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Nitrogen return in an integrated crop-livestock system with irrigation and forage legume

Retorno de nitrogênio em um sistema integrado de produção agropecuária com irrigação e leguminosa forrageira

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Abstract: Expanding the use of different practices in integrated crop livestock system (ICLS) is essential to understanding the dynamics of nitrogen (N) return. This study evaluated the influence of legume and irrigation on nitrogen return in ICLS. The four treatments were: irrigated and non-irrigated x intercropped and not intercropped with legume, in a 2x2 factorial scheme in randomized blocks experimental design with three replications. The ICLS area was cultivated, in winter, with pasture of black oat (*Avena strigosa*) and ryegrass (*Lolium multiflorium*) overseeded in african star (*Cynodon* sp.), and vetch (*Vicia sativa*) in the intercropped paddocks, with rotational grazing method. And, in summer, with corn (*Zea mays*). Data were subjected to analysis of variance (F test, $p<0.05$). There were no significant effects of irrigation and legumes on the return of N through feces, urine, and pasture residues. Grain yield, straw, extraction, export, and return of N by corn were similar among treatments. The average total N return was 335.61 kg ha^{-1}. Irrigation and intercropping with legumes did not influence N return in ICLS, after one-year evaluation.

Key-words: sustainable agriculture; nutrient balance; mixed cropping; grain yield.

Resumo: Ampliar o uso de diferentes práticas em Sistemas Integrados de Produção Agropecuária (SIPA) é essencial para compreender a dinâmica do retorno de nitrogênio (N). Este estudo avaliou a influência da leguminosa e da irrigação no retorno de N em SIPA. Os quatro tratamentos foram arranjados em esquema fatorial 2x2 (irrigação x consorciação), sendo eles, irrigado e não irrigado, consorciado com leguminosa e não consorciado, dispostos em delineamento de blocos ao acaso com três repetições. A área experimental foi cultivada no inverno com pastagem de aveia preta (*Avena strigosa*) mais azevém (*Lolium multiflorium*), e a ervilhaca (*Vicia sativa*), implantada nos tratamentos consorciados, com pastejo rotacionado. No verão, o milho (*Zea mays*) foi cultivado em toda área. Os dados foram submetidos à análise de variância (Teste F, $p>0,05$). Não se observaram efeitos significativos da irrigação e da leguminosa no retorno de N pelas fezes, pela urina e pelos resíduos da pastagem. A produção de grãos, a palhada, a extração, a exportação e o retorno de N pelo milho foram semelhantes entre os tratamentos. O retorno médio total de N foi de 335,61 kg ha^{-1}. Após um ano de avaliação, a irrigação e o consórcio com leguminosa não influenciaram no retorno de N em SIPA.

Palavras-chave: agricultura sustentável; balanço de nutrientes; cultivo misto; rendimento de grãos.

1. Introduction

The increasing adoption of integrated crop-livestock systems (ICLS) presents a sustainable alternative for intensifying agricultural production amid current global demands for food and environmental conservation in the context of climate change [1,2]. Within ICLS, nutrient cycling, which is facilitated by the integration of animals with crops in rotational systems, can enhance the utilization of natural resources across the soil-plant-animal-atmosphere continuum [3], thereby increasing the profitability of these systems [4]. The processes of chewing and digestion by grazing animals act as catalysts for nutrient turnover, accelerating nutrient cycling. Nutrients are returned to the soil through urinary and fecal excretions in forms available for uptake by plant root systems [5].

The use of legumes in ICLS-managed pastures is a technology that can reduce reliance on external inputs and promote higher biomass production, thereby increasing the sustainability of production systems [6]. Incorporating legumes into pastures yields benefits such as biological nitrogen (N_2) fixation [2], enhanced ecosystem diversity, and improvements in animal nutrition through increased crude protein content.

In addition, implementing irrigation systems is an important strategy for balancing forage availability and quality. Irrigation contributes to increased productivity, greater leaf production, and elevated levels of crude protein and forage digestibility [7]. Regarding subsequent crops, specifically maize, Sah *et al.* [8] noted that although adequate water up to the vegetative stage is beneficial, the most critical period for yield occurs from the pre-flowering to grain-filling stages, during which maize yield is particularly sensitive to water availability.

In this context, the combined or individual use of forage legumes and irrigation in winter pastures and summer crops can significantly affect nutrient return and balance, as well as animal and crop production in succession. Specifically, these practices enhance biological N fixation by legumes and improve the effects of water supplementation during periods of water deficit, resulting in greater overall system biomass production.

