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Effect of intercropping between tropical fodder plants with corn and nitrogen fertilization on soil physical properties

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ABSTRACT

The use of diversified crop systems within the same area has received attention as an alternative to monoculture and benefits soil and yield. This study evaluates the effect of nitrogen fertilization and tropical fodder plants on soil physical properties. The experiment was conducted between October 2017 and January 2020 under randomized blocks design, arranged in a sub-sub plot scheme, with additional control and four repetitions. The plots contained fodder species (*Urochloa brizantha* and *Megathyrsus maximus*) intercropped with corn and the additional control (single corn). The subplots comprised the types of fodder plants management (haymaking and grazing), and the sub-sub plots contained the presence or absence of nitrogen fertilization. The following characteristics were evaluated: soil density (Ds), total porosity (Pt), macro (Ma) and microporosity (Mi), and soil resistance to penetration (Rp). After the management, the use of nitrogen (N) in topdressing of fodder plants increased Ma in the 0-0.05 m layer in the first year. Ds was above the critical limit for plant development. However, it tended to reduce. Adopting an integrated crop-livestock system, independently of the fodder species and the type of management used, did not compromise soil physical quality. Thus, it is an excellent alternative to diversity production.

Keywords: Porosity, Soil physical quality, Resistance to penetration, Integrated systems.

Influência de forrageiras tropicais em consórcio com milho e adubação nitrogenada sobre as propriedades físicas do solo

RESUMO

O emprego de sistemas diversificados de produção dentro da mesma área vem ganhando espaço como alternativa de substituição ao monocultivo, assim como seus benefícios no solo e produtivos. O objetivo deste trabalho foi avaliar o efeito da adubação nitrogenada e manejos das forrageiras tropicais nas propriedades físicas do solo. O experimento foi realizado entre outubro de 2017 e janeiro de 2020, em blocos ao acaso em esquema sub-subdivididas com uma testemunha adicional e quatro repetições. As parcelas foram constituídas por espécies forrageiras consorciadas com o milho: *Urochloa brizantha* e *Megathyrsus maximus*, mais a testemunha adicional (milho solteiro). As subparcelas consistiram nos manejos das forrageiras: fenação e pastejo; e nas sub-subparcelas, a presença ou ausência de adubação nitrogenada. Determinou-se densidade do solo (Ds), porosidade total (Pt), macro (Ma) e microporosidade (Mi), e resistência do solo à penetração (Rp). A utilização de nitrogênio (N) em cobertura nas forrageiras, após os manejos, aumentou a quantidade de Ma na camada de 0-0,05 m para o primeiro ano. A Ds está acima do limite considerado crítico para o desenvolvimento das plantas, porém, com tendência à redução. A adoção do SIPA, independente da espécie forrageira utilizada e manejo adotado, não comprometeu a qualidade física do solo, sendo assim, uma ótima alternativa para a diversificação da produção na propriedade..

Palavras-chave: Porosidade, Qualidade física do solo, Resistência à penetração, Sistemas integrados.

1. Introduction

Developing a system that produces cereals, fulfilling the growing global demand, maintaining environmental quality, preserving natural resources, and providing profit for producers, is one of the main challenges of humanity nowadays (Foley et al., 2011). In Brazil, the adoption of diversified production systems has gained more followers as an alternative to monoculture (Carvalho et al., 2016). These diversified systems, such as the integrated crop-livestock system (ICLS), are growing in many regions of the country, optimizing areas where grain crops associated with pastures produce grains and fodder for animals (Bertolini et al., 2013) temporally and spatially (Asai et al., 2018).

This system provides many advantages, such as improving soil physical (Flávio Neto et al., 2015; Moraine et al., 2017), chemical (Silva et al., 2014a), and biological attributes. Besides it favors the cycling and nutrient use efficiency (Martin et al., 2016; Mattei et al., 2018; Ryschawy et al., 2017), these systems reduce costs, diversifying and maintaining financial stability in the farm (Ambus et al., 2018; Franchini et al., 2015).

Although it has an expressive acceptance, there are still many doubts about its adverse effects, especially those concerning soil physical quality due to management systems involving cattle treading and machine traffic (Moraes et al., 2014a). In integrated crop-livestock areas, a leading cause of degradation is compaction (Veiga et al., 2016). When compaction increases, there is higher density, reduced porosity, and consequently higher soil resistance to penetration, difficulting root growth, reducing infiltration and availability of water and nutrients for plants, which reduces yields (Shah et al., 2017).

