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Soil compaction effect on black oat yield in Santa Catarina, Brazil

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ABSTRACT: Cultivated soils, when submitted to agricultural practices, tend to compact due to the pressure exerted by agricultural machines and implements, a process that compromises soil quality and system sustainability. Specific properties of each soil, such as particle size and organic matter content, interfere with the process and degree of compaction and, consequently, plant growth. This study aimed to analyze the effect of different degrees of compaction (DC) on soil physical properties and black oat (*Avena strigosa* Schreb) growth. For this purpose, four soils were collected: *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}), *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}), *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}), and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}). They were submitted to five degrees of compaction (bulk densities corresponding to 80, 85, 90, 95, and 100 % DC), defined by their relation to the maximum density obtained by the Normal Proctor Test. For each DC, porosity, soil water retention curve, penetration resistance, hydraulic conductivity, and aeration capacity were determined. In a greenhouse, the oats were cultivated in the four soils with five different degrees of compaction. The experiment was carried out in a completely randomized design, factorial scheme, and five replications. Crop measurements included the growth rate, shoot dry matter, and forage quality analysis. Soil compaction changed the physical properties of soils. In all tested soils, macroporosity and total porosity decreased, more intensely at LV_{CN}. It had macroporosity below the critical level (0.10 m^3 m^{-3}) from DC 85. Hydraulic conductivity also decreased in all soils, which is evidence of significant environmental degradation from DC 90 onwards. Microporosity increased in the four soils due to compaction effect, and it is one of the reasons why permanent wilting point has increased. It resulted in a problem at NB_{SJ}, mainly because it reduced the available water volume at DC 90, 95, and 100. Penetration resistance has also increased from DC 80 to 100 at all soils, exceeding the limit of 2 MPa in DC 80 for NB_{SJ}, DC 85 for NB_{PA} and LV_{CN}, and DC 95 for CH_{LG}, representing a risk to root development. Regarding black oat crop, there was a reduction in shoot dry matter only in Cambisol and in the higher DC, fiber content keeps within a satisfactory amount, without affecting forage quality in all soils and DC, thus showing that black oat is tolerant to compaction.

Keywords: degree of compaction, soil quality, water availability, forage, Proctor Test.

INTRODUCTION

In the mountain plateau and west region of Santa Catarina (SC), many farmers work with cattle production on pastures, sometimes with native grassland improvement, or using the area integrated with crop plants. Black oat (*Avena strigosa* Schreb) is one of the most used grasses in SC because of the good adaptation to climatic conditions and nutritional quality. The intense technification of many farmers allowed increasing the number of animals per area, which could harm soil quality through compaction that results in higher bulk density and lower macroporosity (Feng et al., 2020). These changes may limit crop growth (Foloni et al., 2006; Obour et al., 2018), affect plant morphological and physiological attributes (Mariotti et al., 2020), and accelerate the environmental degradation. However, with the aid of research, yield and quality properties can be increased without impacting the soil system and resulting in economic returns. For this reason, it is important to check if the development of black oats is affected in compacted areas.

In the western region, the relief varies from rolling to gently rolling, clayey and deep soils are predominant, with medium to high water retention and availability (Reichert et al., 2009) and cation exchange capacity (CEC) (Ciotta et al., 2003). However, these soils are susceptible to compaction (Argenton et al., 2005). On the other hand, Cambisol is a representative soil of SC, and it occurs in most of the fields of Lages, a place for cattle grazing.

In agricultural areas, especially under no-tillage (NT), compaction has been reported, like Reinert et al. (2008), who observed higher bulk density in the 0.08 to 0.15 m layer in this management system. To analyze this effect, some authors have recently determined the degrees of compaction (DC) (Collares et al., 2008; Toyin and Joseph, 2012), defined as the quotient of current bulk density to the maximum bulk density by Proctor test (Lipiec et al., 1991; Silva et al., 1997). It is a parameter associated with macroporosity, air permeability, and penetration resistance.

Few studies directly relate different DC to plant growth in Brazil (Suzuki et al., 2007; Betioli Júnior et al., 2012), generally indicating better crop development near DC 85 % (Suzuki et al., 2007; Sá et al., 2016). However, some authors reported restrictions with some DC (Santos et al., 2005; Silva et al., 2014), according to soil type, culture, and evaluated attribute. Most of the studies related individual properties to plant growth, especially penetration resistance (Lima et al., 2010; Girardello et al., 2014, 2017), but this is just one of the many factors affecting plants. An advantage of DC is that many soil properties can be unveiled with the knowledge of the maximum and current bulk density. Therefore, it is necessary to broaden the studies that relate DC to plant growth, including different crops and soil types.

Soil physical quality properties such as bulk density, porosity, water retention capacity, and penetration resistance, indirectly affect crop development and yield (Hargreaves et al., 2019). In the no-tillage system, restrictions related to compaction may be greater (Peixoto et al., 2019), since soil mobilization is restricted to the sowing line.

Thus, the objective of this study was to evaluate the effect of different degrees of compaction on the physical properties of four soil classes and on the growth and forage quality of black oat.