Therefore, this study aimed to evaluate whether N return through system residues and maize yield are influenced by the application of irrigation and the intercropping of grasses and legumes in an integrated crop-livestock system.

2. Material and methods

The experiment was conducted at the Federal Technological University of Paraná (UTFPR) in Dois Vizinhos, Paraná State, Brazil (25°44″ S, 54°04″ W, 520 m altitude). The local soil is classified as Dystroferric Red Nitosol (Nitossolo Vermelho distroférrico) [9], and the climate is characterized as humid subtropical mesothermal (Cfa) [10], with an annual rainfall of 1800–2000 mm. For more than four years, the experimental area has been cultivated with Bermuda grass (*Cynodon* sp.) during the summer, and overseeded with black oats (*Avena strigosa*) and ryegrass (*Lolium multiflorum*) in the winter under beef cattle grazing.

During the winter and spring of 2016, the area was subdivided into 12 experimental units, each measuring 0.072 ha. Treatments consisted of two factors: irrigation (applied or not applied) and intercropping with legumes (performed or not performed) in the winter pasture. The experimental design was a randomized block in a 2 × 2 factorial arrangement with three replications. In winter, the pasture consisted of black oat and ryegrass, with and without intercropping with vetch (*Vicia sativa*), and with and without irrigation; maize (*Zea mays* L.) was grown in the summer. The soil chemical characteristics are presented in Table 1.

Table 1. Chemical analysis of the soil (0–20 cm) before the experiment.

Soil chemical attributes											
pH $CaCl_2$	SMP index	OM	P	K	Al^{3+}	$H^{+}+Al^{3+}$	Ca^{2+}	Mg^{2+}	SB	V	Al saturation
		g dm^{-3}	mg dm^{-3}	cmolc dm^{-3}						%	
4.76	5.93	39.76	5.21	0.57	0.13	5.32	4.70	2.33	7.60	58.87	1.78

OM: Organic matter; SB: sum of bases.

The sprinkler irrigation system consisted of 60 NY 25 sprisnklers, with a flow rate of 597 L ha^{-1} and an application rate of 2.2 mm h^{-1}, positioned at a height of 2 m, 18 m apart between rows, and 15 m apart between sprinklers. The system was activated when the soil water potential reached a value of 10 kPa or greater, as measured by tensiometers installed in the area. Air temperature and rainfall were monitored at the UTFPR weather station (Figure 1).

The pasture was established at the end of April 2016 by sowing 'BRS 139' black oat using no-tillage, with a seed density of 60 kg ha^{-1} and 0.17 m row spacing. 'Fepagro São Gabriel' ryegrass was sown in the field at a rate of 55 kg ha^{-1}. In intercropped paddocks, 'Ametista' vetch was sown in the same manner as oats, using 30 kg ha^{-1}, with rows perpendicular to those of the oats. Base fertilization consisted of 300 kg ha^{-1} of N-P-K (5-20-20), and urea (45% N) was applied as a top dressing at a total rate of 150 kg ha^{-1} of N, divided into five applications.

Grazing was managed through rotational grazing, with a pre-grazing height of 0.30 m, measured using a ruler at five points in each paddock. Two steers were allocated to each experimental unit (0.072 ha), totaling 24 animals distributed among the treatments. Animal removal was determined by the pre-grazing height in the subsequent paddock, with a minimum residual height of 0.10 m. If the subsequent paddock did not reach the required entry height while the current paddock did, animals were removed, weighed, and kept in a similar area until re-entry was feasible. This period was accounted for in the calculation of the stocking rate.

Twenty-four Angus and Charolais steers, with an initial mean weight of 162 ± 11.3 kg and aged 6–10 months, were used. The animals underwent an 18-day adaptation period in the paddocks, where they remained throughout the winter and spring, totaling 130 days of grazing. At the end of the grazing period, pasture residues were desiccated with glyphosate herbicide (3 L ha^{-1}). The study was approved by the Institutional Animal Care and Use Committee of UTFPR (protocol no. 2016-015).

Maize was sown in mid-November using a no-till system with a seeding rate of 3.6 seeds per linear meter of the "Pioneer 30F53VYH" hybrid and a row spacing of 0.45 m. The basal fertilizer applied was 439 kg ha^{-1} of N-P-K (8-20-10), and a topdressing of 90 kg ha^{-1} of N (urea, 45% N) was performed at the V6 stage. Pest control at the V4 stage employed the pyrethroid lambda-cyhalothrin and the anthranilamide chlorantraniliprole (150 mL ha^{-1}) to control the fall armyworm (*Spodoptera frugiperda*).

