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ORIGINAL ARTICLE

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Forage, carbon accumulation, and soil physical characteristics in a crop–livestock production system

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Abstract

Crop-livestock systems may improve land use and food security; however, heavy grazing can impair the soil physical properties and reduce the forage accumulation of subsequent crops. The study was conducted to evaluate the impact of mechanically harvest or low-intensity grazing on the physical properties of soil and the productivity of an annual pasture, ryegrass (*Lolium multiflorum* L.), and its successive crop, maize (*Zea mays* L.). Pasture and maize were evaluated from 2017 to 2021 and 2021 to 2022, respectively. The ryegrass was either mechanically harvested for silage production or grazed when the pre-defoliation sward height was between 20 and 25 cm. The total forage accumulation increased ($P < 0.08$) by approximately 500 kg ha^{-1} and forage accumulation rate were 25% greater ($P < 0.01$) in grazed pastures than in non-grazed pastures. Different pasture defoliation methods did not affect the physical properties of the soil. The total organic carbon concentration tended to be greater ($P = 0.058$) in the grazed area than in the non-grazed area, and the maize forage accumulation (average = 14,611 kg ha^{-1}) and chemical composition were similar for plants from the previously grazed and non-grazed areas. Four consecutive years of grazing did not impair the physical quality of the soil and DM production in either the pasture or maize silage. Thus, moderate grazing can be sustainably implemented over multiple years without degrading soil structure or reducing the productivity of forage and subsequent crops.

Plain Language Summary

Integrating crops and livestock can enhance land use and food security, but intensive grazing often harms soil structure and reduces crop yields. This study assessed the effects of low-intensity grazing in a crop–livestock system over 4 years. We found that low-intensity grazing had no damage to soil physical quality or dry matter production

Abbreviations: ADF, acid detergent fiber; CP, crude protein; DM, dry matter; NDF, neutral detergent fiber; OM, organic matter; TOC, total organic carbon.

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in either pasture or maize silage. These findings demonstrate the sustainability of this approach, offering a promising solution for resilient and productive agriculture.

1 | INTRODUCTION

The majority of forage species that are used as cover crops have high nutritive value, digestibility, and forage accumulation (Noizère et al., 2018; National Academies of Sciences, 2021). Therefore, crop–livestock systems may be an effective tool for improving land use and food security. However, grazing can impair the physical properties of the soil and decrease the forage accumulation of subsequent crops (Blanco-Canqui et al., 2020). In addition, trampling, animal excreta, and selective grazing may decrease forage accumulation (Jing et al., 2017).

In contrast, 25% to 40% of the carbon (Soussana et al., 2010) and 70% to 95% of the nitrogen (Selbie et al., 2015; Vendramini et al., 2014) consumed by ruminants returns to the pasture through animal excreta. In addition to plant residues, animal excretions can constitute an important source of organic matter (OM). Therefore, pastoral environments may have a considerable capacity to sequester carbon compared with that of systems that use mechanized forage harvest, because animals contribute to a more uniform distribution of nutrients across the landscape through their excretions, thereby enhancing soil fertility and promoting carbon sequestration (Snow et al., 2014; Vigan et al., 2017). For instance, improved pasture systems in tropical regions have demonstrated greater soil organic carbon levels than native forests under certain conditions (Amézquita et al., 2024).

The defoliation method plays a critical role in nutrient cycling and soil sustainability within crop–livestock systems. When forage is mechanically harvested and removed from the field, substantial amounts of nutrients—particularly nitrogen, phosphorus, and potassium—are exported from the system. For instance, haying has been shown to remove up to five times more nutrients than grazing (Wilson et al., 2011), as the entire aboveground biomass, including nutrient-rich plant tissues, is taken off-site. In contrast, grazing animals consume the forage in situ and return a large proportion of ingested nutrients to the soil through excreta, facilitating nutrient recycling and potentially improving soil fertility and organic carbon levels. While non-grazed areas may occasionally produce greater forage mass than grazed pastures (Ates, 2017), low-intensity or moderate grazing has been reported to sustain or even enhance total forage accumulation compared to intensive grazing practices, due to reduced defoliation stress and improved regrowth dynamics (Harrison et al., 2012).

We hypothesized that low-intensity grazing on annual ryegrass (*Lolium multiflorum* L.) over a short-term would not impair the forage accumulation and nutritive value of the forage and its successive maize (*Zea mays* L.) crop. The aim of this work was to assess the effect of grazing on soil physical properties and forage accumulation and subsequent crops over four consecutive years in a subtropical area.

2 | MATERIALS AND METHODS

2.1 | Experimental area and treatment description

The study was conducted in Lages, Santa Catarina, Brazil (50.18° W, 27.47° S; 920 m asl) from 2017 to 2022. The region's climate is classified as humid mesothermal with mild summers (Cfb) according to Koppen's classification, with an average annual temperature of 16.1°C, and an average rainfall of 1780 mm per year, according to the National Institute of Meteorology (INMET, n.d.). The average annual temperature during the experimental period (January 2017 to May 2022) ranged from 15.9°C to 17°C, with an average of 16.4°C (Figure 1). The average annual precipitation for 2017, 2018, 2019, 2020, and 2021 was 1704, 1483, 1334, 1088, and 1296 mm, respectively. The soil is classified as Humic Dystrudept (Agriculture Department, 2014).

Prior to the beginning of the study, the experimental area had been left fallow for over 5 years, with no active crop or livestock production. At the start of the experiment in March 2017, the 0- to 20-cm soil layer in the experimental area had the following chemical properties: pH 5.3, OM 36 g kg^{-1}, cation exchange capacity at pH 7.0, 17.73 cmolc dm^{-3}, phosphorus (P) 4.9 mg dm^{-3}, potassium (K) 146 mg dm^{-3}, aluminum (Al) 0.17 cmolc dm^{-3}, base saturation 510 g kg^{-1}, and clay content 340 g kg^{-1}. The soil was amended if referring to lime application and fertilized based on soil analysis and crop implementation. Soil analyses were conducted every 2 years, and fertilization was defined using the Liming and Fertilization Manual for the states of Rio Grande do Sul and Santa Catarina, Brazil (Comissão de Química e Fertilidade do Solo—RS/SC, 2004).

