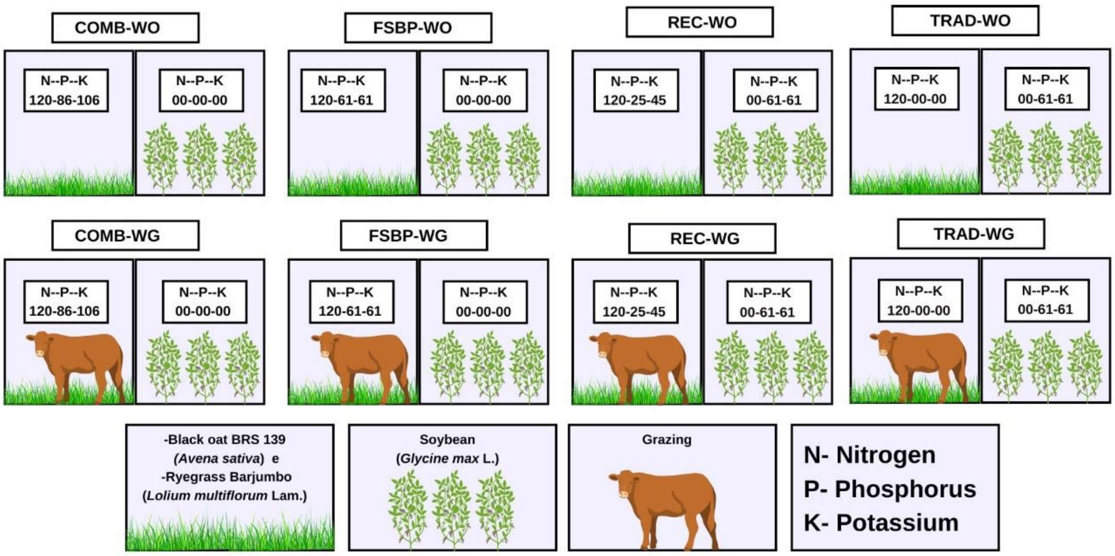

Figure 2. Different strategies of pasture management and fertilizations during the winter phase and summer phases (WO = without grazing; WG = with grazing; COMB = combination of fertilization of soybeans and winter pasture applied during the pasture phase; FSBP = fertilization for soybeans applied during the pasture phase; REC = recommended fertilizations for pasture and soybean applied in their respective phases; TRAD = traditional recommendation, with N fertilization applied during the pasture phase and P and K fertilizers applied during soybean phase).

2.3 Pasture phase / winter

The experiment started in April 2022 with the sowing of a blend consisting of 75% black oat (*Avena sativa* L; BRS 139) and 25% ryegrass (*Lolium multiforium* Lam. Barjumbo) at a seeding density of 80 kg ha^{-1}. Phosphatic fertilization was applied at seeding using superphosphate (16% P_2O_2) based on treatments outlined in Figure 2. Following 37 d from seeding (during black oat tillering stage), N top dressed fertilization at 120 kg N ha^{-1} (46% N urea) and phosphatic fertilization (potassium chlorate with 60% K_2O) were performed with the levels described in Figure 2. In treatments with grazing animals, crossbred beef cattle (11 mo-age and 305 kg body weight) were allocated in paddocks utilizing intermittent stocking. The grazing regime maintained an entry canopy height of 30 cm and an exit canopy height of 15 cm. Grazing commenced on June 4th and ended on November 12th, 2022, with a 10-d deferment period for pasture regrowth between August 20th and August 30th, resulting in a total grazing period of 151 d. The plots underwent 10 grazing cycles, each with an average occupation period of 5 d. Forage production (kg DM ha^{-1}) in treatments involving grazing animals was assessed by measuring the forage mass before and after each grazing cycle, as well as the residual forage mass at the conclusion of the experimental period. Forage mass was determined by collecting forage samples from 5 random areas within each plot at ground level (0.25 m^2 per sample) and weighing them. In plots where no grazing occurred, forage production was assessed at the conclusion of the experimental period using a procedure similar to that described previously. Samples were collected, weighed, and subsequently dried in an air-forced oven at 55 ºC for 72 h.