For pasture evaluations, the rate of dry matter accumulation at pre-grazing (entry) and post-grazing (exit) was determined by harvesting the entire pasture within a 0.25 m^2 quadrat at four locations. Samples were weighed and divided, with one portion used for determining the botanical composition, dead material (%), and vetch (%), and the other portion dried (55 °C for 72 h) to assess dry matter content. Forage mass was calculated before and after grazing. Based on these measurements and the number of days between grazing cycles, the daily accumulation rate and total dry matter production were calculated. On the second day after the animals entered the paddock, pasture samples were collected through simulated grazing [11]. These samples were dried and ground (Willey mill, 1 mm) for in vitro digestibility determination and to determine the N content of the ingested pasture and dead material, which was then analyzed for N content [12,13].

The animals were weighed every 28 days after a 12-hour fast to determine live weight (LW) and stocking rate. For intake and excreta assessments, four steers from the same genetic group were housed in each module for a 7-day adaptation period and a 12-day evaluation period, as per a 4 × 4 Latin square design (4 treatments × 4 periods). Each animal received 10 g of titanium dioxide daily at 10:00 am via esophageal probe. From days 8 to 12, fecal samples were collected rectally twice daily (10:00 am and 4:30 pm), then stored at -10 °C. Fecal samples were dried (forced ventilation at 55 °C for 72 h) and ground (Willey mill, 1 mm) for determination of titanium concentration, fecal output, and daily dry matter intake [14].

Urine samples were collected daily at 10:00 am from days 8 to 12 as spot samples. A 10-mL aliquot was acidified with 40 mL of sulfuric acid (0.036 N) for total N determination, and a separate 50-mL aliquot was retained for creatinine analysis using a commercial kit (LABTEST Diagnostica, Brazil) to estimate daily urine output [15]. Composite urine and fecal samples were analyzed for N content [13].

To evaluate the nutritional status of maize, one week after flowering began, the first leaf below the main ear was collected from 20 consecutive plants in three rows. Grain yield was determined by harvesting ears from two 4-m rows at four locations. All harvested ears were mechanically threshed, and the grains were weighed to determine moisture content and yield, with moisture standardized to 13 %. For crop residue analysis, plants (without grain) from two 1-m rows were collected and weighed. Subsamples of maize leaves, grains, and plant residues were dried (forced ventilation at 55 °C for 72 h), ground (Willey mill, 1 mm), and analyzed for N content [13].

For the statistical analysis, data were subjected to analysis of variance using the F-test, with a significance level of 5 % ($p < 0.05$). If the interaction between factors was not significant, main effects were evaluated independently of each other. In cases of significant interaction, means were compared using the t-test ($p < 0.05$), as Tukey's test was not applicable in certain situations due to data structure. Analyses were performed using the SAS software.

3. Results and discussion

The mean LW, stocking rate, total dry matter production, and pasture residue at the end of the cycle did not differ significantly among the evaluated factors (Table 2). Although previous studies suggest that irrigation increases dry matter production [7], in our study, the regular distribution of rainfall (132 mm/month) was sufficient to meet the plants' water requirements, resulting in limited use of the irrigation system (Figure 1). Consequently, irrigation had no significant impact on either dry matter production or animal stocking rates. The N concentration in the grazing simulation samples and the pasture residue before crop implementation was similar (Table 2). When necessary, irrigation can increase the N content in pastures, leading to a grazed mass with a higher crude protein concentration due to greater differentiation in pasture structure and increased leaf production [7].