The extension and nature of such adverse effects depend on the soil type, cattle trampling, machinery traffic rate, and mainly on soil humidity during management. According to Conte et al. (2011), the presence of animals in the crop may alter the soil resistance to penetration. Nevertheless, such effects are limited to the superficial layers and can be reverted in the following crop. Moreover, under adequate fertilizing conditions, the higher root growth and dry matter production, with more cover hay and carbon incorporation in the soil, helps to reduce the adverse effects. Among the fertilizers with a higher impact on plant development, nitrogen is highlighted due to its high responsivity and necessity to be used in high quantities (Santini et al., 2016).

However, maintaining or enhancing soil quality is a primary factor for a sustainable crop (Stefanoski et al., 2013) and its evaluation, which permits adequate decision-making to preserve the soil and obtain higher yields.

Based on the hypothesis that nitrogen fertilizing and fodder species management alter soil physical quality, this study evaluates the influence of nitrogen fertilizing and tropical fodder species management under an integrated crop-livestock system on soil physical properties.

2. Material and Methods

The experiment was carried out between October 4, 2017, and January 11, 2020, under field conditions at the Experimental Station “Professor Antônio Carlos dos Santos Pessoa” (latitude 24°31'58"S; longitude 54º01'10"W; approximate altitude of 400 m), which belongs to State University of Oeste do Paraná – UNIOESTE (Western Paraná State University), Campus of Marechal Cândido Rondon.

The soil was classified as LATOSSOLO VERMELHO Eutroférrico (LVef) of very clayish texture (Table 1) (Santos et al., 2018). The climate of the region, according to the Köppen classification, is Cfa-type, a humid subtropical climate with average temperatures ranging between 22°C and 23°C, and averaged annual precipitation between 1,600 and 1,800 millimeters (Alvares et al., 2014). The climatic data of the experimental period (Figure 1) were obtained from the Automatic Climatological Station of the UNIOESTE, located approximately 200 m from the experimental area.

The experimental area had been managed under the conventional tillage system with a corn monoculture for grains and silage. For soil characterization, the chemical analysis of the soil was carried out in August 2017. Nevertheless, liming was not required (Table 1). Before sowing, the soil was conventionally tillage with one plow operation and one harrowing operation.

A randomized block design arranged in sub-sub plots scheme with additional treatment (control - single corn) and four repetitions. In the plots (10 x 15 m), the two fodder species were allocated (*Urochloa brizantha* and *Megathyrsus maximus*) and intercropped with corn and additional treatment (control - fallow plot). Two types of management of fodder plants were assigned in the subplots (10 x 7.5 m): haymaking and grazing. The presence or absence of nitrogen fertilization was considered in the sub-sub plots (5 x 7.5 m). Each block had an area of 900 m^2 (45 x 20 m), resulting in a total experimental area of 3.600 m^2.

For the implementation of the experiment in the harvests of 2018/2019 and 2019/2020, the area was desiccated with a sequential herbicide application, in a ten-day interval, using 792 g L^{-1} (i.a) of Glyphosate-isopropylamine salt + 240 g L^{-1} (i.a) of Clethodim.

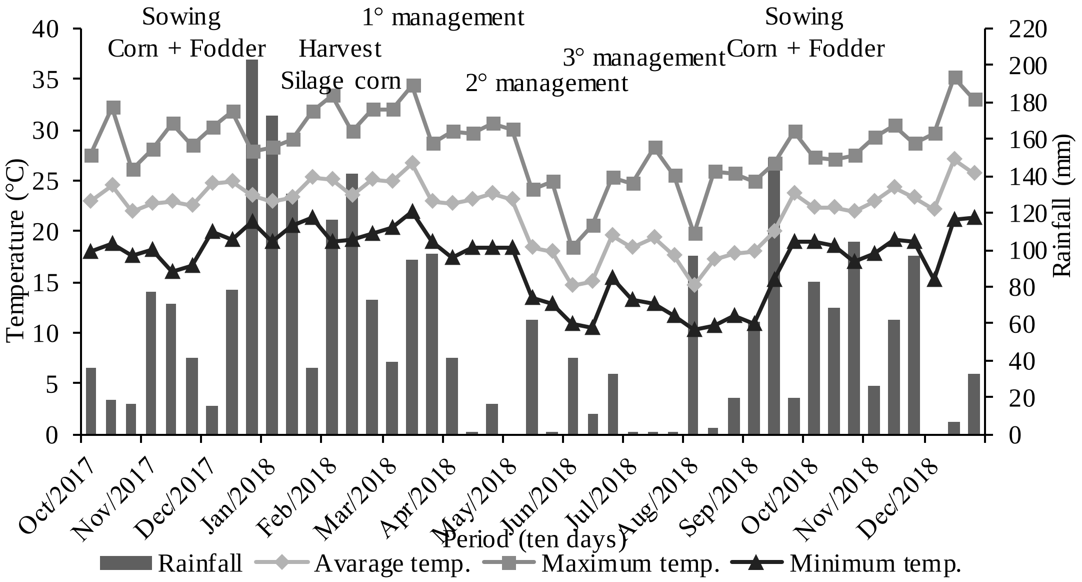

Figure 1. Maximum, average, and minimum air temperature (°C) and accumulated rainfall in ten days during the experimental period from October/2017 to December/2018. Source: UNIOESTE, Marechal Cândido Rondon, PR.