2.4 Soybean phase / summer

The soybean phase started on 16th November 2022 with the seeding of soybeans (cultivar BMX fibra - 6.4 maturity cycle, blooming at 38 d, and reaching maturity at 145 d). Soybeans were planted using a non-till seeder with a row spacing of 50 cm between lines. For both REC and TRAD fertilization strategies, phosphatic and potassic in furrow-fertilization were carried out, applying 61 kg ha^{-1} of P_2O_5 and K_2O.

Weed and pest management practices were implemented throughout the soybean cultivation period. Glyphosate (1.5 L ha^{-1}) and ethephon growth regulator (150 mL ha^{-1}) were applied to the soybean crop 35 d after seeding. An additional control measure was executed at 50 d after seeding, through the application of glyphosate (1.5 L ha^{-1}) and chlorpyrifos (1 L ha^{-1}) for Helicoverpa control. At 65 d after seeding, antifungal agents (bixa fem + protioconazole + trifloxystrobin at 1.0 L ha^{-1}, and thyophanate-methyl + fluazinam at 1.0 L ha^{-1}) were applied. Further fungicide treatments (epoxiconazole + fluxapyroxad + pyraclostrobin at 1.0 L ha^{-1}) and etiprole (1.0 L ha^{-1}) for insect control were applied at 80 and 95 d after soybean seeding.

The plant stand was evaluated 30 d after soybean seeding by counting the number of plants in 10-m rows within each plot. Prior to soybean harvesting, on April 10th, 2023, 10 plants per plot were sampled, and the yield components of soybean plants were assessed. Soybean plant height was measured from ground level to the plant tip using a ruler. The number of pods per plant (NPP) was determined by counting pods with grains on each plant, and the number of grains per plant (NGP) was also recorded. Soybean plants were manually harvested in two random sampling points (2 m^2 each) from each plot, and the grains were weighed with adjustments made for 13% moisture content. Thousand grain weight (TGW) was calculated from 8 evaluations of the mass of 100 kernels.

2.5 Statistical analysis

Data were submitted to analysis of variance homogeneity and residual normality. After verifying statistical assumptions, data were submitted to analysis of variance using R [21]. Treatment means within the fertilization strategy were compared by Tukey's test. Means of pasture management treatments were compared using the F test.

3. RESULTS

An interaction effect between pasture management and fertilization strategies was observed ($P < 0.05$) for forage production during the winter, which showed higher yields in grazed areas (Table 2). In the presence of grazing, winter pasture exhibited increased forage production under the COMP and FSBP fertilization strategies compared to the REC and TRAD strategies, which did not differ from each other. Conversely, in the absence of grazing animals, there was no difference in winter forage production between fertilization strategies.

Table 2. Forage production (ton DM ha^{-1}) of black oat/ryegrass pasture according to the fertilization and pasture management strategies.

Grazing (G)	**Fertilization strategy (FS)**				**Mean**	**SEM**	***P*-value**		
	COMB	**FSBP**	**REC**	**TRAD**			**G**	**FS**	**G x FS**
				Forage production (ton DM ha^{-1})					
With	12.2^{Aa}	12.6^{Aa}	10.6^{Ab}	11.1^{Ab}	11.6^{A}				
Without	5.32^{Ba}	4.88^{Ba}	4.48^{Ba}	4.72^{Ba}	4.85^{B}	0.73	<.001	<.001	0.030
Mean	8.76^{a}	8.74^{a}	7.54^{b}	7.91^{b}	8.22				

COMB = combination of fertilization of soybeans and winter pasture applied during the pasture phase; FSBP = fertilization for soybeans applied during the pasture phase; REC = recommended fertilizations for pasture and soybean applied in their respective phases; TRAD = traditional recommendation, with N fertilization applied during the pasture phase and P and K fertilizers applied during soybean phase. Different capital letters within columns are statistically different for pasture management at F test ($P < 0.05$). Different lowercase letters within rows are statistically different for fertilization strategies at Tukey's test ($P < 0.05$).