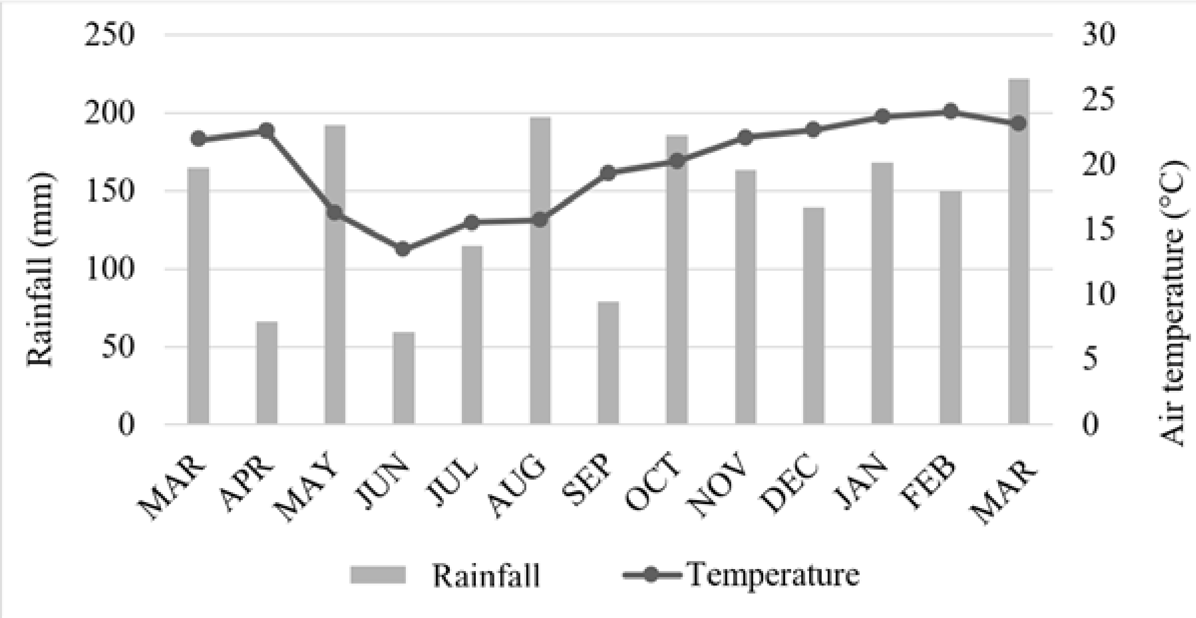

Figure 1. Accumulated rainfall and average air temperature from April 2016 to March 2017 in the experimental area. Dois Vizinhos, Paraná.

Similarly, pastures intercropped with legumes generally present a higher N content, which may be attributed to increased absorption resulting from biological N_2 fixation via symbiosis with bacteria of the Rhizobium genus, thereby raising the crude protein content [16]. However, this effect was not observed in our study, likely due to the low proportion of vetch in the forage canopy (2–5 %), which may be attributed to competition between this species and grasses (oats and ryegrass) [17].

Dry matter intake was similar across treatments, ranging from 3.2 to 3.4 % of LW (Table 2). Daily N intake also did not differ between treatments (Table 2). Similarly, due to the absence of differences in stocking rate, both daily and total N consumption per area were comparable among treatments (Table 2). On average, 282.70 kg ha^{-1} of N were mobilized by the animals during the evaluation period, thereby increasing the cycling of this element within the system. Since only 5–20 % of ingested N is retained by the animal, the remainder is excreted in feces and urine [18,19].

Table 2. Production parameters, nitrogen concentration, and animal consumption during winter/spring (130 days) in an integrated crop-livestock system using irrigation and pasture intercropped with legumes.

	Intercropped	Not intercropped	Mean	Pr>F Irr	Pr>F Interc	Pr>F Irr*Interc	CV (%)
		Live weight (kg)					
Irrigated	215.33	227.65	221.49 ns	0.8761	0.8097	0.8873	7.54
Non-irrigated	221.00	223.19	222.10				
Mean	218.17 ns	225.42					
		Stocking rate (kg LW ha^{-1})					
Irrigated	1782.77	2058.29	1920.53 ns	0.6111	0.3937	0.1536	9.23
Non-irrigated	2016.92	1941.01	1978.97				
Mean	1899.90 ns	1999.65					
		Total dry matter production (kg ha^{-1} DM)					
Irrigated	11746.89	11180.50	11463.70 ns	0.7273	0.5010	0.9114	13.25
Non-irrigated	12203.13	11416.69	11809.91				
Mean	11975.01 ns	11298.60					
		Pasture residue at the end of the grazing cycle (kg ha^{-1} DM)					
Irrigated	3621.00	3147.33	3384.16 ns	0.0952	0.4076	0.3240	15.91
Non-irrigated	2908.04	2950.76	2929.40				
Mean	3264.52 ns	3049.04					
		N concentration in the grazing simulation (g kg^{-1} DM)					
Irrigated	34.38	32.56	33.47 ns	0.3540	0.6457	0,5841	18,33
Non-irrigated	34.11	34.31	34.21				
Mean	34.25 ns	33.44					
		N concentration in pasture residue (g kg^{-1} DM)					
Irrigated	25.45	26.40	25.93 ns	0.7569	0.9220	0.3900	9.32
Non-irrigated	26.14	24.95	25.55				
Mean	25.80 ns	25.68					
		Daily dry matter intake (g kg^{-1} LW day^{-1})					
Irrigated	33.79	33.32	33.56 ns	0.8170	0.7987	0.7506	8.39
Non-irrigated	32.10	32.65	32.38				
Mean	32.95 ns	32.99					
		Daily N intake (g kg LW^{-1} day^{-1})					
Irrigated	1.16	1.09	1.13 ns	0.8571	0.8571	0.6539	19.51
Non-irrigated	1.09	1.12	1.11				
Mean	1.13 ns	1.11					
		Daily N consumption per area (kg ha^{-1} day^{-1})					
Irrigated	2.07	2.24	2.16 ns	0.7547	0.5751	0.4377	9.08
Non-irrigated	2.21	2.18	2.20				
Mean	2.14 ns	2.21					
		Total N consumption per area (kg ha^{-1})					
Irrigated	269.08	291.20	280.14 ns	0.7545	0.6095	0.4413	9.10
Non-irrigated	287.30	283.40	285.35				
Mean	278.05 ns	287.30					