MATERIALS AND METHODS

Soils sampling

The soils were collected in the layer 0.00-0.20 m, in four cities of Santa Catarina, in 2017, including *Latossolo Vermelho distrófico retrático* (Ferasol LV$_{CN}$), *Cambissolo Húmico alumínico típico* (Cambisol CH$_{LG}$), *Nitossolo Bruno distrófico típico* (Nitisol NB$_{PA}$), and

Nitossolo Bruno distrófico húmico (Nitisol NB_{SJ}), respectively in the cities of Campos Novos (27° 21' 26.9" S and 51° 17' 15.9" W), Lages (27° 47' 1.7" S and 50° 18' 21.8" W), Painel (27° 53' 15.0" S and 50° 9' 40.2" W) and São Joaquim (28° 15' 12.4" S and 49° 57' 4.0" W). Afterwards, the soil was air dried, manually crushed, and sieved at 2.00 mm. Then the following physical and chemical properties were analyzed: organic matter content, pH(H_2O), pH(SMP), P, K, Ca, Mg, Al, [H+Al], CEC (Tedesco et al., 1995); and clay, silt, and sand content (Gee and Bauder, 1986) (Table 1).

The soil sample (2 kg) was placed in a plastic bag and moistened until it reached friability. From this moisture, water was added at an interval of 0.02 kg kg^{-1} to the other seven samples. Maximum bulk density (BD_m) and optimum gravimetric moisture (GM_o) were determined by the Proctor test, following the Brazilian Association of Technical Standards, NBR 7.1822/86 (ABNT, 1986). Two replicas were used to the test without material reuse, totaling 80 samples. To the obtained data, a second-order polynomial equation was fitted to obtain the BD_m and GM_o.

Laboratory experiment

The experiment was carried out in the soil physics and management laboratory of the Santa Catarina State University (UDESC), analyzing the physical properties of soil quality. The BD_m obtained in the Proctor test was used to find the corresponding bulk density (BD) of the DC, using equation 1. To do so, five DC were established: 80, 85, 90, 95, and 100 %. These DC were chosen to mimic increasing densities, from non-compacted soils to very compacted soils, to find out if there is a DC in which the black oat development is affected.

$$DC = 100 \times (BD/BD_m)$$
Eq. 1

Volumetric stainless-steel cylinders with 0.05 m of height, 0.06 m of diameter, and a volume of 141 cm^3 were used. At the bottom of the cylinder, a permeable cloth was put and secured by an elastic rubber to prevent soil losses. The samples were assembled with soil mass that corresponded to the pre-established BD, placed in the cylinder, and gradually compressed until the required soil mass corresponded exactly to the cylinder volume.

To determine the soil water retention curve (WRC) and porosity, samples (three repetitions) were saturated for 48 h and weighed. Then, they were taken to a sand tension table, subjecting to tensions of 1, 6, and 10 kPa (Gubiani et al., 2009) and Richards chambers under 33, 100, 300, 500, and 1500 kPa (Libardi, 2005). With the data of tension and volumetric moisture, the WRC was fitted (van Genuchten, 1980) using a soil water retention curve software (Dourado Neto et al., 2000). With the WRC,

Table 1. Soil physical and chemical properties before acidity and fertility correction

Soil	Clay	Silt	Sand	OM	pH H_2O	pH SMP	P	K	Ca^{2+}	Mg^{2+}	Al^{3+}	H+Al	CEC_{ef}	CEC_{pH7}
	———————— g kg^{-1} ————————						— mg dm^{-3} —		——————— $cmol_c$ dm^{-3} ———————					
LV_{CN}[1]	620	90	290	34	4.9	4.9	0.1	38	0.6	0.9	2.3	15.4	3.9	17.0
CH_{LG}	510	170	320	40	5.1	4.5	2.9	170	2.6	1.9	4.1	24.4	9.0	29.3
NB_{PA}	720	80	200	53	4.6	4.6	0.9	55	1.1	0.9	2.9	21.8	5.1	23.9
NB_{SJ}	570	210	220	50	4.6	4.3	1.3	49	1.0	0.7	4.2	30.7	6.0	32.6

[1] *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}); *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}); *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}); and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}). Soil texture was determined by the pipette method; Organic carbon (OC) was determined by Walkley and Black method, modified by Tedesco et al. (1995); OM (organic matter) = 1.72 × OC; P and K: extracted by Mehlich-1; Ca^{2+}, Mg^{2+}, and Al^{3+}: extracted by KCl 1 mol L^{-1}; CEC_{ef}: effective cation exchange capacity is the sum of the concentrations of Ca^{2+}, Mg^{2+}, and Al^{3+}; H+Al: extracted with calcium acetate at pH 7.0; CEC_{pH7} is the sum of the concentrations of Ca^{2+}, Mg^{2+}, and H+Al .

total porosity (TP: the ratio between the volume of water retained in the saturated soil and soil volume), microporosity (Micro: the ratio between the volume of water retained in the soil at the water tension of 6 kPa and soil volume), macroporosity (Macro: the difference between TP and Micro), field capacity (FC: soil moisture at 10 kPa), permanent wilting point (PWP: soil moisture at 1500 kPa), available water (AW: soil moisture retained between tensions of 10 and 1500 kPa), and aeration capacity (AC: water-free pores, after the soil drains at tension of 10 kPa) of the soil was calculated (Danielson and Sutherland, 1986).

Soil samples with different DC were equilibrated at 10 kPa tension to determine penetration resistance (PR; three repetitions), and others were saturated to determine hydraulic conductivity (Ks; three repetitions). The PR was carried out in a bench penetrometer (Model - MA 933 – Marconi) equipped with a stem with 3 mm of diameter, at a constant velocity of 30 mm min^{-1}. To remove the edge effect, data of the first and last centimeter of the sample were rejected, averaging the three intermediate centimeters. Hydraulic conductivity analysis was performed in a falling head permeameter associated with the software "Ksat 2008", according to Gubiani et al. (2010).