The treatments consisted of annual ryegrass, with or without grazing, followed by a maize crop, established in 150 m^2 plots arranged in a randomized complete block design with four replications. The ryegrass pastures were sown immediately after the maize harvest using a no-till system (Semeato SHM 11/13 seed drill), at a seeding rate of 25 kg ha^{-1}. Nitrogen fertilization totaled 150 kg N ha^{-1}, applied as urea in

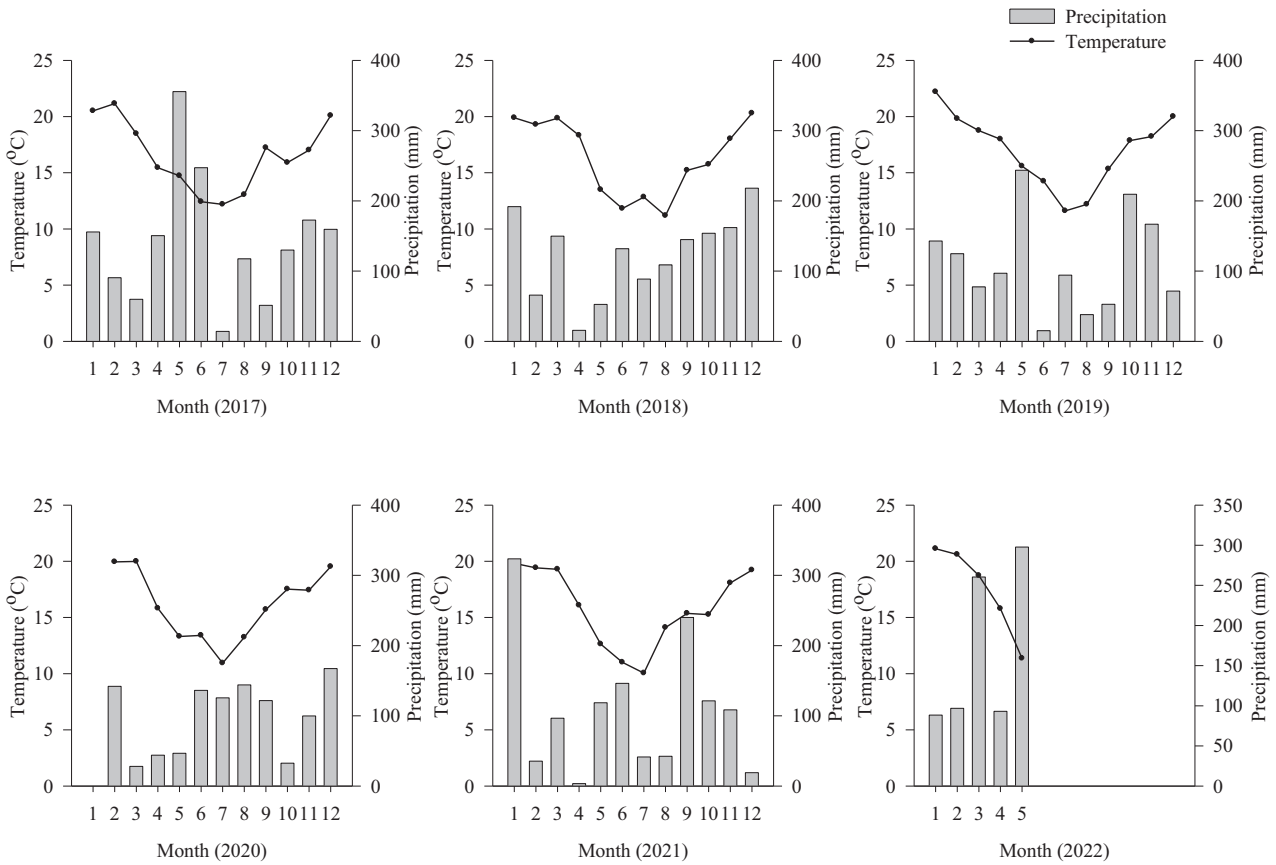


FIGURE 1 Air temperature and precipitation during the experimental period.

three split applications: one at the beginning of tillering and the other two following the first and second grazing cycles. No herbicides were applied for weed control in the pasture. Maize was planted after chemical desiccation of the ryegrass with glyphosate, using a Genius 50 × 50 planter, at a target density of 60,000 plants ha^{-1}. Nitrogen topdressing was performed at the V3–V5 growth stages, with a rate of 150 kg N ha^{-1}.

Pasture evaluations were conducted over 4 years (2017, 2018, 2019, and 2021), and data were analyzed by season to account for the effects of seasonality on pasture variables. Two seasons were defined: winter (from the first defoliation event to September 22) and spring (from September 23 to the last defoliation event). Pastures were seeded on April 25, 2017, May 14, 2018, May 21, 2019, and April 20, 2021. The first defoliation events occurred on July 13, August 15, August 8, and July 7, while the last defoliation events were recorded on October 20, October 31, November 18, and October 25 in 2017, 2018, 2019, and 2021, respectively. In 2020, due to restrictions imposed by the COVID-19 pandemic, data collection was not carried out; however, the experimental plots continued to receive their respective treatments to ensure continuity of the system.

Maize crop evaluations were carried out in 2021 and 2022 to assess the medium-term impacts of prior land-use management, given that the experimental plots had been subjected to grazed and ungrazed treatments since 2017. This interval was selected to allow potential differences in soil properties and crop performance, due to the contrasting management histories (grazed vs. ungrazed), to become apparent. Maize was sown on November 18, 2020, and November 26, 2021, and harvested on March 15, 2021, and April 4, 2022.