ns = Not significant by the F test at a 5% probability of error.

The daily production of feces and urine was not significantly affected by irrigation or by intercropping with vetch, and N concentrations in urine and feces also did not differ among treatments (Table 3). On average, the N content in feces was 27.25 g kg^{-1} DM, which is consistent with the 27–32 g kg^{-1} DM reported by Garcia *et al.* [20]. In urine, the average N concentration was 7.60 g L^{-1}, similar to the 7.2 g L^{-1} reported by Selbie *et al.* [21] as being typical for beef cattle urine.

Table 3. Nitrogen production and concentration in animal excreta during winter/spring (130 days) in an integrated crop-livestock system using irrigation and pasture intercropped with legumes.

	Intercropped	Not intercropped	Mean	Pr>F Irr	Pr>F Interc	Pr>F Irr*Interc	CV (%)
Feces production (g kg^{-1} LW day^{-1})							
Irrigated	6.02	5.19	5.61 ^{ns}	0.2320	0.1213	0.0589	8.06
Non-irrigated	5.28	5.37	5.33				
Mean	5.65 ^{ns}	5.28					
Urine production (mL kg^{-1} LW day^{-1})							
Irrigated	60.44	68.58	64.51 ^{ns}	0.5068	0.6661	0.3809	19.30
Non-irrigated	61.79	58.98	60.39				
Mean	61.12 ^{ns}	63.78					
N concentration in feces (g kg^{-1} DM)							
Irrigated	26.89	27.81	27.35 ^{ns}	0.9303	0.5846	0.8896	16.12
Non-irrigated	26.38	27.93	27.16				
Mean	26.64 ^{ns}	27.87					
N concentration in urine (g L^{-1})							
Irrigated	7.76	7.43	7.60 ^{ns}	0.9793	0.1450	0.3463	14.90
Non-irrigated	8.33	6.88	7.61				
Mean	8.05 ^{ns}	7.16					
Daily return of N through feces (g kg^{-1} LW day^{-1})							
Irrigated	0.16	0.15	0.16 ^{ns}	0.3707	0.9194	0.3707	16.33
Non-irrigated	0.14	0.15	0.15				
Mean	0.15 ^{ns}	0.15					
Daily return of N through urine (g kg^{-1} LW day^{-1})							
Irrigated	0.47	0.51	0.49 ^{ns}	0.5384	0.5384	0.1113	17.66
Non-irrigated	0.51	0.41	0.46				
Mean	0.49 ^{ns}	0.46					
Daily return of N through excreta (g kg^{-1} LW day^{-1})							
Irrigated	0.63	0.66	0.65 ^{ns}	0.4691	0.4691	0.2106	14.11
Non-irrigated	0.65	0.56	0.61				
Mean	0.64 ^{ns}	0.61					
Total daily return of N by excreta per area (kg ha^{-1} day^{-1})							
Irrigated	1.12 ^{Ba}	1.36 ^{Aa}	1.24	0.6351	0.9093	0.0134*	9.54
Non-irrigated	1.31 ^{Aa}	1.09 ^{Ab}	1.20				
Mean	1.22	1.23					
Total return of N per area during winter (kg ha^{-1})							
Irrigated	237.96	258.16	248.06 ^{ns}	0.1928	0.5212	0.0754	9.87
Non-irrigated	247.20	207.65	227.43				
Mean	242.58 ^{ns}	232.91					

^{ns} Not significant by the F test at a 5% probability of error. Means followed by equal superscript uppercase letters in the row and superscript lowercase letters in the column do not differ by the T-test ($p > 0.05$).

