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Soil physical attributes in an integrated crop-livestock system with pasture managed under different sward canopy heights and different timings of nitrogen application

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Abstract

This study aimed to evaluate the physical attributes of soil in an integrated crop-livestock system with winter pastures managed under different N fertilization timings and canopy heights after winter and the soybean crop. The experimental design used was randomized blocks with the treatments in a 2 × 2 factorial arrangement (two canopy heights and two N application timings), with three area replications. The canopy heights were 11 and 24 cm kept by continuous stocking grazing method since May to November (175 days). Fertilization timings as N-pasture fertilization and N-corn fertilization (phase before the winter pasture). Treatments characterized as N fertilization inversion were applied with fertilization timings as N-pasture fertilization and N-corn fertilization (phase before the winter pasture). Soil density, total porosity, and moisture content were evaluated after winter pasture (black oat + annual ryegrass) and after the subsequent summer soybean crop. The sampling spots were georeferenced and analyzed using geostatistics, considering the position in the slope of landscape. Soil physical attributes were not influenced by canopy height nor N fertilization timing (P>0.05). Soil density was reduced by 13.3% (from 1.11 to 0.98 g cm^{-3}), whereas total porosity (from 0.58 to 0.62%) and moisture content (from 32.73 to 35.73%) increased by 6.9% and 9.2% after the soybean crop in relation to the values obtained in the winter pasture. The higher elevation areas had higher moisture content, total porosity, and lower density than the lower elevation areas, regardless of the time of evaluation. Well-drained soils were more resistant to compaction by animal trampling than moderately drained soils. In well-managed integrated crop-livestock systems in humid subtropical climate regions, the surface compaction of clayey soils in winter pastures is light, non-limiting, and disappears after the subsequent summer crop.

Keywords: Fertilizer inversion; Moisture; Soil Density; Soybean; Total porosity.

Introduction

Soil may present considerable spatial variability in physical attributes caused by management (e.g., agricultural machinery traffic, grazing intensity, and tillering system), or natural causes (e.g., texture and landscape slope position) (Guzman and Kaisi, 2011). It is important to identify the causes of likely physical trait depletion (e.g., increase in density and decrease in porosity) to avoid such variation. Moreover, physical traits interact with the chemical properties of soil (Brubaker et al., 1993).

The use of integrated crop-livestock systems (ICLS) combined with strategies such as no-tillage systems, crop rotation, and pasture-based animal production represents a promising strategy to increase food production and environmental sustainability (Franzluebbers et al., 2014). However, most farmers do not adopt ICLS because they believe that animal tramping may cause soil compaction and deplete the subsequent cash-crop yield. In fact, there is no physical soil damage if the correct grazing intensity is used in an ICLS (Andreolla et al., 2014; Carvalho et al., 2016; Rauber et al., 2021), and the effect of animal trampling is concentrated at specific sites and is reversible (Bonetti et al., 2015). Soil compaction by animal grazing use can be reversed with high root biomass production and avoided with an increase in soil organic carbon (Bonaudo et al., 2014).

Depending on grazing management and landscape slope position, water flow may present different patterns of distribution, and consequently, the soil physical and chemical attributes may present a great variability. Thus, geostatistical methods represent an important tool to study this variability because they allow the identification of different patterns and trends, as well as the degree of spatial dependence (Molin et al., 2015).

Therefore, we hypothesized that (1) different canopy heights of winter pasture can alter soil physical attributes in an ICLS; (2) N fertilization in winter pasture tends to increase forage production and reduce damage to soil physical attributes in an ICLS; (3) the winter grazing period does not limit the physical attributes of the soil for the successor grain crop; (4) total porosity and soil density in an ICLS present different patterns, even under the same grazing management, because the main driver is the landscape slope position. Thus, the objective of this study was to evaluate the soil physical attributes in an ICLS with pasture managed under different N fertilization timings and canopy heights after winter and the soybean crop.