2.2 | Forage mass, forage accumulation, and nutritive value of pastures

Both grazed and non-grazed pastures were defoliated when they reached the pre-defoliation height range from 20 cm to 25 cm. Grazed pastures were defoliated by lactating dairy cows with a target post-grazing height between 50% and 60% of the pre-defoliation height (10 cm to 15 cm), which was considered moderate grazing for the purpose of this study (Bernardon et al., 2021). Non-grazed pastures were mechanically harvested at 5-cm stubble height to mimic the defoliation height usually used for silage production. Actual pre- and

post-defoliation sward heights were measured using a 0.5-m sward stick by averaging the first contact of 50 readings taken randomly throughout each experimental unit. Defoliation severity was calculated as the relative reduction in sward height, using the equation: Defoliation severity = (pre-defoliation sward height − post-defoliation sward height) / pre-defoliation sward height. Forage mass was measured before and after defoliation events from three 0.1-m^2 quadrats per experimental unit. The sampling locations were selected based on a visual assessment of the entire plot area to ensure that they were representative of the overall pasture condition. The quadrats were cut at ground level using scissors, and samples were dried in a forced-air drying oven for 72 h at 60°C. The forage accumulation rate was calculated as the difference between the pre-grazing forage mass and the previous post-grazing forage mass divided by the number of days between each defoliation event (average = 35 days). The nutritive value was determined throughout the grazing season in pasture samples collected by hand plucking or mechanical harvesting from grazed or non-grazed pastures.

2.3 | Maize measurements

Maize was evaluated in 2021 and 2022. When the entire plant reached 35% dry matter (DM) concentration, two rows of 10 m $plot^{-1}$ were cut 20 cm above ground level. Samples were weighed, and 6 plants row^{-1} were subsampled for morphological separation (leaf, stem, and cob + bract + grain). The other plants were grounded in a mill with a 5 cm sieve. One sample per plot was dried in a forced-air drying oven for 72 h at 60°C to determine the DM concentration and chemical composition of whole maize plants. For chemical analysis, the dried samples were ground in a Wiley-type mill using a 1 mm sieve.

2.4 | Forage and crop nutritive value

Dry matter concentration was determined by drying samples at 105°C for 24 h. Ash concentration was measured by combustion in a muffle furnace at 550°C for 4 h, and the OM concentration was quantified based on the mass difference. The total nitrogen concentration was measured using the Dumas combustion method 968.06 (Latimer, 2019) with the Leco FP 528 equipment (LC, Leco Corporation). Neutral detergent fiber (NDF) concentration was analyzed using the ANKOM A220 system (ANKOM Technology) with heat-stable α-amylase and without sodium sulfite, following (Mertens, 2002) with modifications. Acid detergent fiber (ADF) concentration was determined according to AOAC Method 973.18 (Latimer, 2019).

2.5 | Soil measurements

Soil sampled was conducted for the determination of the physical properties from 2017 to 2021. Two sampling points were collected per plot in the 0- to 5-, 5- to 10-, 10- to 20-, and 20- to 30-cm layers. Soil bulk density and porosity analyses were performed based on the principles of a volumetric ring (Embrapa, 2011). Total organic carbon (TOC) concentration was determined in the soil samples collected at the same depths as described above. The samples were dried in a forced-air drying oven at 60°C and macerated. TOC analyses were performed using a TOC/total nitrogen elemental analyzer (Analytik Jena Multi N/C 2100). The carbon stock was calculated based on the equivalent soil mass, correcting for the different effects that management systems may have on soil bulk density in each sampled layer (Wendt & Hauser, 2013).

2.6 | Statistical analysis

Data were analyzed using the MIXED procedure in SAS v.9.2 (SAS Institute Inc.). Variables related to forage accumulation and maize DM yield were analyzed considering year and block as random effects, and treatment as fixed. Pre-defoliation canopy height, total forage accumulation, forage accumulation rate, nutritive value, and plant composition (leaf, steam + pseudo-steam and dead material) of ryegrass were analyzed considering the year and block as random effects, and treatment, season, and the treatment × season interaction as fixed. Data on soil physical properties and TOC concentration were analyzed considering the fixed effect of treatment, the random effect of block, the fixed effect of depth, and the treatment × depth interaction.

3 | RESULTS

3.1 | Forage accumulation

The annual forage accumulation increased ($P < 0.08$) by approximately 500 kg ha^{-1} (Figure 2), and the forage accumulation rate was 25% greater ($P = 0.006$) in the grazed than in the mechanically harvested plots (Table 1). Pre-defoliation forage mass was greater ($P = 0.003$) in grazed areas than in non-grazed areas and during winter than in spring. Defoliation severity was lower ($P < 0.001$) in grazed areas than in mechanical harvested areas, with the lowest value observed in grazing plots during spring (interaction treatment × season: $P < 0.001$). Crude protein (CP) concentration increased in grazed forage samples compared with that in non-grazed samples ($P < 0.001$) and in spring than in winter ($P = 0.019$).