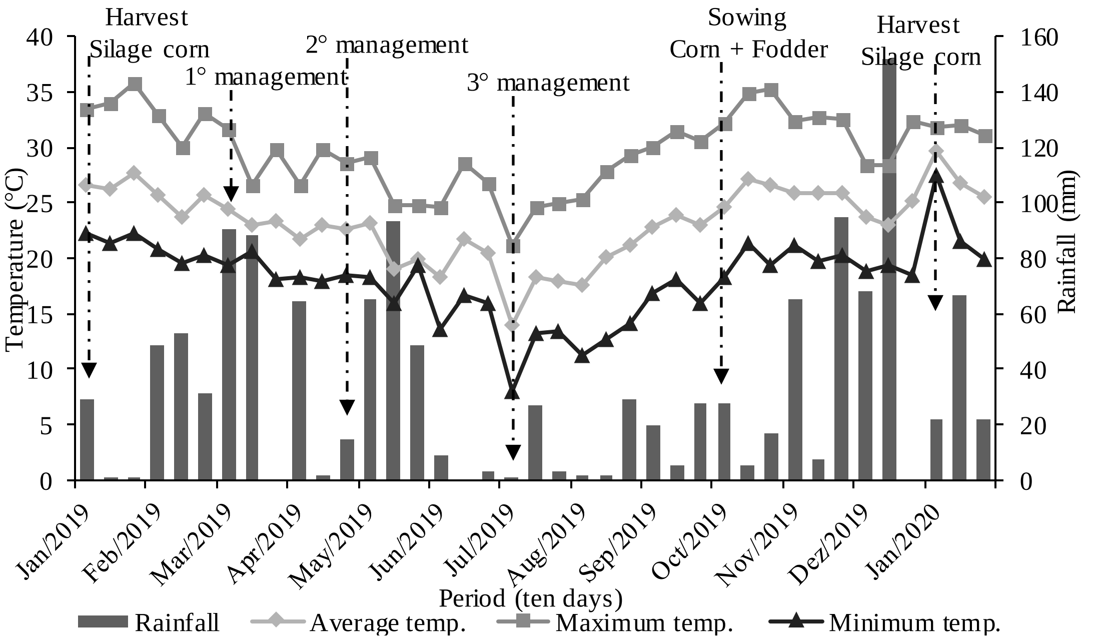

Figure 2. Maximum, average, and minimum air temperature (°C) and accumulated rainfall in ten days during the experimental period from January/2019 to January/2020. Source: UNIOESTE, Marechal Cândido Rondon, PR

Table 1. Chemical and particle-size characteristics of the soil in the 0-0.10 and 0.10-0.20 m layers before the experiment implementation (2017)

Layers	P	OM	pH	H+Al	Al^{3+}	K^+	Ca^{2+}	Mg^{2+}	SB	CEC
m	mg dm^{-3}	g dm^{-3}	$CaCl_2$	------------------------		$cmol_c$ dm^{-3}	------------------------			
0 – 0.1	32.89	19.14	6.29	3.36	0.00	0.26	5.71	3.29	9.26	12.62
0.1 – 0.2	21.14	19.14	6.04	3.97	0.00	0.24	5.39	3.05	8.68	12.65
Layers		BS		Clay		Silt			Sand	
m		%		--------------------------------		g kg^{-1}	---------------------------------			
0 – 0.1		73.39		655		290.18			54.82	
0.1 – 0.2		68.61		740		202.04			57.96	

P and K – Extractor Mehlich^{-1}; Al, Ca, and Mg – Extractor KCl 1 mol L^{-1}; H+Al – pH SMP (7.5).

The sowing of the single corn and intercropped with the fodder species *Urochloa brizantha* cv. Braúna and *Megathyrsus maximus* cv. Áries occurred on October 4, 2017 (hybrid COODETEC 384 PW), September 24, 2018 (hybrid COODETEC 384 PW), and October 4, 2019 (hybrid MORGAN 30A91 PW). The sowing was mechanized using 36 kg ha^{-1} of N, 53 kg ha^{-1} of P_2O_5, 53 kg ha^{-1} of K_2O, five seeds per meter, 5 cm depth of seed deposition layer, and 0.75 m distance between the rows, resulting in an estimated population of 66,666 plants ha^{-1}. The seeds used were treated with pesticide and fungicide, respectively: Imidacloprid (150 g L^{-1} i.a) + Thiodicarb (450 g L^{-1} i.a), and Carbendazim (150 g L^{-1} i.a) + Tiram (350 g L^{-1} i.a).