Results and discussion

Canopy heights, N fertilization timings, and sampling season

There was no interaction (P > 0.05) between the evaluated variation factors (canopy height, N fertilization timing, and evaluation season) for density, total porosity, and soil moisture content. Likewise, soil physical attributes were not influenced (P > 0.05) by canopy height and N fertilization timing after winter grazing or after the summer soybean crop (Table 1). Soil density decreased by 13.3% (P < 0.05), whereas total porosity and moisture content increased by 6.9% and 9.2%, respectively, after the soybean crop in relation to values obtained for the winter pasture.

Soil compaction by cattle trampling results from static tension (up to 200 kPa) caused by the transfer of the weight of the animal to the soil from the reduced specific area of hooves (Di et al., 2001), which can be increased by the movement of animals in search of food (Tuohy et al., 2013). The density of soil can be increased in the surface layer (0–5 cm) (Flores et al., 2007), tending to decrease total macroporosity and water infiltration in the soil (Roesch et al., 2019). Furthermore, an increase in soil density leads to the disruption of soil aggregates (Shah et al., 2017), causing the expulsion of water out of the aggregates owing to the loss of pore space (Baumgartl and Horn, 1991).

The soil density values (1.10–1.13 g cm^{-3}) (Fig. 1 B) obtained after winter grazing were not limiting for the soybean crop as this limitation typically occurs with high soil densities (≥1.4 g cm^{-3}) (Silva and Cabeda, 2006; Bonini et al., 2008). The soil density results demonstrate that in a well-managed ICLS, even if there is a slight increase in soil bulk density during the winter grazing period, this increase is reversed during the summer cropping phase, indicating that the pressure exerted by the hooves of the animals on the ground is less than the soil's carrying capacity for plastic deformation (Conte et al., 2011).

The prevention and reversal of soil compaction are achieved through sustainable practices, including no-tillage, adequate residue management, high production of plant biomass (including roots), short fallow period between crops, crop rotation, type of equipment, and speed of planting operations (Derpsch, 2001; Sawant et al., 2016; Abdalla et al., 2018). The ICLS increases the production of root biomass and soil organic carbon because of the presence of animals and their benefits on nutrient cycling and soil microbiological activity (Carvalho et al., 2010; Moraes et al., 2014). Over time, the combined effect of these factors allows the development of improved soil properties (emerging properties) for the efficient use of nutrients and maintenance of soil quality (Moraes et al., 2014).

Some researchers report that the height of the pasture, determined by the animal stocking, and the N fertilization of the pasture can have a relevant effect on the soil bulk density after a period of grazing (Carvalho et al., 2014; Abdalla et al., 2018). However, the intensity of soil compaction is related to stress attenuation by pasture biomass, which is directly proportional to the amount of biomass on the soil surface (Braida et al., 2006). According to Moraes et al. (2014), total forage production is more important than forage residue for the maintenance and improvement in soil quality. In this study, the total forage production did not differ between treatments, which together with the average forage mass was considered high (13.9 and 2.6; 8.7 and 2.5; 13.9 and 1.8; 8.4 and 1.4 t DM ha^{-1}, for the treatments: high sward height pasture with N applied in the pasture - HPNP, high sward height pasture with N applied in the crop - HPNC, low sward height pasture with N applied in the pasture - LPNP, and low sward height pasture with N applied in the crop - LPNC, respectively), which indicates high root production. In addition, the developing of 'emerging properties' of soil in the ICLS (Moraes et al., 2014) may support the explanation for the lack of variation in soil physical attributes among the evaluated variation factors.