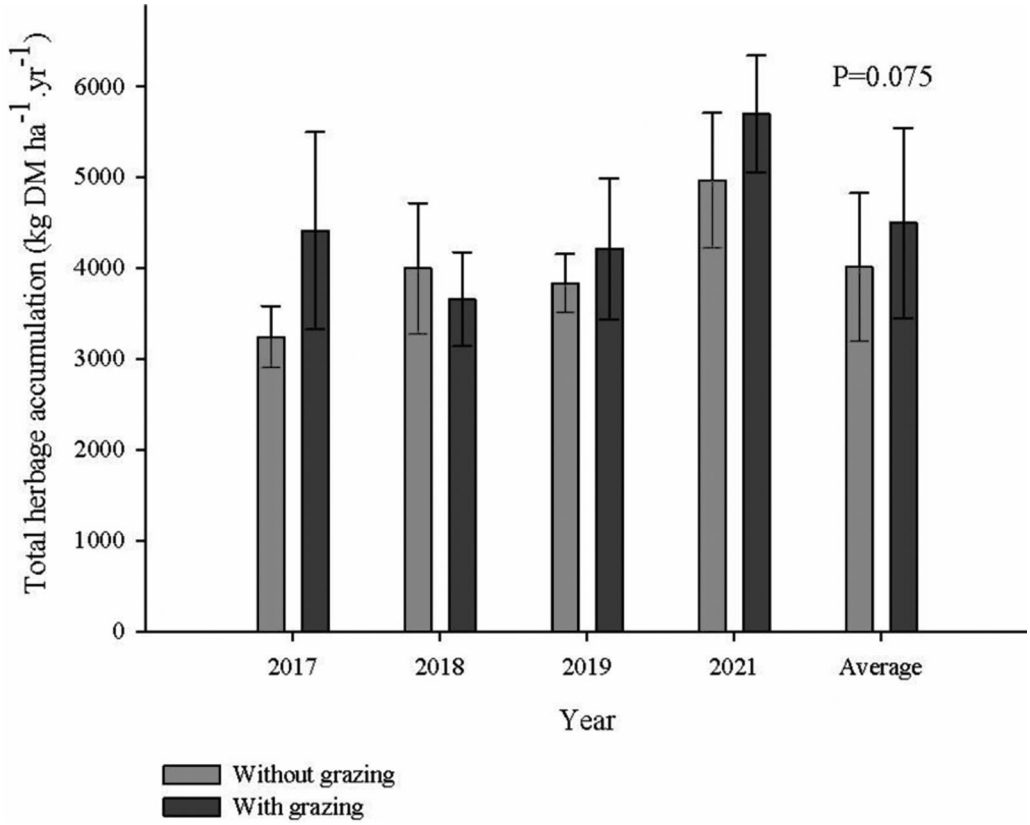


FIGURE 2 Total herbage accumulation of annual ryegrass (*Lolium multiflorum*) grazed or mechanical harvest for 4 years. Averages of assessments conducted in 2017, 2018, 2019, and 2021. DM, dry matter.

TABLE 1 Forage characteristics of annual ryegrass (*Lolium multiflorum* L.) grazed or mechanically harvested in five consecutive years (2017, 2018, 2019, 2020, and 2021) during winter and spring months.

	Harvest		Grazed			*P*-value		
Response variables	**Winter**	**Spring**	**Winter**	**Spring**	**SEM**	**Treatment**	**Season**	**Treat × Season**
Pre-defoliation forage mass (kg DM ha^{-1})	2047	1585	2220	1916	79.7	0.003	<0.001	0.324
Post-defoliation forage mass (kg DM ha^{-1})	1378a	1105b	1428a	1850a	81.9	<0.001	0.371	<0.001
Forage accumulation rate (kg ha^{-1}·day^{-1})	24.7	24.5	27.1	33.5	1.74	0.006	0.148	0.108
Pre-grazing canopy height (cm)	23.1b	24.4a	24.2a	24.4a	0.28	0.011	0.015	0.042
Post-grazing canopy height (cm)	8.53	8.56	11.7	12.1	0.230	<0.001	0.455	0.152
Defoliation severity[a] (%)	60.1a	62.5a	51.8b	41.5b	1.60	<0.001	0.017	<0.001
Chemical composition (g kg^{-1} DM)								
Organic matter	895	892	904	902	2.48	<0.001	0.341	0.823
Crude protein	194	199	237	260	5.58	<0.001	0.019	0.126
Neutral detergent fiber	436a	516a	441a	494b	4.17	0.053	<0.001	0.003
Acid detergent fiber	221a	266 a	209b	233b	3.53	<0.001	<0.001	0.005
Plant composition (% DM)								
Leaf	64.3	37.2	60.8	33.6	1.59	0.027	<0.001	0.953
Steam + pseudo-steam	26.2	39.1	28.4	40.6	1.57	0.232	<0.001	0.811
Dead material	9.49	23.7	10.7	25.8	1.52	0.260	<0.001	0.757

Note: Means followed by the same letters do not differ significantly according to Tukey's test ($P > 0.05$).

[a]Defoliation severity = (pre-defoliation sward height − post-defoliation sward height)/ pre-defoliation sward height.

TABLE 2 Forage accumulation and chemical composition of maize (*Zea mays*) cultivated in areas previously harvested or grazed during the cool season from 2017 to 2021[a].

	Treatments			
Response variables	**Harvest**	**Grazed**	**SEM**	***P*-value**
Forage accumulation (kg DM ha^{-1})	14,967	14,255	811	0.55
Chemical composition (g kg^{-1} DM)				
Organic matter	967	963	8.3	0.01
Crude protein	77.9	84.5	12.8	0.01
Neutral detergent fiber	614	599	11.0	0.37
Acid detergent fiber	293	288	65.0	0.60
Morphological composition (% DM)				
Leaf	14.9	16.2	0.56	0.149
Steam	25.5	27.1	0.99	0.279
Cob + bracts + grains	59.4	56.7	1.15	0.131

Abbreviations: DM, dry matter; SEM, standard error of the mean.
[a]Data collected in the 2021 and 2022 harvests.

The NDF concentration was greater ($P < 0.001$) in spring than in winter. Leaf proportion was 27% greater in ryegrass grown in winter than in spring ($P < 0.001$).

3.2 | Crop production

The forage accumulation of whole maize plants was similar between treatments (average = 14,611 kg ha^{-1}), but the OM and CP concentrations were greater ($P < 0.01$) in previously grazed than in non-grazed areas (Table 2). The NDF and ADF concentrations of whole maize plants were similar between treatments. Similarly, the proportions of steam and cob + bracts + grains did not differ between treatments, averaging 16%, 26% and 58% of the DM, respectively.

3.3 | Soil characteristics

Soil bulk density was greater ($P = 0.07$) in areas subjected to grazing compared to non-grazed areas, with averages of 1.35 and 1.30 g cm^{-1}, respectively (Figure 3). Considering that baseline soil bulk density in 2017 was 1.00 g cm^{-3} (data not shown), these values represent increases of approximately 35% and 30%, respectively, for grazed and non-grazed areas. Soil porosity, microporosity, and macroporosity did not differ between treatments. Soil bulk density was lower ($P < 0.05$) in the 20- to 30-cm depth, whereas macroporosity was greater ($P < 0.05$) in the 20- to 30-cm layer regardless of the defoliation strategy. The TOC concentration increased ($P = 0.058$) in the grazed area and decreased ($P < 0.001$) with increasing depth in the sampled layers (Figure 4).

4 | DISCUSSION

4.1 | Effect of grazing on forage accumulation and its chemical composition

The greater total forage accumulation and daily forage accumulation observed in grazed plots was attributed to the higher post-defoliation canopy height ($P < 0.01$) in the grazed treatment, as well as to the nutrient input from animal excreta. When grazing is properly managed and overgrazing is avoided, a greater forage mass maintains a higher residual leaf area, which enhances light interception, photosynthesis, and the rate of biomass accumulation following defoliation event (Carvalho et al., 2018). Therefore, the greater forage accumulation rate observed in the grazing plots cannot be attributed solely to the defoliation strategies but to the residual leaf area. In contrast, mechanically harvested areas have more uniform removal of forage mass and potentially growing points during harvesting, which compromised the plants' ability to rapidly recover. Without adequate photosynthetic area, plants must rely on energy reserves stored in the roots to initiate regrowth, a slower process that can be further hindered by consecutive harvests depleting these reserves. Consequently, the residual forage mass in the grazed plots likely played a crucial role in supporting faster regrowth and greater overall yield by preserving active photosynthetic capacity and minimizing stress on energy storage. Grace et al. (2019) did not find any difference in forage accumulation between treatments in a study comparing grazed or mechanically harvested multispecies swards with the same post-defoliation sward height.