In the first harvest (2017/2018), the fodder plants were broadcast sown, and then a harrowing was used for their incorporation in the soil. In the second (2018/2019) and third (2019/2020) harvests, the fodder plants were mechanically sown between the rows right after the corn crop implementation. Independently from how the fodder plants were sown, 6 and 5 kg ha^{-1} of pure and viable seeds of *Urochloa brizantha* cv. Braúna and *Megathyrsus maximus* cv. Áries were used, respectively.

Regarding the phytosanitary traits of the corn crop, pesticide and fungicide application was conducted according to the necessity. Nevertheless, there was no herbicide application nor manual weed control. In the corn crop, the topdressing fertilization with nitrogen (N) was made using 200 kg ha^{-1} of N in urea in two applications, broadcast and without incorporation, when corn was at the phenological stages V4 and V6. Rains occurred soon after the applications. The harvest of the silage corn occurred at stage R5, i.e., when the grains were at the hard flour stage or with 2/3 of the milk line.

After the corn was cut for silage, the fodder plants received the first application of N in topdressing (100 kg ha^{-1} of N in the form of urea) for the treatments with nitrogen fertilization in the sub-subplot. After this phase, the area was kept untouched for between 30 and 40 days until the plants reached adequate height for grazing (±50 cm) (Jochims et al., 2018). The types of management adopted were grazing and haymaking, with criteria based on the canopy height of plants of around 50 cm (Jochims et al., 2018). Both types, grazing and haymaking, started simultaneously, and the interval between them corresponded to the period required for the growth of fodder plants.

Twenty Holstein-Friesians cows in the lactation phase with an average weight of 650 kg were employed for grazing. Grazing occurred for two hours each day in the morning until the stubble reached around 15 cm (Jochims et al., 2018) to avoid damages in the apical meristems of plants. The cuts for haymaking were mechanically conducted at the height of 15-20 cm (Jochims et al., 2018), utilizing a hay mower attached to a tractor. Afterward, the material was dehydrated and baled.

After the management, the area was kept untouched for enough period to allow the development of the fodder plants. Then, the two management systems were conducted similarly to the first crop. In 2018, the two types of management started at 50, 91, and 158 days after the harvest (DAH) of silage corn and 57, 117, and 189 DAC in 2019. For both years, three grazings and three cuts for haymaking were made. Right after the management and the collection of hay bales, the treatments with nitrogen fertilization received N as topdressing fertilization at the dosage of 100 kg ha^{-1} in the form of urea, resulting in 400 kg ha^{-1} of N applied on the fodder plants.

Finishing fodder plants management and anticipating the succession corn crop (326 days after seeding – DAS – in intercropping in 2018, and 319 DAS in intercropping in 2019), undeformed sample collection occurred to determine the soil physical properties. Three undeformed samples were collected in the useful area of each plot in the layers of 0-0.05, 0.05-0.10, and 0.10-0.20 m using iron rings of known volume. In the Soil Physics Laboratory of the Center of Agrarian Sciences/UNIOESTE, macroporosity (Ma), microporosity (Mi), total porosity (Pt), and soil density (Ds) were determined by the method of a volumetric ring in tension table (Teixeira et al., 2017).

In the same period, the soil resistance to penetration was determined using a digital soil compaction meter penetroLOG-Falker-PLG1020. The readings were taken in two distinct and random points in each sub-sub plot until the depth of 0.40 m. Moreover, soil samples were collected to determine gravimetric moisture. The data were submitted to the analysis of variance. When the F-test results presented significance, the Tukey test at 5% probability was applied to compare the means, or the Dunnett test at 5% probability when the interaction factorial vs. additional treatment (witness) was significant.

3. Results and Discussion

In 2018, nitrogen fertilization (presence or absence of N in topdressing on fodder plants after management) altered Ma in the soil layer of 0-0.05 m (Table 2). The other variables were not influenced by the treatments studied. For soil macroporosity, the layer of 0.0-0.05 m had higher values when the fodder plants had nitrogen fertilization after each type of management (0.05 m^3 m^3) than the treatments without N fertilization (0.03 m^3 m^3) in 2018 (Table 2).

Table 2. Mean values of macroporosity (Ma) in the soil ($m^3 m^{-3}$) managed with an integrated crop-livestock system with and without nitrogen fertilizing, 2018.

N Fertilization	Ma ($m^3 m^{-3}$)		
	0.0-0.05 m	0.05-0.10 m	0.10-0.20
With N	0.05 a	0.04 a	0.04 a
Without N	0.03 b	0.05 a	0.04 a

Means followed by the same lowercase letter in the column do not differ statistically by the Tukey test at 5 % probability.