In addition, the daily return of N from feces and urine was similar between treatments (Table 3), which can be attributed to the absence of differences in the crude protein content of the forage consumed. Nitrogen excretion in urine and feces is dependent on the crude protein concentration in the feed (22). The total return of N via animal excretion averaged 158.18 kg ha^{-1}, with 76 % excreted through urine and 24 % through feces. These results corroborate the findings of Lessa *et al.* (23), who reported that most of the N excreted by cattle is returned to the soil via urine.

In urine, 60–90 % of N is present as urea, which is converted to ammonia in the soil by urease, increasing the susceptibility of N to losses (24). The extent of these losses depends on various factors, including temperature, vegetation cover, humidity, and soil texture. In pastures, urinary N can be lost primarily through volatilization, as well as through surface runoff, while denitrification results in losses as N_2 and N_2O (25).

The total N return per hectare was lower in both treatments without irrigation and legumes, as well as in the treatment with irrigation and legumes (Table 3). Although the initial hypothesis anticipated a greater N return in the legume-intercropped treatment, the proportion of legumes in the pasture was low (5–10 %), likely due to competition with grasses, natural selection, and other uncontrollable factors (26). A comparable situation was observed with irrigation, whose effectiveness was mitigated by evenly distributed rainfall throughout the experimental period (Figure 1), which may have offset the expected effects of irrigation and legume intercropping. During the cultivation of summer maize, N concentrations in the flag leaf did not differ among treatments (Table 4). According to the Brazilian Society of Soil Science (27), leaf N levels of 2.7–3.5 % are considered adequate for maize development. No differences were observed in the N content of grains and straw (Table 4). Grain yield remained, on average, at 9497 kg ha^{-1}, and straw yield averaged 10,976 kg ha^{-1}; the irrigation and legume intercropping treatments influenced either one during winter (Table 4). As in the winter and spring periods, the average monthly rainfall of 162 mm, distributed evenly (Figure 1), was sufficient to meet the plants' water requirements. The similarity in grain yield between the grass-legume consortia may be attributed to the low presence of legumes in the pasture, which did not result in a substantial increase in residual N.

Table 4. Maize parameters in an integrated crop-livestock system using irrigation and pasture intercropped with legumes.

	Intercropped	Not intercropped	Mean	Pr>F Irr	Pr>F Interc	Pr>F Irr*Interc	CV (%)
	N concentration in the flag leaf (g kg DM^{-1})						
Irrigated	33.88	30.99	32.44 ^{ns}	0.2702	0.4726	0.1712	9.91
Non-irrigated	33.50	34.42	33.96				
Mean	33.69 ^{ns}	32.71					
	N concentration in grains (g kg DM^{-1})						
Irrigated	9.62	9.66	9.64 ^{ns}	0.0863	0.8312	0.7641	9.12
Non-irrigated	10.62	10.38	10.50				
Mean	10.12 ^{ns}	10.02					
	N concentration in straw (g kg DM^{-1})						
Irrigated	10.44	9.42	9.93 ^{ns}	0.5048	0.5403	0.4115	15.81
Non-irrigated	9.38	9.53	9.46				
Mean	9.91 ^{ns}	9.48					
	Grain yield (kg ha^{-1})						
Irrigated	8683.34	9930.56	9306.95 ^{ns}	0.4733	0.1259	0.4391	11.45
Non-irrigated	9472.23	9900.01	9686.12				
Mean	9077.79 ^{ns}	9915.29					
	Straw production (kg ha^{-1})						
Irrigated	10,710.55	12,182.81	11,446.68 ^{ns}	0.2527	0.2418	0.5303	13.94
Non-irrigated	10,275.15	10,733.91	10,504.53				
Mean	10,492.85 ^{ns}	11,458.36					
	N extraction (kg ha^{-1})						
Irrigated	190.90	188.43	189.67 ^{ns}	0.3353	0.3381	0.2538	9.86
Non-irrigated	188.50	212.90	200.70				
Mean	189.70 ^{ns}	200.67					

^{ns} = Not significant by the F test at 5% probability of error.