The greater CP concentration of grazing forage was attributed to animals grazing a layer of sward with a greater

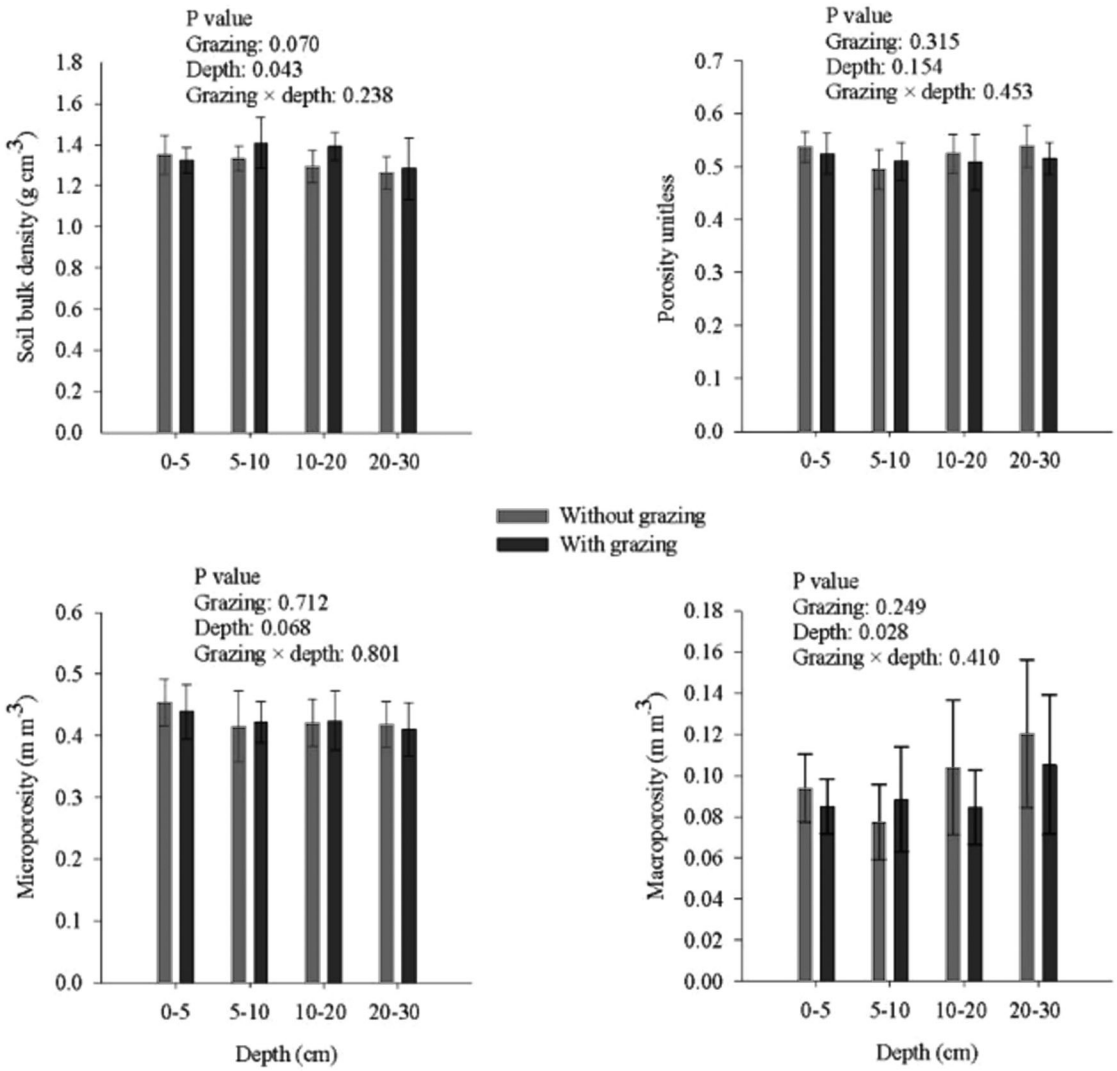


FIGURE 3 Soil physical properties in areas of annual ryegrass (*Lolium multiflorum*) grazed or mechanical harvest followed by the crop (*Zea mays*) for five consecutive years (2017–2021). Data collected in 2022.

leaf proportion and lower stem + pseudo-steam concentration. The post-grazing defoliation sward was 4-cm higher (12.5 vs. 8.5 cm), and defoliation severity was 15% lower (47% vs. 62%) in the grazing plots than in the mechanical harvest plots. These results are consistent with those reported by Simon et al. (2021), who evaluated the nutritive value of cover crops specifically oat (*Avena sativa* L.) and triticale (× *Triticosecale* Wittm.) over a 6-year period. They reported greater CP and lower NDF and ADF concentrations in grazed forage compared to cut forage, primarily due to differences in the timing of forage removal. However, it has been shown that defoliation can lead to a decline in CP and an increase in fiber fractions such as NDF, as plants shift their energy toward rebuilding structural tissues and maintaining regrowth under stress conditions (Donaghy et al., 2008)

4.2 | Effect of rotational grazing on crop forage accumulation and its chemical composition for silage

The lack of differences in maize forage accumulation between treatments in the current study is likely due to the fact that grazing did not impair soil bulk density or porosity (Figure 3), which will be addressed below. This result is consistent with previous studies, in which previously grazed areas did not significantly affect the forage accumulation of maize for silage production (Blanco-Canqui et al., 2020; dos Santos et al., 2018; Vizioli et al., 2018). When assessing annual ryegrass for silage production (mechanically harvested) or grazing in a crop–livestock system in southern Brazil, the forage accumulation of successive crops (maize for silage) did not differ between the defoliation strategies of previous forage (dos