Greenhouse experiment

An experiment was carried out with black oat cultivation inside pots, conducted in a greenhouse of the Agroveterinary Science Center of UDESC, *campus* of Lages. The productive and nutritive characteristics of the plant were analyzed after growing in soils with different DC. The pH of the soils was corrected to 6.0 with dolomitic limestone (CaO: 29 %, MgO: 19 %, and relative power of total neutralization: 100 %) and placed in bags for about 40 days. After that, they received NPK fertilizer as recommended by the "liming and fertilizing manual for the RS and SC states" (CQFS – RS/SC, 2016) for pasture culture.

The pots consisted of three vertically stacked cylinders with 0.10 m of diameter (PVC), the upper and lower cylinders were 0.10 m high, and the central one was 0.07 m high. The upper and lower cylinders received soil mass corresponding to DC 80, while the central one received the treatments, corresponding to DC 80, DC 85, DC 90, DC 95, and DC 100. In the upper cylinder, the soil was placed up to 0.08 m, leaving space for irrigation. There were five repetitions totaling 100 experimental units. The BD was planned to simulate the no-tillage system, which is soil compaction in the 0.08-0.13 m layer.

During the entire experiment, the soil moisture in the pots was controlled by irrigation every three days. Moisture control was performed weighing pot by pot every three days, and, when necessary, add water up to the moisture of 85 % of field capacity. The FC was previously determined for each bulk density. Thus, each treatment had a specific bulk density and field capacity.

The oat was sown on May 17th, 2018, with a density of 80 kg ha^{-1} at a depth of 0.5 cm. When it reached 0.10 m of height, thinning was performed, keeping four plants per pot. When it reached 0.20–0.25 m, the crop management was started, measuring the height with a graduate ruler, and the plants were cut until 0.10 m over the soil surface to determine the shoot dry matter (SDM 65 °C). In all, eight cuts were made. Average dry mass production and daily growth rate (GR) were calculated. Shoot dry matter of the eight cuts was ground in a knife, milled, and packed, to determine neutral detergent fiber (NDF) and acid detergent fiber (ADF) (van Soest, 1994).

The data were submitted to the Kolmogorov-Smirnov test to analyze the Normal distribution and homogeneity of variance. Means of the soil physical properties were compared by the Tukey test ($p<0.05$). Crop characteristics were regressed according to DC.

RESULTS

Soil physical properties

Increasing the degree of compaction changed soil physical properties. Lower hydraulic conductivity, total porosity, macroporosity (Table 2), and available water (Table 3) were observed, as well as higher penetration resistance, microporosity (Table 2), field capacity, and permanent wilting point (Table 3).

In the highest DC, an increase of the microporosity was observed in all soils, and the largest differences were seen in NB_{PA}, which has the largest macroporosity (Table 2). Also, lower macroporosity was observed in all soils, due to an increase in DC. In LV_{CN}, CH_{LG}, NB_{PA}, and NB_{SJ}, the values ranged from 0.13 to 0.02, 0.16 to 0.04, 0.21 to 0.06, and 0.15 to 0.06 $m^3\,m^{-3}$, respectively. It reached the critical limit of 0.10 $m^3\,m^{-3}$ (Vomocil and Flocker, 1961) at DC 85, 90, 100, and 90 %, respectively.

Table 2. Soil physical properties at different degrees of compaction (DC)

DC[1]	BD	PR	Ks	AC	TP	Micro	Macro
%	g cm⁻³	MPa	mm h⁻¹	———————— $m^3\,m^{-3}$ ————————			
				LV_{CN}[2]			
80	1.00	1.7 d[3]	175 a	0.17	0.60 a	0.47 b	0.13 a
85	1.07	3.2 c	87 b	0.12	0.57 ab	0.49 a	0.08 b
90	1.13	3.9 bc	45 c	0.09	0.55 b	0.50 a	0.05 c
95	1.19	4.6 b	20 c	0.06	0.54 b	0.50 a	0.04 c
100	1.26	9.7 a	10 c	0.04	0.53 c	0.51 a	0.02 d
				CH_{LG}			
80	1.13	1.0 c	124 a	0.19	0.58 a	0.41 c	0.16 a
85	1.21	1.6 c	13 ab	0.14	0.56 a	0.45 b	0.11 b
90	1.28	1.7 bc	2.0 b	0.13	0.56 a	0.47 ab	0.09 bc
95	1.35	2.5 b	0.4 b	0.08	0.54 ab	0.49 a	0.06 cd
100	1.42	4.9 a	0.1 b	0.06	0.52 b	0.48 a	0.04 d
				NB_{PA}			
80	1.05	1.6 d	177 a	0.23	0.65 a	0.44 d	0.21 a
85	1.13	2.8 d	79 ab	0.20	0.64 a	0.46 c	0.18 ab
90	1.19	3.8 c	25 b	0.18	0.64 a	0.49 b	0.15 b
95	1.26	7.0 b	1.4 b	0.13	0.62 a	0.51 a	0.11 c
100	1.32	9.8 a	0.1 b	0.08	0.57 b	0.51 a	0.06 d
				NB_{SJ}			
80	0.97	2.2 d	483 a	0.18	0.59 a	0.44 b	0.15 a
85	1.03	3.1 cd	395 a	0.13	0.59 a	0.48 ab	0.11 b
90	1.09	3.3 c	146 b	0.13	0.60 a	0.51 a	0.09 c
95	1.16	5.5 b	15 b	0.10	0.58 ab	0.50 a	0.08 c
100	1.24	6.8 a	13 b	0.07	0.55 b	0.49 a	0.06 d