Spatial variability in soil physical attributes

The highest values of bulk soil density occurred at low elevation points in the landscape (Fig. 1A and 2B). The two bands that presented the highest values of soil density after grazing (between 1.11 and 1.15 cm^{-3} and between 1.15 and 1.2 g cm^{-3}) (Fig. 1B) occurred in association with the two bands of low elevation, 853 and 856 m, respectively (Fig. 1A). The relationship between soil physical attributes and their position in the landscape may be related to water dynamics (Zebarth et al., 2002). As the water content in the soil increases, the adhesion force between the particles approaches zero, which favors pore collapse and compaction (Silva and Cabeda, 2006). Considering that in natural conditions, the water tends to accumulate in areas of low elevation in the landscape, and in combination with the fact that the last few months of the experimental period were very rainy and coincided with the grazing period, it is likely that animal trampling caused an increase in the local soil density values (Costa et al., 2009) (Fig. 1C).

Low soil density was associated with sites of high elevation in the landscape after pasture or summer cropping (Fig. 1B and 1C), i.e., sites with lower elevation had higher values of soil density, whereas the converse was observed at higher elevation sites in the landscape. The low content of stagnant water in the sites with elevated landscape reduces the lubricating effect of water on the soil particles, imparting greater resistance of the structure to the pressures of an external agent (Vepraskas, 1984).

At locations with high elevation and areas of less dense soils, the moisture content was high (Fig. 2A and 2B). This is owing to the improved preservation of the structure, and consequently, of the soil micropores at these points. It is important to highlight that at high elevations, the soil tends to be deep, which keeps the water table more distant from the surface, reducing the risk of waterlogging, and consequently, preserving the soil structure.

During the grazing period, when the rainfall was frequent, humidity in the soil remained at high levels for a large part of the cycle, especially at the low elevation sites, because of the natural water flow and the water table being close to the surface (Fig. 2A). This causes animal trampling to increase soil density while reducing its load-carrying capacity (Collares et al., 2011).

In general, low elevation areas of the landscape presented low values of total porosity after winter grazing (Fig. 2C) or after the summer soybean crop (Fig. 2D). The macropores correspond to the pore class most influenced by soil compaction, and the collapse of this set of pores directly reflects the hydraulic conductivity and redistribution of water in the system (Carvalho et al., 2016). Thus, in areas of high soil densities, the number of macropores will be low,

Table 1. Density, total porosity and soil moisture content after winter pasture (initial) and after soybean crop phase (final) according treatments.

Canopy heights (CH)	N fertilization timings (NFT)		Mean	P - value		
	NC	NP		CH	NFT	CH*NFT
Initial soil density (g cm^{-3})						
HP	1.11±0.09	1.11±0.04	1.11±0.06			
LP	1.13±0.06	1.10±0.02	1.12±0.05	0.914	0.678	0.777
Mean	1.12±0.07	1.11±0.03	1.11±0.02^{a}			
Final soil density (g cm^{-3})						
HP	0.96±0.05	0.98±0.04	0.97±0.04			
LP	0.98±0.04	0.97±0.04	0.980.04	0.941	0.998	0.678
Mean	0.97±0.04	0.98±0.04	0.98±0.04^{b}			
Initial total porosity (m^3 m^{-3})						
HP	0.58±0.02	0.58±0.01	0.58±0.02			
LP	0.57±0.01	0.58±0.02	0.58±0.02	0.863	0.932	0.932
Mean	0.58±0.02	0.58±0.02	0.58±0.02^{b}			
Final total porosity (m^3 m^{-3})						
HP	0.64±0.02	0.62±0.02	0.63±0.02			
LP	0.62±0.01	0.63±0.02	0.62±0.01	0.911	0.975	0.711
Mean	0.63±0.01	0.62±0.01	0.62±0.02^{a}			
Initial humidity (%)						
HP	32.21±3.64	33.63±4.23	32.92±3.62			
LP	33.27±5.17	31.82±2.58	32.54±3.74	0.845	0.997	0.584
Mean	32.74±4.04	32.73±3.29	32.73±4.29^{b}			
Final humidity (%)						
HP	35.81±1.47	35.59±0.74	35.70±1.04			
LP	35.71±0.23	35.84±1.38	35.78±0.89	0.912	0.945	0.794
Mean	35.76±0.94	35.72±1.00	35.73±1.10^{a}			

HP = high pasture; LP = low pasture; NP = N in pasture; NC = N in crop. Means followed by different lowercase letters differ (P<0.05) by the Tukey's test [comparison for the time of evaluation (after pasture or after tillage) for the same variable (density, total porosity or soil moisture)].