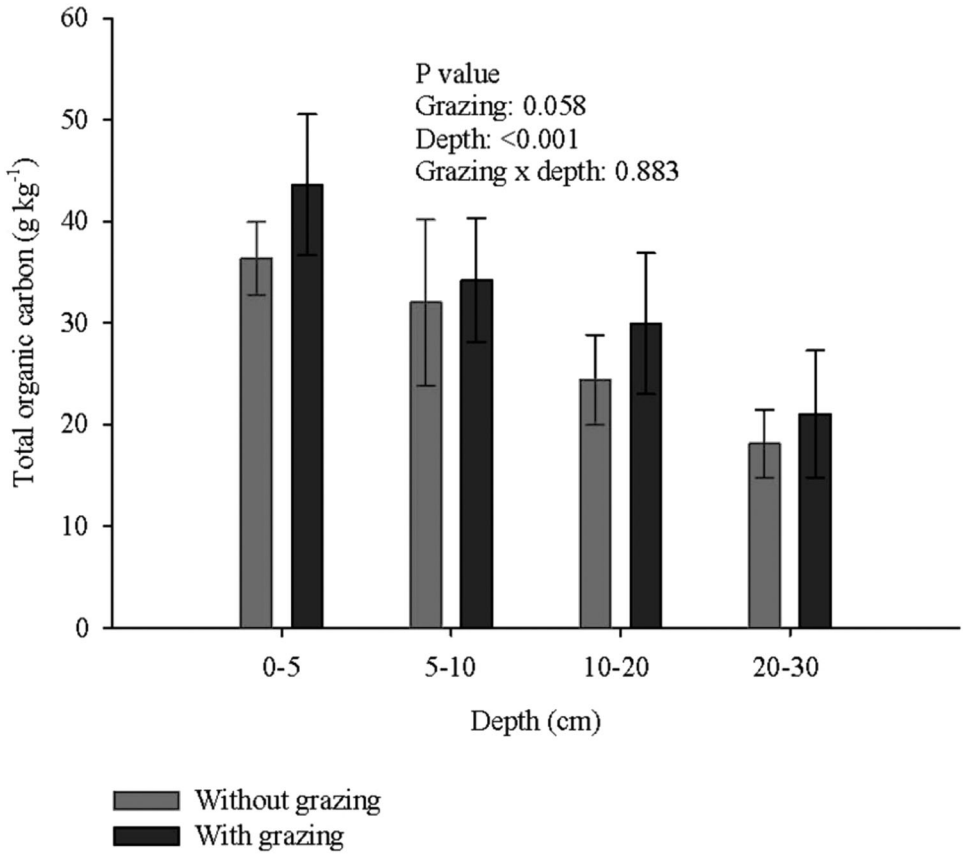


FIGURE 4 Total soil carbon concentration in areas of annual ryegrass (*Lolium multiflorum*) managed under two defoliation strategies (grazed or mechanically harvested) followed by the crop (*Zea mays*) for five consecutive years (2017–2021). Data collected in 2022.

Santos et al., 2018). Similarly, no difference in maize DM production was observed when ryegrass cover was managed by grazing or harvested mechanically after nine years of management (Vizioli et al., 2018).

The results of the chemical composition of whole maize plants harvested in areas previously grazed or mechanically harvested are also in agreement with those of other studies that concluded that in a medium-term experiment, grazing throughout the previous season did not impair the CP concentration of maize for silage production (dos Santos et al., 2018). The increase in CP concentration in maize cultivated in crop–livestock systems in the medium term can be attributed to animal grazing, which acts as a catalyzing agent and promotes renewal of the area and roots, deposition of excreta in the soil, and nutrient cycling, mainly from nitrogen (dos Santos et al., 2018).

4.3 | Effect of grazing on soil physical proprieties and soil organic carbon

The slight increase in soil bulk density under grazing was not sufficient to negatively affect crop forage accumulation when compared to the non-grazed treatment. Trampling during grazing events can increase soil bulk density (Moreira et al., 2014); however, direct effects of grazing such as increased soil bulk density (Lai & Kumar, 2020) and soil mechanical resistance (Evans et al., 2012) have been observed to depths of up to 15 cm. In contrast, grazing can also enhance soil biological activity and promote compensatory root growth, where plants adapt by increasing root length density (Rauber et al., 2021). In a 3-year study with a no-till system, grazing was observed to have small effects on increasing soil bulk density without any restriction on the root growth of successive cultures (Blanco-Canqui et al., 2020). This could be attributed to the compaction process caused by grazing events not reaching physical soil restrictions, which could negatively affect plant development (Peterson et al., 2020). Furthermore, the effects of trampling on the physical properties of soil are ephemeral or momentary when moderate grazing intensities are used (Ambus et al., 2018). In this study, grazing intensity was not greater than 50% of the pre-defoliation sward height. Additionally, the lack of an effect of ryegrass defoliation management on soil porosity, macroporosity, and microporosity corroborates the results of Vizioli et al. (2018). They evaluated the influence of pasture management on soil physical properties and concluded that pasture management under no-tillage in succession to maize crops

did not compromise the physical properties of the studied soil.

The slight increase in TOC concentration observed under the grazing treatment can be attributed to the deposition of animal excreta and enhanced nutrient cycling promoted by this defoliation strategy. Prior to treatment imposition, TOC in the 0- to 5-cm soil layer averaged 37.8 g kg^{-1} (data not shown). After 5 years, TOC decreased to 36.3 g kg^{-1} in non-grazed areas, whereas it increased to 42.6 g kg^{-1} in grazed areas. These results can be explained by the fact that the addition of animal excreta enhances soil biological activity, increases soil carbon concentration, and promotes nutrient cycling (Blanco-Canqui et al., 2015), primarily due to the stimulatory effect of dung and urine deposition on soil microbial communities. Greater microbial activity plays a key role in the decomposition of OM and the cycling of nutrients, contributing to the formation and stabilization of soil organic carbon (Wei et al., 2023). Thus, grazing allows for the recycling of nutrients from feces and urine deposition, which can increase soil TOC (Simon et al., 2021). Furthermore, the residual aboveground biomass for grazing is greater than that left after mechanical defoliation because of the greater post-defoliation height and greater amounts of plant damage associated with trampling (da Silva et al., 2022). Tilhou et al. (2021) also found greater TOC concentrations in the soil (0–5 cm) of grazed paddocks than in hay harvests. This effect may also be partially attributed to the role of residual aboveground biomass in supporting a diverse and active microbial community. Moreover, it is well established that greater residual biomass is positively correlated with increased root biomass, which contributes to soil organic carbon through root turnover and the release of root exudates (Zhao et al., 2022).