[1] DC: degree of compaction determined with the equation DC = 100 × (BD/BD_m); BD: bulk density determined by volumetric cylinder method; PR: penetration resistance obtained with bench penetrometer; Ks: saturated hydraulic conductivity determined with falling head permeameter; AC: aeration capacity obtained with the equation AC = TP-FC; TP: total porosity determined by saturation method; Micro: microporosity; Macro: macroporosity (Micro and Macro determined by the tension table method). [2] *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}); *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}); *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}); and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}). [3] Mean values followed by the same letter, in the column for each soil, do not differ by Tukey test (p<0.05).
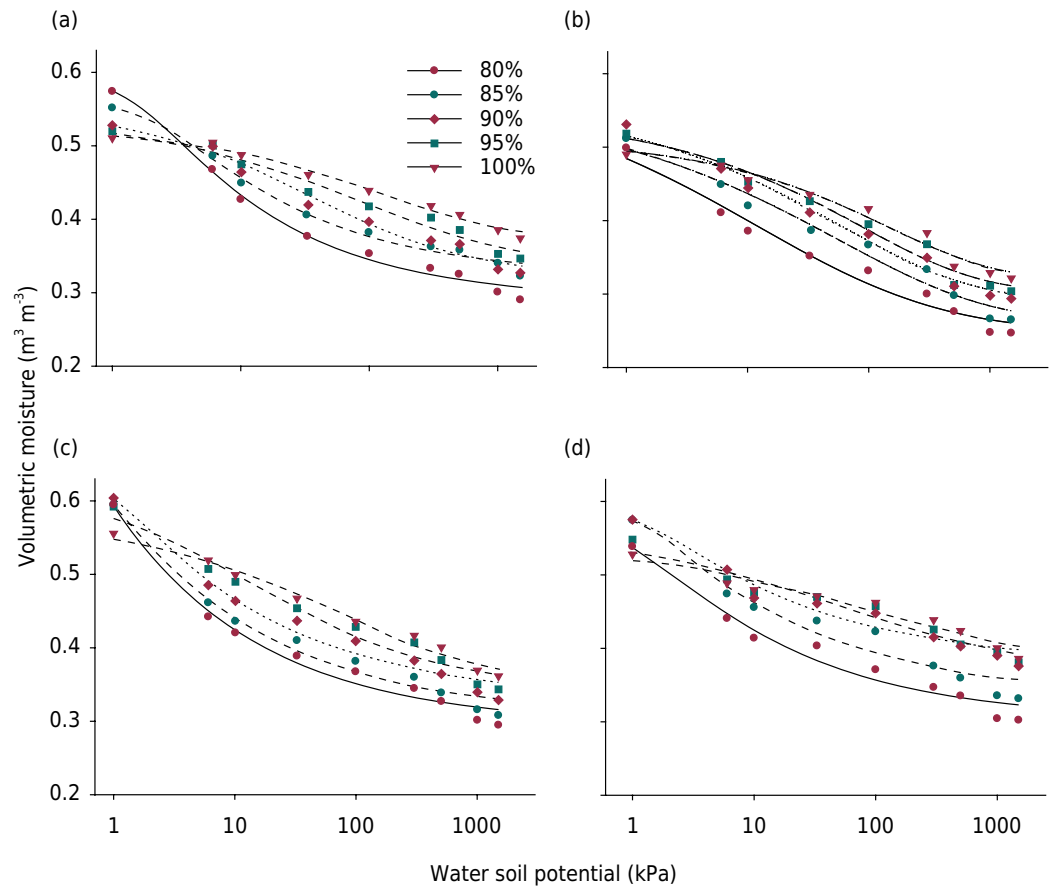
Figure 1. Water retention curve of *Latossolo Vermelho distrófico retrático* (Ferralsol LV$_{CN}$) (a), *Cambissolo Húmico alumínico típico* (Cambisol CH$_{LG}$) (b), *Nitossolo Bruno distrófico típico* (Nitisol NB$_{PA}$) (c), and *Nitossolo Bruno distrófico húmico* (Nitisol NB$_{SJ}$) (d), at different degrees of compaction, fitted by the Van Genuchten Equation.

Table 3. Field capacity (FC), permanent wilting point (PWP), and available water content (AW) for the evaluated soils, at different degrees of compaction (DC)

DC	LV$_{CN}$[1]			CH$_{LG}$			NB$_{PA}$			NB$_{SJ}$		
	FC	**PWP**	**AW**	**FC**	**PWP**	**AW**	**FC**	**PWP**	**AW**	**FC**	**PWP**	**AW**
%						cm^3 cm^{-3}						
80	0.427	0.290	0.137 a[2]	0.384	0.247	0.137 b	0.423	0.295	0.128 ab	0.404	0.302	0.102 ab
85	0.451	0.323	0.128 ab	0.415	0.265	0.150 ab	0.435	0.308	0.127 b	0.455	0.332	0.123 a
90	0.464	0.323	0.141 a	0.442	0.294	0.148 ab	0.464	0.329	0.135 ab	0.466	0.376	0.090 b
95	0.476	0.347	0.129 a	0.457	0.304	0.153 a	0.486	0.343	0.143 a	0.474	0.381	0.093 b
100	0.487	0.374	0.113 b	0.461	0.321	0.140 ab	0.495	0.361	0.134 ab	0.477	0.386	0.091 b