Table 2. Meteorological data of experimental period.

	Precipitation (mm)	MT (°C)	AT (°C)	MT (°C)
Mar/2014	285.0	24.9	18.6	14.2
Apr/2014	146.5	22.4	16.9	13.2
May/2014	264.1	19.3	13.3	9.4
June/2014	590.3	17.9	12.8	9.6
July/2014	124.2	18.2	12.0	8.0
Aug/2014	150.1	21.6	11.0	7.4
Sept/2014	373.0	21.8	15.7	11.8
Oct/2014	119.2	26.2	18.9	13.0
Nov/2014	191.3	25.4	18.9	14.6
Dec/2014	220.9	25.3	20.4	15.0
Jan/2015	273.2	27.0	21.1	17.2
Feb/2015	172.7	26.5	20.4	15.4
Mar/2015	70.9	26.2	19.4	14.9
Abr/2015	15.6	23.4	16.4	12.5

MF = Maximum temperature; AT = Average temperature; MT = Minimum temperature.

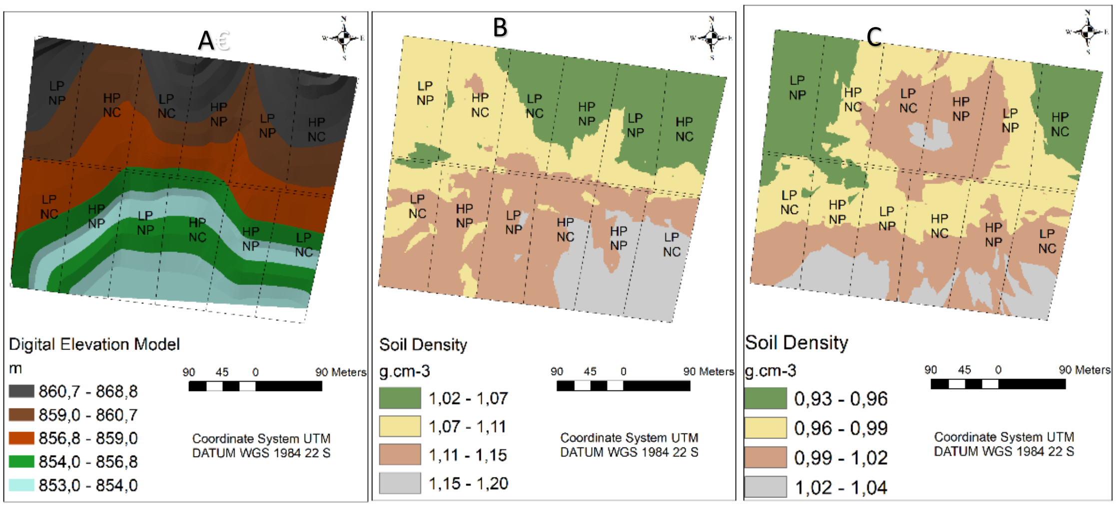

Fig 1. Relief of the study area, initial and final spatial variability of soil density according treatments (A = Relief of the study area; B = Initial spatial variability of soil density; C = Final spatial variability of soil density; HPNP = High pasture with N in pasture; HPNC = High pasture with N in crop; LPNP = Low pasture with N in pasture; LPNC = Low pasture with N in crop).