5 | CONCLUSIONS

After four consecutive years of moderate grazing (grazing severity <50% of pre-grazing sward height) throughout the cool season, grazing did not impair the physical quality of the soil, accumulated biomass, or the nutritive value of either the annual pasture or the subsequent maize crop grown for silage. These findings highlight the potential sustainability of this agricultural practice in subtropical regions. The maintenance of soil quality under moderate grazing can be partially attributed to the positive effects of animal excreta and residual plant biomass, which enhance soil microbial activity, nutrient cycling, and carbon inputs through root turnover and organic residue decomposition. Collectively, these mechanisms contribute to the stabilization of soil structure and the accumulation of soil organic carbon, reinforcing the long-term resilience and productivity of integrated crop–livestock systems.

AUTHOR CONTRIBUTIONS

Mariana N. de Souza: Data curation; formal analysis; investigation; methodology; writing—original draft. **Renata da Rosa Dornelles**: Investigation; methodology. **Álvaro L. Mafra**: Validation; writing—review and editing. **Henrique M. N. Ribeiro-Filho**: Conceptualization; funding acquisition; project administration; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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REFERENCES

Agriculture Department. (2014). *Keys to soil taxonomy* (12th ed.). Government Printing Office.

Ambus, J. V., Reichert, J. M., Gubiani, P. I., & de Faccio Carvalho, P. C. (2018). Changes in composition and functional soil properties in long-term no-till integrated crop-livestock system. *Geoderma*, *330*(December 2017), 232–243. https://doi.org/10.1016/j.geoderma.2018.06.005

Amézquita, M. C., Ibrahim, M., Llanderal, T., Buurman, P., & Amézquita, E. (2024). Carbon sequestration in pastures, silvo-pastoral systems and forests in four regions of the Latin American tropics. In F. Montagnini (Ed.), *Environmental services of agroforestry systems* (pp. 31–49). CRC Press. https://doi.org/10.1201/9781003578307-2

Ates, E. (2017). Slope aspect has effects on vegetation and forage traits of anthropogenic pasture under two grazing treatments. *Revista de la Facultad de Agronomía de la Universidad del Zulia*, *34*, 236–252.

Bernardon, A., Miqueloto, T., Winter, F. L., de Medeiros Neto, C., & Sbrissia, A. F. (2021). Herbage accumulation dynamics in mixed pastures composed of kikuyugrass and tall fescue as affected by grazing management. *Grass and Forage Science*, *76*(4), 508–521. https://doi.org/10.1111/GFS.12549

Blanco-Canqui, H., Drewnoski, M. E., MacDonald, J. C., Redfearn, D. D., Parsons, J., Lesoing, G. W., & Williams, T. (2020). Does cover crop grazing damage soils and reduce crop yields? *Agrosystems, Geosciences & Environment*, *3*(1), e20102. https://doi.org/10.1002/agg2.20102

Blanco-Canqui, H., Hergert, G. W., & Nielsen, R. A. (2015). Cattle manure application reduces soil compactibility and increases water retention after 71 years. *Soil Science Society of America Journal*, *79*(1), 212–223. https://doi.org/10.2136/sssaj2014.06.0252

Carvalho, P. C. D. F., Peterson, C. A., de A Nunes, P. A., Martins, A. P., de Souza Filho, W., Bertolazi, V. T., Kunrath, T. R., de Moraes, A., & Anghinoni, I. (2018). Animal production and soil characteristics from integrated crop-livestock systems: Toward sustainable intensification. *Journal of Animal Science*, *96*(8), 3513–3525. https://doi.org/10.1093/jas/sky085

Comissão de Química e Fertilidade do Solo—RS/SC. (2004). *Manual de adubação e calagem para os Estados do Rio Grande do Sul e Santa Catarina*. Comissão de Química e fertilidade do Solo—RS/SC.

da Silva, L. S., Sollenberger, L. E., Kimberly Mullenix, M., Kohmann, M. M., Dubeux, J. C. B., & Silveira, M. L. (2022). Soil carbon and nitrogen stocks in nitrogen-fertilized grass and legume-grass forage systems. *Nutrient Cycling in Agroecosystems*, *122*(1), 105–117. https://doi.org/10.1007/s10705-021-10188-9

Donaghy, D. J., Turner, L. R., & Adamczewski, K. A. (2008). Effect of defoliation management on water-soluble carbohydrate energy reserves, dry matter yields, and herbage quality of tall fescue. *Agronomy Journal*, *100*(1), 122–127. https://doi.org/10.2134/AGRONJ2007.0016

dos Santos, J. A., da Fonseca, A. F., Barth, G., & Zardo Filho, R. (2018). Silage maize quality in different uses of Italian ryegrass and soil management methods after liming. *Archives of Agronomy and Soil Science*, *64*(2), 173–184. https://doi.org/10.1080/03650340.2017.1338832

Embrapa. (2011). *Manual de Métodos de Análise de Solo* (2nd ed.). Embrapa Solos.

Evans, C. R. W., Krzic, M., Broersma, K., & Thompson, D. J. (2012). Long-term grazing effects on grassland soil properties in southern British Columbia. *Canadian Journal of Soil Science*, *92*(4), 685–693. https://doi.org/10.4141/CJSS2011-070

Grace, C., Boland, T. M., Sheridan, H., Brennan, E., Fritch, R., & Lynch, M. B. (2019). The effect of grazing versus cutting on dry matter production of multispecies and perennial ryegrass-only swards. *Grass and Forage Science*, *74*(3), 437–449. https://doi.org/10.1111/gfs.12440

Harrison, M. T., Evans, J. R., & Moore, A. D. (2012). Using a mathematical framework to examine physiological changes in winter wheat after livestock grazing. 2. Model validation and effects of grazing management. *Field Crops Research*, *136*, 127–137. https://doi.org/10.1016/J.FCR.2012.06.014

INMET. (n.d.). *Instituto Nacional de Meteorologia do Brasil—Normais Climatológicas (1991/2020)*. https://portal.inmet.gov.br/normais

Jing, J., Søegaard, K., Cong, W. F., & Eriksen, J. (2017). Species diversity effects on productivity, persistence and quality of multispecies swards in a four-year experiment. *PLoS ONE*, *12*(1), e0169208. https://doi.org/10.1371/journal.pone.0169208

Lai, L., & Kumar, S. (2020). A global meta-analysis of livestock grazing impacts on soil properties. *PLoS ONE*, *15*(8), e0236638. https://doi.org/10.1371/JOURNAL.PONE.0236638

Latimer, G. W. (Ed). (2019). *Official methods of analysis* (21st ed.). AOAC.