Plant stand and height were not influenced ($P > 0.05$) by the factors under investigation (Table 3). In grazed areas, the number of pods per plant (NP) and number of grains per pod (NG) were higher, while the weight of a thousand grains (TGW) was lower. These variables remained unaffected by fertilization strategies. The soybean grain productivity was not affected ($P > 0.05$) by the presence of grazing in the previous winter crop (Table 3). The COMB fertilization strategy resulted in the highest ($P < 0.001$) soybean grain productivity, while the TRAD strategy showed comparable productivity to the REC strategy and lower productivity compared to the FSBP strategy.

Table 3. Soybeans yield components according to the fertilization and pasture management strategies.

Item	**Grazing**		**Fertilization strategy (FS)**				**SEM**	***P*-value**		
	With	**Without**	**COMB**	**FSBP**	**REC**	**TRAD**		**G**	**FS**	**G x FS**
PS	254	249	255	258	240	258	3.68	0.358	0.364	0.614
PH	84.5	90.0	84.6	87.6	90.1	87.8	1.20	0.050	0.458	0.732
NP	71.0	59.0	64.0	65.0	69.0	64.0	2.10	0.007	0.709	0.876
NG	158	131	140	143	157	141	4.55	0.003	0.443	0.723
TGW	159	165	166	160	163	160	1.51	0.031	0.488	0.826
SGP	4.83	4.78	5.08^{a}	4.78^{b}	4.73^{bc}	4.61^{c}	0.04	0.321	<.001	0.065

PS = plant stand (10^3 × plants/ha); PH = plant height (cm); NP = number of pods per plant; NG = number of grains per plant; TGW = thousand grain weight (g); SGP = soybean grain productivity (ton DM ha^{-1}); COMB = combination of fertilization for both soybeans and winter pasture applied during the pasture phase; FSBP = fertilization for soybeans applied during the pasture phase; REC = recommended fertilizations for pasture and soybean applied in their respective phases; TRAD = traditional recommendation, with N fertilization applied during the pasture phase and P and K fertilizers applied during soybean phase.

4. DISCUSSION

The increased forage productivity in areas grazed during the winter is attributed to the positive impact of grazing activity on the growth dynamics of tillers and compensatory growth of plants. Grazing stimulates tillering, which in turn promotes increased leaf renewal and growth, ultimately leading to improved production and quality of forage [22]. These findings are consistent with those of Soares et al. (2023) [23], who observed that plots of black oat subjected to defoliation management showed higher forage production than plots without defoliation management. On the other hand, the enhanced forage production in areas subjected to grazing during the winter season and fertilized with higher doses of P and K (COMB and FSBP) can be attributed to the greater nutrient input and compensatory growth of plants [24]. This supports the notion that optimizing forage productivity in grazed areas is positively linked to increased fertilization. In areas devoid of grazing activity, the constraint on increasing forage production via enhanced nutrient input is associated with the net photosynthesis rate, affected by self-shading among plants. Each pasture exhibits an optimal management range wherein conditions conductive to forage accumulation are sustained by a positive balance between photosynthesis and respiration, thereby promoting biomass production [25].