[1] *Latossolo Vermelho distrófico retrático* (Ferralsol LV$_{CN}$); *Cambissolo Húmico alumínico típico* (Cambisol CH$_{LG}$); *Nitossolo Bruno distrófico típico* (Nitisol NB$_{PA}$); and *Nitossolo Bruno distrófico húmico* (Nitisol NB$_{SJ}$); DC: degree of compaction determined with the equation DC = 100 × (BD/BD$_m$); FC: field capacity; PWP: permanent wilting point; AW: available water. FC and PWP determined by tension table and Richard chambers method; AW obtained with the equation AW = FC - PWP. [2] Mean values followed by the same letter in the column, do not differ by Tukey test (p<0.05).

The AC was low in the higher DC. The LV$_{CN}$ presented the largest reduction in AC, from 0.17 to 0.04 m^3 m^{-3}, that is, a 76 % reduction in this property. Other soils also lost 60 to 70 % in AC (Table 2).

There was a significant reduction in the hydraulic conductivity of saturated soil (Ks) in increasing DC in all soils, with greater losses mainly from intermediate DC (Table 2). The

minimum and maximum range for the same soil was seen in LV_{CN} (175 to 10 mm h^{-1}) and CH_{LG} (124 to 0.1 mm h^{-1}), and the coefficient of variation of 21 to 156 % was found for these soils, respectively.

When DC increased, the volume of water retained at 10 kPa (FC) and 1500 kPa (PWP) increased as well (Figure 1). The increase in water volume from DC 80 to DC 100 was similar between soils, FC showed increases of 0.06 and 0.08 cm^3 cm^{-3} for LV_{CN} and CH_{LG}, respectively, and PWP increased a minimum of 0.07 cm^3 cm^{-3} for NB_{PA} and a maximum of 0.08 cm^3 cm^{-3} for LV_{CN} and NB_{SJ} (Table 3). Unlike FC and PWP, the AW volume did not have a defined behavior between the studied soils and varied according to DC.

The highest AW volume was seen on CH_{LG} at DC 95 but only differed from DC 80 for this soil. The LV_{CN} presented DC 90 with higher AW volume, but it did not differ from DC 80, 85, and 95. The NB_{PA} presented DC 85 with lower AW volume, which differed from DC 95 with higher AW. Finally, DC 85 had higher AW in NB_{SJ}, and it was statistically superior to DC 90, 95, and 100 (Table 3).

An increase of PR with the largest DC was found, and it peaked at up to 10 MPa in the largest LV_{CN} and NB_{PA} DC, which may inhibit the growth of many crops. From DC 80 to 100, the increase in PR was 1.7 to 9.7, 1.0 to 4.9, 1.6 to 9.8, and 2.2 to 6.8 MPa for LV_{CN}, CH_{LG}, NB_{PA}, and NB_{SJ}, respectively (Table 2). This result shows that soils with high clay content offer much more restriction to root growth when compacted, but when not degraded, they provide good structure and conditions for root development.
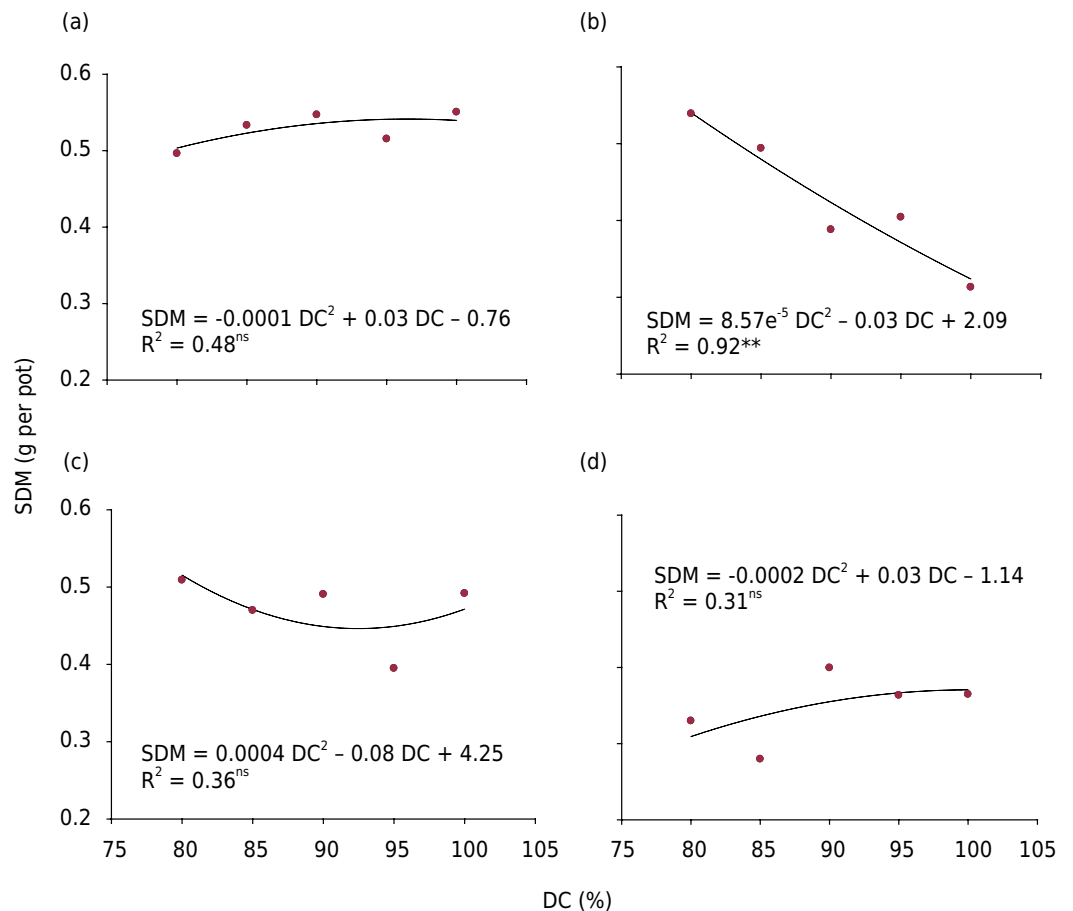