In this study, nitrogen in topdressing fertilization on fodder plants tends to enhance the physical soil conditions by modifying the structure of plants, increasing fodder (Cassol et al., 2011; Quatrin et al., 2015) and root production, enhancing significantly aeration, water infiltration (Loss et al., 2014) and, consequently, the number of macropores.

Concerning the results obtained in 2019 for Ma, Mi, Pt, and Ds (Table 3), no significant differences were observed for the layers studied independently from the species, management, and nitrogen fertilizing used. For all soil layers in 2018 and 2019, there was no significant interaction ($p>0.05$) regarding factorial scheme vs. additional treatment (control), which indicates that, regardless of the species, both the management and the nitrogen fertilizing had no significant differences from the control.

In all types of management, the macropores values found are considered restrictive to growth and vegetal development since they remained below 0.10 m^3 m^{-3} (Andreolla et al., 2014). The macropores must be higher than 0.10 m^3 m^{-3} to guarantee gas exchanges and the root system growth (Andreolla et al., 2015a). The low values for Ma may be related to the high values for Ds (Table 3). While evaluating different vegetal covers and types of management, Silva et al. (2014b) observed that *Urochloa brizantha* grazing increased Ds and soil resistance to penetration, possibly due to cattle trampling in the area.

There was no significant difference between the treatments for microporosity, the values remaining between 0.40 m^3 m^{-3} and 0.48 m^3 m^{-3} (Table 3). According to Souza et al. (2019), soil management does not modify this property. On the other hand, Richart et al. (2005) state that pore size distribution ranged according to the soil use and management system. Thus, soils from native forests have a higher Ma than areas under a no-tillage system, where machine traffic increases Ds, favoring the occurrence of micropores.

In general, Pt values are not expressively altered by the type of management. While studying pastures under a no-tillage system, Moreira et al. (2012) and Balbinot Junior et al. (2011) observed that cattle trampling did not present evidence of negatively affecting physical attributes of soil. Moreover, subsequent roots of crops contribute to better physical quality of soils even with cattle trampling and machine traffic. Corroborating our results, Conte et al. (2011), while studying physical attributes evolution in a Latossolo Vermelho under an integrated crop-livestock system in the state of Rio Grande do Sul, verified that the Pt was not significantly altered after seven years under this type of management.

Pt is the sum of Ma and Mi (Sartori et al., 2016). Nevertheless, when mainly composed of macropores, the soil presents a low water retention capacity, making it susceptible to physical degradation (Arcoverde et al., 2015). Moreover, according to the same authors, soils with Pt below 0.35 m^3 m^{-3} are considered restrictive, difficulting their use for agricultural aims. To be considered an ideal soil, it must present physical characteristics such as volume and pore dimension adequate for water and air input, movement, and retention, attending to the necessities of crops (Silva et al., 2012). According to Kiehl (1979), the soil may be classified as ideal when presenting a Pt proportion of 50%, 1/3 macropores, and 2/3 micropores.

Regarding soil compaction, during the two years of the study, the soil density (Ds) values had no significant difference ($p>0.05$). Independently of the fodder species, management, and nitrogen fertilizing used, the values ranged between 1.32 g m^{-3} and 1.69 g m^{-3} (Table 3). Reinert et al. (2008) and Reichert et al. (2009) suggested critical Ds values in clayish soil, ranging from 1.30 to 1.40 g cm^{-3}. Therefore, considering this research and the soil texture class, the Ds values observed in our study are above the critical values for the three evaluated layers.

Although the statistical comparison between the years was not conducted, it can be observed that Ds values for the first year were numerically higher than the second (Table 3). This fact may be related to the deposition of organic residues on the soil surface, which decreases the impact of animal and machine traffic (Silva et al., 2016). Moreover, for the second year, none of the values found for the factorial treatments were above the values found for the control treatment, a behavior found in all soil layers (Table 3).

Such results for Ds may be explained by the capacity of fodder plants to form large masses of vegetal residues on the surface and inside the soil, which can soften the negative impact of cattle trampling and distribute the weight of machinery evenly (Morais et al., 2012; Silva et al., 2016). In the control treatment (fallow), this result can be attributed, besides the absence of fodder plants/vegetal material, to soil preparation with plowing and harrowing (Oliveira et al., 2013), conducted before the experiment implementation in 2017.

Table 3. Mean values of the control and the treatments provided by the factorial scheme on macroporosity (Ma), microporosity (Mi), total porosity (Pt), and soil density (Ds), conducted under an integrated crop-livestock system in 2018 and 2019.