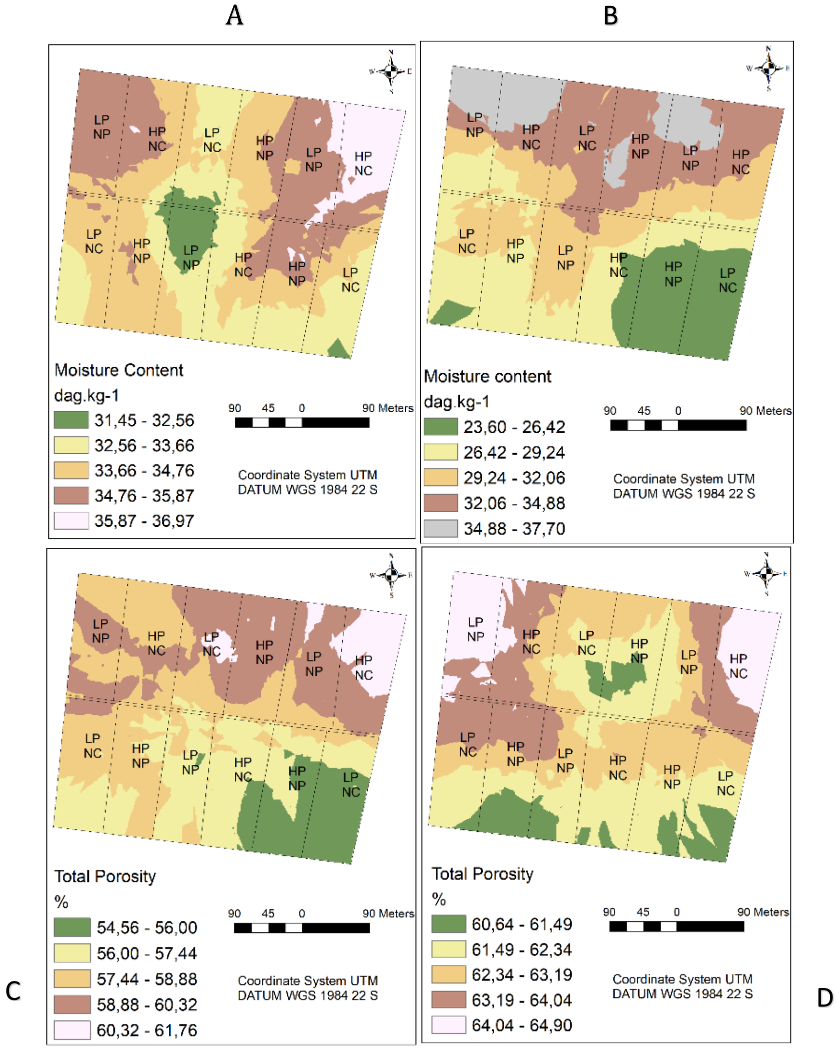

Fig 2. Soil physical attributes and moisture content in the study area. (A) Spatial variability of moisture content after pasture; (B) Spatial variability of moisture content after soybean crop. (C) Spatial variability of total porosity after pasture, (D) Spatial variability of total porosity after soybean crop. Location of the experiments: HPNP - High pasture with N applied in the pasture; HPNC - High pasture with N applied in the crop; LPNP - Low pasture with N applied in the pasture; LPNC - Low pasture with N applied in the crop.

Table 3. Soil chemical analysis after pasture grazing (initial) and after soybean crop (final).

Items	pH	OM	P	K	Ca	Mg	CEC	V
	$CaCl_2$	g dm^{-3}	----mg dm^{-3}-----		------ $cmol_c$ dm^{-3}-------			%
Initial	4.94	36.30	4.57	87.87	3.85	1.97	10.41	55.95
Final	4.89	39.84	4.95	89.70	4.42	2.75	12.62	58.56
Mean	4.92	38.07	4.76	88.79	4.14	2.36	11.52	57.26

OM = organic matter by humid digestion; P and K extracted with $Mehlich^{-1}$ solution; pH in $CaCl_2$ 1:2,5; Ca and Mg exchangeable with KCl 1 mol L^{-1}; CEG = Cations Exchange Capacity.

reducing the efficiency of water infiltration and presenting low moisture content in the sample collected subsequently.