Figure 2. Shoot dry matter (SDM) evaluated at different degrees of compaction (DC) in a *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}) (a), *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}) (b), *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}) (c), and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}) (d). [ns] and ** : not significant and significant at 10 % of probability according to the regression test, respectively.

Compaction effects on black oat development

Counteracting all effects of compaction on soil physical quality properties, oat development in soils with increasing DC did not have its growth affected, except in CH_{LG}, where shoot dry matter (SDM) reduced 42 %, from 0.54 to 0.31 g per pot, or 688 to 395 kg ha^{-1} (Figure 2b). The other soils showed no change in SDM or a definite pattern, oscillating between DC (Figure 2).

In LV_{CN}, unlike the Cambisol, the highest productivity occurred in DC 100 (0.55 g per pot/ 700 kg ha^{-1}) and the lowest in DC 80 (0.50 g per pot/ 637 kg ha^{-1}) (Figure 2a). In NB_{PA}, DC 80 and DC 95 were highest (0.51 g per pot/ 650 kg ha^{-1}) and lowest (0.40 g per pot/ 509 kg ha^{-1}) values, respectively (Figure 2c). The DC 90 and 85 with an average yield of 0.40 and 0.28 g per pot (509 and 357 kg ha^{-1}) represented the extreme values for the NB_{SJ} (Figure 2d).

The growth rate (GR) did not differ significantly, despite the same decreasing behavior of the SDM was observed (Figure 3). Differences in NDF were observed only in CH_{LG}, and ADF in CH_{LG} and NB_{PA} (Figure 4). Despite this difference, the absolute values did not differ much, with NDF ranging from 41.4 to 36.8 %, and ADF from 15.6 to 13.6 % on Cambisol, at DC 80 to DC 100, respectively. The ADF at NB_{PA} fluctuated from 14.8 % at DC 80 to 17.3 % at DC 100.

The NDF values ranged from 43.0 to 40.5, 40.6 to 36.2, and 46.0 to 48.2 % of DC 80 to 100 at LV_{CN}, NB_{PA}, and NB_{SJ}, respectively. And ADF fluctuated from 15.1 to 14.6, and 15.5 to 16.7 % of DC 80 to 100 at LV_{CN} and NB_{SJ}, respectively (Figure 4).
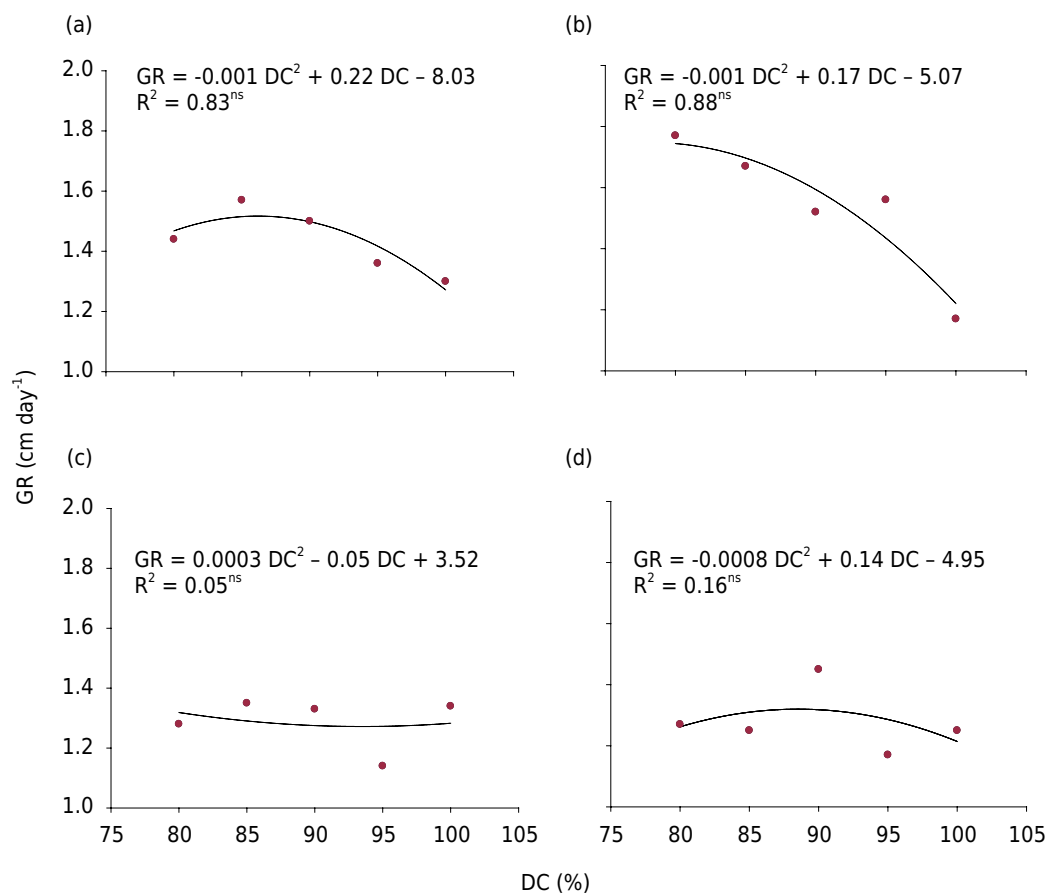