Management	Ma (2018)			Ma (2019)		
	0-0.05	0.05-0.1	0.1-0.2	0-0.05	0.05-0.1	0.1-0.2
Control treatment	0.03	0.06	0.04	0.04	0.04	0.03
M. maximus/Haymaking/Without N	0.07 ns	0.04 ns	0.03 ns	0.03 ns	0.03 ns	0.03 ns
M. maximus/Haymaking/With N	0.04 ns	0.06 ns	0.03 ns	0.03 ns	0.04 ns	0.03 ns
M. maximus/Grazing/Without N	0.05 ns	0.03 ns	0.04 ns	0.03 ns	0.04 ns	0.03 ns
M. maximus/Grazing/With N	0.03 ns	0.03 ns	0.04 ns	0.04 ns	0.04 ns	0.03 ns
U. brizantha/Haymaking/Without N	0.04 ns	0.04 ns	0.03 ns	0.03 ns	0.03 ns	0.03 ns
U. brizantha/Haymaking/With N	0.03 ns	0.05 ns	0.04 ns	0.03 ns	0.03 ns	0.03 ns
U. brizantha/Grazing/Without N	0.04 ns	0.04 ns	0.04 ns	0.03 ns	0.03 ns	0.02 ns
U. brizantha/Grazing/With N	0.03 ns	0.05 ns	0.04 ns	0.03 ns	0.04 ns	0.03 ns
Average	0.04	0.04	0.04	0.03	0.04	0.03
	Mi (2018)			Mi (2019)		
Control treatment	0.44	0.45	0.43	0.45	0.44	0.44
⋮						
M. maximus/Haymaking/Without N	0.46 ns	0.48 ns	0.45 ns	0.45 ns	0.45 ns	0.44 ns
M. maximus/Haymaking/With N	0.47 ns	0.43 ns	0.46 ns	0.46 ns	0.43 ns	0.40 ns
M. maximus/Grazing/Without N	0.45 ns	0.44 ns	0.45 ns	0.45 ns	0.45 ns	0.45 ns
M. maximus/Grazing/With N	0.46 ns	0.43 ns	0.45 ns	0.46 ns	0.44 ns	0.43 ns
U. brizantha/Haymaking/Without N	0.46 ns	0.40 ns	0.42 ns	0.46 ns	0.45 ns	0.42 ns
U. brizantha/Haymaking/With N	0.45 ns	0.45 ns	0.44 ns	0.46 ns	0.43 ns	0.46 ns
U. brizantha/Grazing/Without N	0.47 ns	0.46 ns	0.41 ns	0.46 ns	0.42 ns	0.44 ns
U. brizantha/Grazing/With N	0.46 ns	0.45 ns	0.46 ns	0.44 ns	0.46 ns	0.42 ns
Average	0.46	0.44	0.44	0.45	0.44	0.43
	Pt (2018)			Pt (2019)		
Control treatment	0.47	0.50	0.47	0.48	0.47	0.47
⋮						
M. maximus/Haymaking/Without N	0.53 ns	0.51 ns	0.48 ns	0.48 ns	0.48 ns	0.47 ns
M. maximus/Haymaking/With N	0.50 ns	0.49 ns	0.49 ns	0.49 ns	0.47 ns	0.43 ns
M. maximus/Grazing/Without N	0.50 ns	0.48 ns	0.49 ns	0.48 ns	0.48 ns	0.48 ns
M. maximus/Grazing/With N	0.49 ns	0.46 ns	0.49 ns	0.50 ns	0.49 ns	0.46 ns
U. brizantha/Haymaking/Without N	0.51 ns	0.44 ns	0.46 ns	0.48 ns	0.48 ns	0.45 ns
U. brizantha/Haymaking/With N	0.48 ns	0.50 ns	0.48 ns	0.48 ns	0.46 ns	0.48 ns
U. brizantha/Grazing/Without N	0.51 ns	0.50 ns	0.45 ns	0.49 ns	0.45 ns	0.47 ns
U. brizantha/Grazing/With N	0.49 ns	0.49 ns	0.49 ns	0.47 ns	0.49 ns	0.45 ns
Average	0.50	0.49	0.48	0.48	0.47	0.46
	Ds (2018)			Ds (2019)		
Control treatment	1.66	1.63	1.65	1.51	1.53	1.53
⋮						
M. maximus/Haymaking/Without N	1.59 ns	1.60 ns	1.56 ns	1.45 ns	1.47 ns	1.43 ns
M. maximus/Haymaking/With N	1.64 ns	1.57 ns	1.69 ns	1.40 ns	1.35 ns	1.47 ns
M. maximus/Grazing/Without N	1.65 ns	1.61 ns	1.61 ns	1.36 ns	1.33 ns	1.35 ns
M. maximus/Grazing/With N	1.66 ns	1.62 ns	1.59 ns	1.32 ns	1.34 ns	1.33 ns
U. brizantha/Haymaking/Without N	1.65 ns	1.56 ns	1.60 ns	1.46 ns	1.45 ns	1.41 ns
U. brizantha/Haymaking/With N	1.63 ns	1.62 ns	1.58 ns	1.46 ns	1.44 ns	1.45 ns
U. brizantha/Grazing/Without N	1.63 ns	1.65 ns	1.55 ns	1.45 ns	1.37 ns	1.33 ns
U. brizantha/Grazing/With N	1.65 ns	1.65 ns	1.63 ns	1.41 ns	1.39 ns	1.34 ns
Average	1.64	1.61	1.61	1.43	1.41	1.40