Materials and methods

Site description

This study was conducted in Abelardo Luz (26°31'S, 51°35'W; altitude 850 m), Santa Catarina, Brazil, from May 2014 to April 2015. The soil in the area is classified as a Rhodic Hapludox (Soil Survey Staff, 2014) with a very clayey texture. The climate of the region is classified as a Cfb type (humid subtropical), according to the Köppen classification system (Alvares et al., 2014), with well-distributed precipitation throughout the year and mild summers. The meteorological data observed throughout the experimental period are presented in Table 2. The chemical properties of soil in the 0–0.2 m layer after pasture grazing and soybean cropping are shown in Table 3.

Experimental phases

The experiment began with *Sorghum bicolor* grazing in the summer of 2012/2013, followed by black oat (*Avena strigosa*) grazing in the winter of 2013. Subsequently, corn (*Zea mays*) was planted for grain production in the summer of 2013/2014, and black oat + annual ryegrass (*Lolium multiflorum*) for grazing in the winter of 2014. Soybeans (*Glycine max*) were cultivated for grain production in the summer of 2014/15. This study focusses on the assessments performed after the winter pasture (May 2014) and after the summer soybean cropping (April 2015). However, we chose to describe the methodological aspects of maize cropping that started in October 2013, when the N fertilization treatment was applied. Since the beginning of this experimental protocol (September 2012), the same treatments have been applied (timing of N fertilization and maintenance of canopy height), although the observed values of canopy heights (low or high) may have varied according to forage species and agricultural year. This treatment (canopy height) simulated high or low grazing intensities by different animal stocking rates in the pasture phase.

Experimental design and treatments

The experimental design was a randomized complete block with three replicates (paddocks). Treatments were arranged in a 2 × 2 factorial arrangement (two winter pasture canopy heights and two N fertilization timings). The target canopy heights were 10 cm (low sward height pasture, LP) and 25 cm (high sward height pasture, HP). The canopy height was monitored weekly, using a graduated ruler (centimeters), and the actual average canopy heights were 11 and 24 cm for low and high canopy heights, respectively.

The N fertilization timing represents a fertilization inversion; that is, the areas that were fertilized with N in the winter did not receive fertilization in the summer and vice-versa.

Therefore, in this study, the N fertilization timing (dose of 200 kg N ha^{-1}) consisted of two treatments: N-pasture fertilization (NP) or N-corn fertilization (NC). Thus, in summer, the NC plots received 200 kg N ha^{-1}, whereas the plots designated as NP did not. However, in winter, the plots designated as NP received 200 kg N ha^{-1} and the NC plots did not. Total amount of nutrients applied along the year was the same for all treatments.

Nitrogen fertilization of NC plots was applied on November 13, 2013, at the V6 stage and on May 8, 2014 in the NP plots, 35 days after sowing the pasture (start of tillering). The N fertilization for both application timings was as a single dose application in the form of urea (45% of N), under favorable weather and soil moisture conditions for maximum utilization of the fertilizer.

Study period

The agricultural year started when the corn hybrid (Maximus) was sown on October 10, 2013, in a no-till system with 0.8 m row spacing. For chemical fertilization 352 kg of 2-20-18 (NPK) was used at sowing. After the corn grain harvest, the field was desiccated with the application of 1.33 L ha^{-1} of glyphosate on March 29, 2014. A mixture of black oat (BRS 139) and annual ryegrass (Barjumbo) was sown on April 3, 2014, using a no-tillage system, with a spacing of 0.17 m between rows. The sowing densities of black oat and annual ryegrass seeds were 100 and 25 kg ha^{-1}, respectively. At that time, the field was fertilized with 7 kg of N ha^{-1}, 70.4 kg of P_2O_5 ha^{-1}, and 63.4 kg of K_2O ha^{-1} as an N-P-K formulation.