Figure 3. Growth rate (GR) evaluated at different degrees of compaction (DC) of *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}) (a), *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}) (b), *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}) (c), and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}) (d). ns: not significant to regression test at 10 % of probability.
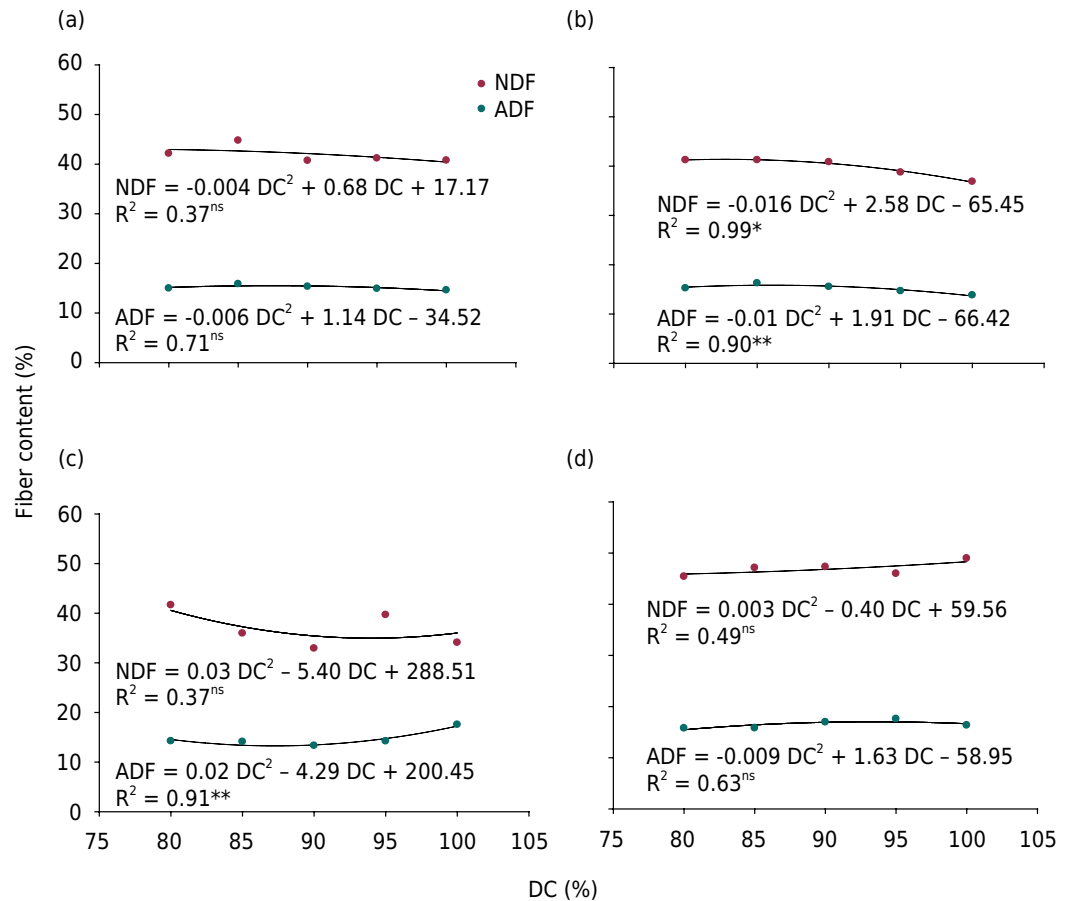
(a)

NDF = $-0.004 DC^2 + 0.68 DC + 17.17$
$R^2 = 0.37^{ns}$

ADF = $-0.006 DC^2 + 1.14 DC - 34.52$
$R^2 = 0.71^{ns}$

(b)

NDF = $-0.016 DC^2 + 2.58 DC - 65.45$
$R^2 = 0.99^*$

ADF = $-0.01 DC^2 + 1.91 DC - 66.42$
$R^2 = 0.90^{**}$

(c)

NDF = $0.03 DC^2 - 5.40 DC + 288.51$
$R^2 = 0.37^{ns}$

ADF = $0.02 DC^2 - 4.29 DC + 200.45$
$R^2 = 0.91^{**}$

(d)

NDF = $0.003 DC^2 - 0.40 DC + 59.56$
$R^2 = 0.49^{ns}$

ADF = $-0.009 DC^2 + 1.63 DC - 58.95$
$R^2 = 0.63^{ns}$

Figure 4. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) evaluated at different degrees of compaction (DC) of *Latossolo Vermelho distrófico retrático* (Ferralsol LV_{CN}) (a), *Cambissolo Húmico alumínico típico* (Cambisol CH_{LG}) (b), *Nitossolo Bruno distrófico típico* (Nitisol NB_{PA}) (c), and *Nitossolo Bruno distrófico húmico* (Nitisol NB_{SJ}) (d). [ns], *, and **: not significant and significant at 5 and 10 % of probability to the regression test, respectively.