$^{+}$ significant and higher than the control treatment by the Dunnett test at 5% probability; - significant and lower than the control treatment by the Dunnett test at 5% probability; ns: not significant by the Dunnett's test at 5% probability.

While evaluating Ds in crop and livestock systems, Seron et al. (2013) state that, even without significant difference (p>0.05) between the treatments, there is evidence of higher values in the crop system and justify this behavior by more increased machinery traffic than in grazing. Similar results were found by Loss et al. (2014) and Rosset et al. (2014). While evaluating the physical and chemical attributes of soil under different management systems, these studies verified lower Ds values for integrated systems than monocultures in some soil layers, confirming the benefits of integrated systems.

In contrast, the results presented do not agree with the theory mentioned by Kunz et al. (2013), which states that the pressure of animal trampling is higher than machinery as its weight is distributed in a broader area, reducing inherent risks to compaction and, consequently, Ds. Physical properties of soil are interdependent; modifying one property promotes alterations in all others. Therefore, Ds is the most studied and monitored physical property, primarily due to the high relation between Pt and Ds, i.e., the increase in Ds reduces the porous space of soil (Tezolin et al., 2021).

Soil resistance to penetration, after fodder plants management and before the implementation of the corn crop in 2018, presented significance (p>0.05) for the factorial vs. additional treatment (fallow) for the soil layers of 0-0.05 m, 0.05-0.10 m, 0.10-0.15 m, 0.15-0.20 m, 0.20-0.25 m, and 0.25-0.30 m (Table 4). In 2019, a significant difference was observed (p>0.05) for factorial vs. additional for the layer of 0-0.05 m. For the other layers, the management systems employed did not promote alterations in the resistance to penetration (Table 4).

The interaction between factorial scheme vs. additional treatment influenced the soil resistance to penetration in the first 0.30 m (Table 4). Generally, the values from the factorial scheme were statistically lower than the additional treatment. From the 0.05-0.10 m layer until 0.25-0.30 m layer, there was a difference only in the first year of the experiment (Table 4). The results ranged, and this difference probably occurred due to the spatial variability of the soil resistance to penetration in the areas where the cuts for haymaking and grazing were made.

According to Maluf & Campos (2012), the leading cause of soil degradation is compaction, which results from increases in Ds and Rp. Such a scenario is often observed in areas with heavy machinery traffic or cattle trampling (Souza et al., 2012), especially in humid periods (Oliveira et al., 2017) and clayish soils (Kunz et al., 2013).

Table 4. Mean values of the witness and the treatments from the factorial for the soil resistance to penetration (Rp), conducted in an integrated crop-livestock system in 2018

Management	Rp (MPa)							
	0-0.05 m		0.05-0.10 m		0.10-0.15 m		0.15-0.20 m	
	2018	2019	2018	2019	2018	2019	2018	2019
Control treatment	1.02	0.93	2.08	1.78	2.01	1.77	1.89	1.80
M. maximus/Haymaking/Without N	0.36^{-}	0.93^{ns}	1.54^{ns}	1.88^{ns}	1.50^{ns}	1.90^{ns}	1.43^{-}	1.88^{ns}
M. maximus/Haymaking/With N	0.61^{ns}	0.85^{ns}	1.56^{ns}	2.12^{ns}	1.41^{-}	2.57^{ns}	1.37^{-}	2.39^{ns}
M. maximus/Grazing/Without N	0.27^{-}	0.18^{-}	1.16^{-}	1.62^{ns}	1.34^{-}	1.55^{ns}	1.33^{-}	1.34^{ns}
M. maximus/Grazing/With N	0.23^{-}	0.22^{-}	1.22^{-}	1.82^{ns}	1.44^{-}	2.01^{ns}	1.40^{-}	1.83^{ns}
U. brizantha/Haymaking/Without N	0.33^{-}	0.95^{ns}	1.11^{-}	1.63^{ns}	1.29^{-}	1.65^{ns}	1.34^{-}	1.65^{ns}
U. brizantha/Haymaking/With N	0.56^{ns}	0.78^{ns}	1.51^{ns}	1.61^{ns}	1.40^{-}	1.66^{ns}	1.36^{-}	1.61^{ns}
U. brizantha/Grazing/Without N	0.40^{-}	0.38^{ns}	1.31^{-}	1.64^{ns}	1.51^{ns}	1.90^{ns}	1.56^{ns}	1.64^{ns}
U. brizantha/Grazing/With N	0.45^{-}	0.21^{-}	1.45^{ns}	1.41^{ns}	1.50^{ns}	1.89^{ns}	1.42^{-}	1.72^{ns}
Average	0.47	0.60	1.44	1.72	1.49	1.88	1.46	1.76