Mertens, R. D. (2002). Gravimetric determination of amylase-treated neutral detergent fiber in feeds with refluxing in beakers or crucibles: Collaborative study. *Journal of AOAC International*, *85*(6), 1217–1240. https://doi.org/10.1093/jaoac/85.6.1217

Moreira, W. H., Tormena, C. A., Junior, E. B., Petean, L. P., & Alves, S. J. (2014). Influência da altura de pastejo de azevém e aveia em atributos físicos de um Latossolo Vermelho Distroférrico, após sete anos sob integração lavoura-pecuária. *Revista Brasileira de Ciência Do Solo*, *38*, 1315–1326. https://doi.org/10.1590/S0100-06832014000400027

National Academies of Sciences. (2021). *Nutrient requirements of dairy cattle* (8th ed.). The National Academies Press.

Noizère, P., Sauvant, D., & Delaby, L. (Eds.). (2018). *INRA Feeding system for ruminants*. Wageningen Academic Publishers.

Peterson, C. A., Deiss, L., & Gaudin, A. C. M. (2020). Commercial integrated crop-livestock systems achieve comparable crop yields to specialized production systems: A meta-analysis. *PLoS ONE*, *15*(5), 1–25. https://doi.org/10.1371/journal.pone.0231840

Rauber, L. R., Sequinatto, L., Kaiser, D. R., Bertol, I., Baldissera, T. C., Garagorry, F. C., Sbrissia, A. F., Pereira, G. E., & Pinto, C. E. (2021). Soil physical properties in a natural highland grassland in southern Brazil subjected to a range of grazing heights. *Agriculture Ecosystems and Environment*, *319*(November 2020), 107515. https://doi.org/10.1016/j.agee.2021.107515

Selbie, D. R., Buckthought, L. E., & Shepherd, M. A. (2015). The challenge of the urine patch for managing nitrogen in grazed pasture systems. *Advances in Agronomy*, *129*, 229–292. https://doi.org/10.1016/BS.AGRON.2014.09.004

Simon, L. M., Obour, A. K., Holman, J. D., Johnson, S. K., & Roozeboom, K. L. (2021). Forage productivity and soil properties in dual-purpose cover crop systems. *Agronomy Journal*, *113*(6), 5569–5583. https://doi.org/10.1002/agj2.20877

Snow, V. O., Rotz, C. A., Moore, A. D., Martin-Clouaire, R., Johnson, I. R., Hutchings, N. J., & Eckard, R. J. (2014). The challenges—and some solutions—to process-based modelling of grazed agricultural systems. *Environmental Modelling and Software*, *62*, 420–436. https://doi.org/10.1016/J.ENVSOFT.2014.03.009

Soussana, J. F., Tallec, T., & Blanfort, V. (2010). Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal*, *4*(3), 334–350. https://doi.org/10.1017/S1751731109990784

Tilhou, N. W., Nave, R. L. G., Jagadamma, S., Eash, N., & Mulliniks, J. T. (2021). Forage species and summer management impacts on soil carbon and nitrogen in winter stockpiled grazing systems. *Agrosystems, Geosciences & Environment*, *4*(1), 1–12. https://doi.org/10.1002/agg2.20132

Vendramini, J. M. B., Dubeux, J. C. B., & Silveira, M. L. (2014). Nutrient cycling in tropical pasture ecosystems. *Revista Brasileirade Ciencias Agrarias*, *9*(2), 308–315. https://doi.org/10.5039/agraria.v9i2a3730

Vigan, A., Lasseur, J., Benoit, M., Mouillot, F., Eugène, M., Mansard, L., Vigne, M., Lecomte, P., & Dutilly, C. (2017). Evaluating livestock mobility as a strategy for climate change mitigation: Combining models to address the specificities of pastoral systems. *Agriculture Ecosystems and Environment*, *242*, 89–101. https://doi.org/10.1016/J.AGEE.2017.03.020

Vizioli, B., Cavalieri-Polizeli, K. M. V., & Barth, G. (2018). Influência de manejos de azevém sobre as propriedades físicas de um Latossolo

Bruno. *Pesquisa Agropecuaria Brasileira*, *53*(8), 952–960. https://doi.org/10.1590/S0100-204X2018000800010

Wei, Y., Wei, B., Ryo, M., Bi, Y., Sun, X., Zhang, Y., & Liu, N. (2023). Grazing facilitates litter-derived soil organic carbon formation in grasslands by fostering microbial involvement through microenvironment modification. *Catena*, *232*, 107389. https://doi.org/10.1016/J.CATENA.2023.107389

Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, *64*(1), 58–65. https://doi.org/10.1111/EJSS.12002

Wilson, C., Undi, M., Tenuta, M., Tremorin, D., Coppi, L., Flaten, D., Wittenberg, K. M., & Ominski, K. H. (2011). Utilization of liquid hog manure to fertilize grasslands in southeast Manitoba: Impact of application timing and forage harvest strategy on nutrient utilization and accumulation. *Nutrient Cycling in Agroecosystems*, *91*(2), 155–171. https://doi.org/10.1007/s10705-011-9453-1

Zhao, Y., Tian, Y., Gao, Q., Li, X., Zhang, Y., Ding, Y., Ouyang, S., Yurtaev, A., & Kuzyakov, Y. (2022). Moderate grazing increases newly assimilated carbon allocation belowground. *Rhizosphere*, *22*, 100547. https://doi.org/10.1016/J.RHISPH.2022.100547

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