The areas not subjected to grazing during the winter season exhibited an average forage production of 4,765 kg DM ha^{-1}. Despite this relatively high amount of crop residue, it did not jeopardize the plantability and establishment of the soybean crop. No differences were observed in plant stand of soybeans after 30 d of seeding between areas with and without grazing. The observed crop residues exceed the required amount (3,000 kg DM ha^{-1}) for soil conservation promotion. However, there is no cause for concern as detrimental effects from excessive soil cover become apparent at levels reaching approximately 6,000 kg DM ha^{-1} [26]. Excessive biomass cover can lead to clogging, irregularities in the opening of furrows, irregular deposition of seeds and fertilizers, and irregular emergence of seedlings [27] which could compromise the final plant stand. The plant stand is positively associated with grain productivity despite the high plasticity of soybean plants [28]. The similar plant stand among treatments can partially explain the lack of effects on soybean yield components and grain production. In general, an increase in plant population reduces the number of pods and grains per plant, while increasing TGW when edaphoclimatic conditions are not limiting [28]. The yield components as well as soybean productivity can be influenced by levels of phosphatic and potassic fertilization, particularly in soils with limited availability of nutrients [29, 30]. Khanam et al. (2016) [29] observed that P doses up to 75.2 kg ha^{-1} and K doses up to 99.6 kg ha^{-1} linearly increased the number of pods and grain per plant, as well as the TGW in soybeans. The lack of effect of different fertilization strategies (which differ in P e K amounts) on yield components of soybeans was not expected. The high fertility of the soil and the area's history of management based on crop-livestock integration may have contributed to reducing the impact of fertilization strategies on soybean yield components.

Although COMB strategy displays similar doses of P and K compared to REC strategy, COMB fertilization resulted in higher soybean productivity, fact due to increased winter forage production. This suggests enhanced nutrient input to soybeans through nutrient cycling, along with the presence of soil with superior characteristics. Asmann et al. (2017) [31] observed that black wheat and ryegrass pasture residue contained an average 2.6 g kg^{-1} P and 15 g kg^{-1} K. Based on the latter and accounting for the winter forage production, it is estimated that the amounts of P and K were 16.2% superior in COMB strategy compared to REC. Increasing biomass and incorporating organic matter into the soil improves soil structure by opening preferential channels, stabilizing aggregates, and raising soil macro and microporosity [26]. In addition, according to these researchers, the increase in biomass favors soil biology by increasing microbial mass and diversity, as well as other biological agents, such as annelids, which favor soil chemistry and physics. Microorganisms act directly in processes related to plant growth, solubilizing inorganic phosphates, producing phytohormones, and carrying out biological nitrogen fixation [26].

In this context, the superior soil conditions resulting from increased winter forage production may have offset the lower levels of P and K in the FSBP strategy compared to REC, resulting in comparable soybean productivity in both strategies. These results demonstrate that inverted fertilization enables a reduction in the usage of chemical fertilizers and improves sustainability of agribusiness. Guera et al. (2020) [32] observed that the preemptive phosphatic fertilization in winter pasture increased soybean crop productivity by enhancing soil concentrations of carbon and improving P utilization by plants.

On the other hand, the comparable soybean productivity between the REC and TRAD strategies can be associated with the similar winter forage production. These results demonstrate that wheat and ryegrass forage production in TRAD strategy was dependent on nutrients and fertility of the soil. These results also indicate that in highly fertile soil, traditional recommendations for P and K fertilization in winter pasture are adequate only for the replacement of exported nutrients. While this type of fertilization is crucial for soil conservation, it is not efficient for increasing forage production compared to not utilizing phosphatic and potassic fertilization, at least in the short-term. Results can also be partially attributed to nutrient adsorption [33]. It is important to recall that nitrogen is the most critical and imperative nutrient assimilated by plants for proper growth and development, either as ammonia or nitrates [34], and it was present in all evaluated fertilization strategies.

In the current study, soybean productivity was not increased by the presence of grazing animals during the winter. However, the result of this study supports the notion that proper pasture management during the winter does not compromise grain productivity in the subsequent summer, thereby enabling animal production during the winter as an additional season compared to the systems that utilize winter cover crops and produce grains in the summer. The absence of grazing activity effects on soybean productivity observed in this study may be associated with the high soil fertility and the history of integrated crop-livestock management in the experimental area (Table 1). The soil retains a memory of the historical use of agricultural areas [35], wherein the benefits of grazing activity persist between seasons. In agreement with the current study, authors did not observe impaired soybean productivity following the utilization of grazing animals on winter pasture [36].

6. CONCLUSION

The COMB fertilization strategy increased soybean yields regardless of the addition of grazing animals to the system.

Grazing on black oat/ryegrass pasture during the winter increases pasture forage production.

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