Management	Rp (MPa)							
	0.20-0.25 m		0.25-0.30 m		0.30-0.35 m		0.35-0.40 m	
	2018	2019	2018	2019	2018	2019	2018	2019
Control treatment	1.87	1.63	1.74	1.41	1.47	1.33	1.62	1.31
⋮								
M. maximus/Haymaking/Without N	1.43^{ns}	1.84^{ns}	1.35^{ns}	1.58^{ns}	1.44^{ns}	1.42^{ns}	1.57^{ns}	1.42^{ns}
M. maximus/Haymaking/With N	1.39^{ns}	2.28^{ns}	1.37^{ns}	1.88^{ns}	1.26^{ns}	1.52^{ns}	1.23^{ns}	1.33^{ns}
M. maximus/Grazing/Without N	1.53^{ns}	1.31^{ns}	1.53^{ns}	1.43^{ns}	1.74^{ns}	1.44^{ns}	1.63^{ns}	1.26^{ns}
M. maximus/Grazing/With N	1.34^{-}	1.78^{ns}	1.34^{ns}	1.84^{ns}	1.47^{ns}	1.96^{ns}	1.44^{ns}	1.55^{ns}
U. brizantha/Haymaking/Without N	1.33^{-}	1.58^{ns}	1.36^{ns}	1.40^{ns}	1.40^{ns}	1.20^{ns}	1.47^{ns}	1.15^{ns}
U. brizantha/Haymaking/With N	1.29^{-}	1.55^{ns}	1.24^{-}	1.55^{ns}	1.30^{ns}	1.48^{ns}	1.41^{ns}	1.51^{ns}
U. brizantha/Grazing/Without N	1.68^{ns}	1.60^{ns}	1.62^{ns}	1.48^{ns}	1.53^{ns}	1.35^{ns}	1.45^{ns}	1.33^{ns}
U. brizantha/Grazing/With N	1.50^{ns}	1.72^{ns}	1.52^{ns}	1.43^{ns}	1.44^{ns}	1.17^{ns}	1.45^{ns}	1.15^{ns}
Average	1.48	1.70	1.45	1.56	1.47	1.43	1.47	1.33

$^{+}$ significant and higher than the control treatment by the Dunnett test at 5% probability; - significant and lower than the control treatment by the Dunnett test at 5% probability; ns: not significant by the Dunnett test at 5% probability.

Although some values are adopted for the critical RP level, many factors may influence these results, especially humidity when managing fodder plants and sowing, besides Ds (Mattei et al., 2020). Similarly, Lima et al. (2013) emphasize that the increase of Ds results in higher Rp, which may restrict the development and yield of crops.

At the moment of evaluation, the soil gravimetric moisture values were 20% and 22% until 40 cm deep for 2018 and 2019, and Rp values ranged from 0.23 MPa to 2.01 MPa in the first year and from 0.21 MPa to 2.57 MPa in the second. According to Petean et al. (2010) and Andreolla et al. (2015b), values above 2.5 MPa limit the soil resistance to penetration. On the other hand, Moraes et al. (2014b) report that values above 3.5 MPa are a limitation for clayish soils with no-till farming in the state of Paraná.

Among the factors that interfere in these results, we highlight the condition of adequate soil moisture when the animals entered the grazing area and the machinery for haymaking cuts. Physical soil degradation in integrated systems presents a strict negative relation with the stocking rate and the soil moisture (Ribeiro; Souza, 2018).

4. Conclusions

Nitrogen fertilization in top dressing after fodder plants management increased the number of macropores in the layer of 0-0.05 m. Ds values are above the critical limit for plant development. However, it tended to reduce.

The adoption of the integrated system, independently of the fodder species and the type of management adopted (haymaking or grazing), did not compromise the physical quality of the soil. Thus, it is an excellent alternative to diversify the production of the farm.

Authors' Contribution

Eloisa Mattei, Paulo Sérgio Rabello de Oliveira, Carlos Augusto Rocha de Moraes Rego, Jeferson Tiago Piano e Lucas da Silveira, contributed to the implementation of the experimente, data collection, writing, interpretation and revision of the manuscript.

Carlos Alexandre Costa Crusciol, contributed to the writing, interpretation and revision os the manuscript

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