Continuous stocking and variable stocking rates (Mott and Lucas, 1952) were used to maintain the intended canopy heights. Thirty-six Charolais × Nellore steers with an average body weight (BW) of 280 kg were used. The grazing period started on May 19, 2014, when the average canopy height was 30 cm, and lasted 175 days, until November 10, 2014. The average stocking rates in the LPNC and HPNC treatments were 801 and 584 kg BW ha^{-1}, whereas in treatments LPNP and HPNP were 937 and 933 kg BW ha^{-1}, respectively.

At the end of the grazing period, the biomass residue on the soil (straw) for the LPNC and HPNC treatments were 1244 and 2110 kg of dry matter ha^{-1}, whereas in treatments LPNP and HPNP were 1461 and 4398 kg of dry matter ha^{-1}, respectively. Pasture desiccation was performed 18 days after the removal of the animals from the paddocks, with the herbicide Gramocil® (paraquat + diuron) at a dosage of 2.5 L ha^{-1}. Immediately after desiccation of the pasture, the soybean seeds (NS5909) were inoculated (MasterFix ®, 3 mL kg^{-1} of seed) and seeded with seed-fertilizer equipped with a single cutting disc and stem-type trencher, at a density of 13 seeds per meter and spacing of 0.45 m between rows. In addition, basic fertilization was performed as recommended by the Soil Chemistry and Fertility Commission (CQFS, 2004), using 214 kg ha^{-1} of monoammonium phosphate in sowing lines and 150 kg ha^{-1} of potassium (KCl) applied spreading on cover. Application of insecticides to control caterpillars and bedbugs, as well as fungicides for Asian rust, leaf blight, brown spot, and powdery mildew were performed in all paddocks. The soybean was harvested on April 07, 2015, using a CASE 2799 axial harvester.

Traits measured

In each paddock, eight undisturbed soil samples were collected at depths between 2.5 and 7.5 cm. The soil was sampled three days after the removal of the animals from the area (November 13, 2014) and four days after the soybean harvest (April 11, 2015). During this sampling, the geographic coordinates of the collection sites were registered using a GPS system (model RTK) with a precision of 3–5 mm. The Datum WGS84/UTM zone 22S coordinate system was used. These geographic coordinates were used to generate the contour lines and obtain a digital elevation model using triangulated irregular network interpolation (Kumler, 1994) (Fig. 1A).

Soil density was determined using the volumetric ring method (Embrapa, 1997). After collection, the samples were dried in an oven with forced air circulation at 105–110 °C until reaching a constant mass and weighed. Soil density (g cm^{-3}) was determined by dividing the dry soil mass by the ring volume. The moisture content was determined using the standard gravimetric method, based on the dry soil mass determined in an oven at 105–110 °C (Embrapa, 1997).

The soil total porosity was measured around the points used to analyze the soil density. This variable is used to determine the total amount of pores occupied by water or air present in soil samples (Embrapa, 1997), using the following equation:

$$Pt = \frac{100\ (a - b)}{a}$$

Pt = total porosity
a = real density (2.65 g cm^{-3})
b = apparent density.

Statistical analysis

The data were analyzed using SAS PROC MIXED (*Statistical Analysis System*, version 9.2), considering fixed effects (canopy heights, N fertilization timing, sampling season, and their interactions) and random effects (blocks). Means were compared using Tukey's test ($\alpha = 0.05$). The spatial variability in the soil characteristics was analyzed using geostatistical analysis. Thus, the semivariograms generated from the geographic coordinates were interpolated using the kriging method, using the QGIS 3.1 version software.

Conclusion

Soil drainage has a greater influence on soil physical attributes in relation to nitrogen fertilization timing and grazing intensity of black oat + annual ryegrass pastures in well-managed ICLS. Well-drained soils were resistant to trampling, whereas moderately drained soils were more susceptible. In well-managed ICLS in humid subtropical climate regions, the surface compaction of clayey soils in winter pastures is minimal, non-limiting, and disappears after the subsequent summer cultivation.

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