The total N return via pasture residue prior to the cultivation phase was similar among the treatments (Figure 2B), as there were no significant differences in either the amount or content of N in the residue, with an average of 79.56 kg ha^{-1} of N. However, the return of urinary N per hectare exhibited a significant interaction (Figure 2B), with lower values observed in the treatments with legume irrigation and those without legumes under non-irrigated conditions. Although the daily N return through urine per unit of LW did not show a significant interaction (Table 3), this difference may be attributed to the stocking rate, which directly influences the N return per area. Thus, despite similar proportional excretion across treatments, the total amount of N excreted per hectare differed. Since urinary N represents, on average, 76% of the total N excreted, this difference was also reflected in the total N return (urine + feces), which explains the lower values observed in these two treatments.

On average, the total N return in winter/spring was 237.7 kg ha^{-1}, of which 67% corresponded to N returned via feces and urine, and 33% to N derived from pasture residue.

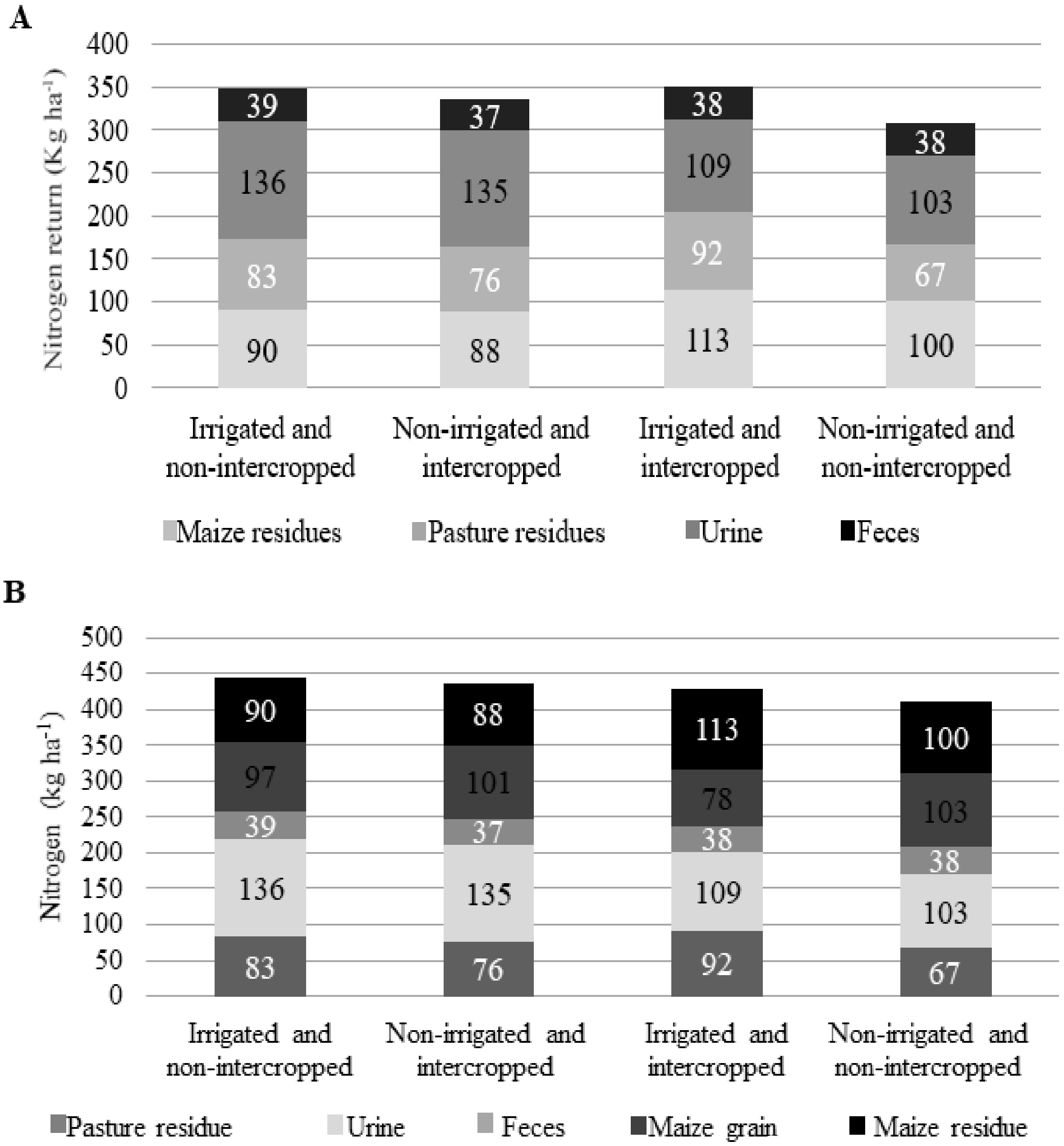

Figure 2. (A) Total nitrogen return and (B) amount of nitrogen measured in an integrated crop-livestock system using irrigation and pasture intercropped with legumes.

Considering agricultural practices, the mean N export was 94.69 kg ha^{-1} in grain ($p = 0.3490$) and 97.87 kg ha^{-1} in straw ($p = 0.4115$), with no significant differences among the evaluated factors and treatments. The relationship with grain yield and straw dry matter resulted in means of 9.95 and 8.97 kg ton^{-1} N in straw and grain, respectively. The combined export in grain and return in straw amounted to 195.18 kg ha^{-1} N, with no differences observed between treatments. The total N returned to the system was approximately 336 kg ha^{-1}, comprised primarily of N from maize residues (29%), pasture residues (24%), urinary N (36%), and fecal N (11%) (Figure 2). Of the total N returned, 71% occurred during the winter/spring period, with the majority derived from animal excreta.

Although the total N return per hectare showed a significant interaction between irrigation and legume intercropping, with lower values observed in the irrigated and non-irrigated legume treatments, it is important to note that these practices, when well established, can still contribute to the sustainability of the system. Irrigation can improve nutrient distribution and uptake by roots, as well as reduce losses through volatilization, particularly under water deficit conditions. Similarly, the inclusion of legumes can reduce the need for N fertilizers by promoting biological N fixation and decreasing N losses. Thus, even though the present study did not demonstrate this effect, the agronomic advantages of these practices may be more evident in systems with higher legume participation in the canopy and more intensive irrigation [28].

In addition to the N returned during winter and spring, 29 % of the total N return originated from maize crop residues, representing 98 kg ha^{-1} N retained in 10,976 kg ha^{-1} of straw, which remains in the soil and is available for decomposition and mineralization by the subsequent crop. In this context, it can be inferred that the amount of N supplied via fertilizers was sufficient to meet the demands of both winter/spring meat production and summer maize production. However, the actual balance can only be quantified by considering the N present in the soil and residues, as this constitutes the portion remaining in the system to be made available and utilized by the subsequent crop in ICLS.

The N exported by maize was similar among treatments. By adding the N exported by maize to the N returned to the soil, the total measured N in the system was, on average, 430 kg ha^{-1}. Although this does not represent the exact amount of N atoms cycled through the system, due to the dynamic nature of the nutrient, these values allow for an assessment of nutrient utilization and comparisons across different management practices regarding N use efficiency. Of the 430 kg ha^{-1} total N measured in the system, 18 % originated from pasture residues, 28 % from urine, and 9 % from feces, which together account for the winter total of 237 kg ha^{-1}, corresponding to 55 % of the total N in the system over the evaluation period (Figure 2).

Considering the total N applied as fertilizer throughout the experimental period (pasture + crops), 290 kg ha^{-1}, and the total N returned, approximately 335 kg ha^{-1}, one can note that the efficient use and maintenance of the nutrient within the system is essential, as the N returned exceeds the N applied. This occurs mainly due to the role of grazing animals in mobilizing N from pasture through grazing and recycling the nutrient via their excreta. As a result, N can be recycled multiple times within the system, enhancing its efficiency. Nevertheless, there is also a greater risk of losses, since N in feces and urine is more susceptible to loss than when retained in plant biomass.

4. Conclusion

The animals' N intake during the winter was not affected by irrigation or the legume consortium. Similarly, N returned via post-grazing residues, fecal excretion, and urinary excretion per unit of live weight was not influenced by the treatments. Nevertheless, N return via urine per hectare was lower in treatments with irrigation associated with the legume, as well as in those without irrigation or legume. Maize grain yield was similar between irrigated and non-irrigated areas, as well as between areas with and without intercropping during the winter. Hence, our findings lead us to conclude that the use of irrigation and intercropping with vetch does not significantly alter the total amount of N returned and cycled within the system, which exhibited an average value of 335.61 kg ha^{-1}.

Conflict of interest statement

The authors declare no conflict of interest.

Data availability statement

Data will be made available on request to the corresponding author.

Author contributions

Conceptualization: J.A. Farias Filho and L.R. Sartor; Investigation: J.A. Farias Filho; Methodology: J.A. Farias Filho; Project management: L.R. Sartor; Visualização: C. Amadori and M. Danna; Writing (original draft): J.A. Farias Filho; Writing (review and editing): L.R. Sartor , C. Amadori, M. Danna and L.F.G. Menezes.

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