DISCUSSION

Although some studies do not report microporosity increase with soil compaction (Silva et al., 1997,2018), in this study, microporosity increases due to DC increase, which confirms that reducing the diameter of the larger pores creates smaller pores, as reported by Schaffrath et al. (2008), who highlight the relationship of porosity to soil density and how management can reduce the proportion of larger pores by turning them into micro.

Related to macroporosity, it was verified that in NB_{PA}, where organic matter (OM) is higher, macroporosity was less affected, and it only reached the critical limit in DC 100. This limit is 0.10 m^3 m^{-3} because below it occurs lower development of the roots (Vomocil and Flocker, 1961). In LV_{CN}, with a lower OM content, the critical limit was reached at DC 85. Araújo et al. (2004) reported the indirect effect of soil OM, which was lower in cultivated soil than the native forest. Because of this reduction, they reported higher susceptibility to soil compaction, increasing bulk density, and reducing macroporosity. Cavalcanti et al. (2019) show the importance of increasing OM on soil physical properties in a Ultisol grown with sugarcane, which reduces bulk density and minimizes the compaction process. The NB_{SJ} and CH_{LG} had similar behavior, with volume below the critical limit close to DC 90. These two soils have a similar clay content, which is arranged between the silt and sand particles, similarly modifying the porosity. However, the higher OM content of NB_{SJ} compared to CH_{LG} makes this rearrangement maintain a slightly larger volume of macropores in NB_{SJ}. The relationship between texture and OM content was detailed in the study of Braida et al. (2010).

Differences in soil porosity usually modify water and air fluxes. The AC is related to pores with a diameter above 30 μm, in which oxygen and carbon dioxide diffusion occur, among other gases. According to some authors (Baver and Farnsworth, 1940; Stolzi, 1974; Tormena et al., 1998), AC is classified as low when AC <0.10 m^3 m^{-3}. In LV_{CN}, AC was low from DC 90 (Table 2), showing its sensitivity to degradation by compaction. The factors that lead to the reduction of macroporosity are the same factors that contribute to the lower aeration capacity because, both properties are closely connected. The other three soils were below this limit at DC 95 (CH_{LG}) and 100 (NB_{PA} and NB_{SJ}).

The air-filled porosity (AP), which is the difference between TP and current soil volumetric moisture, in this study was higher than 0.10 m^3 m^{-3} in all the soils and DC. It is a property that differs from the AC because AP varies according to soil moisture.

Water movement in the soil varies according to some porosity aspects (volume, size, shape, and continuity), and it has an indirect influence on many soil properties. Reichert et al. (2007) report the relation between saturated hydraulic conductivity and porosity and proposes two hypotheses to obtain a critical Ks value, one of which is based on a macroporosity of 0.10 m^3 m^{-3}. Macropores are the first to decrease when DC increases, and their absence affects water flow. In the different soils, there was a wide variation in Ks in the DC where macroporosity was closer to 0.10 m^3 m^{-3} (DC 85 on LV_{CN}, DC 90 on CH_{LG}, DC 100 on NB_{PA}, and DC 90 on NB_{SJ}), e.g., from 1.0 at NB_{PA} to 150 mm h^{-1} at NB_{SJ} (Table 2). So, despite the different soil types evaluated, this variation confirms that this attribute depends not only on pore volume but also on other aspects (Gonçalves and Moraes, 2012).

Soil texture seems to have a greater influence when evaluating different soils. However, it is necessary to carry out a complex study with many soils to determine the relationship between clay, silt, and sand fractions and their interactions on saturated hydraulic conductivity.

Despite the differences presented, relatively high values were statistically equal to low values (Table 2), due to the high coefficients of variation. Lima et al. (2012) report Ks variation coefficient between 111 to 248 %, which is why a relatively large number of samples are required to detect statistically significant differences (Gurovich, 1982; Mesquita and Moraes, 2004).

Because only one soil (CH_{LG}) has shown a significant reduction in black oat yield and the fiber contents remained within an adequate standard for forage quality, Ks does not seem to be a limiting factor to the crop. However, for environmental issues, DC increases represent a risk of soil erosion (Prats et al., 2019).

The variation of the DC affects AW content, but it does not show the same trend between soils, which indicates that AW also has a relationship with other properties, such as the distribution of textural fractions, mineralogy, and OM content. Generally, higher AW content was observed between DC 85 and DC 95 (Table 3). Awe et al. (2020) show that low BD and high macroporosity decrease AW, and Fidalski et al. (2013) emphasized that soils with the sandiest granulometry, with high macroporosity, tend to provide low water content due to lower FC.

Micropore related changes in macropores volume were observed. Therefore, total porosity decreases according to the DC increase. Field capacity also increases, but with lower intensity than the increase in PWP (Figure 1 and Table 3). Thereby, AW volume decreases, as discussed by Klein and Libardi (2002).

The DC was directly related to penetration resistance (PR). The determination of PR was performed with soil moisture standardized to 10 kPa tension. Therefore, the difference is due to DC increase, particle approximation, and highest cohesion. The texture effect can be seen in clayey soils (LV_{CN} and NB_{PA}) with higher PR, between 1.5 and 10 MPa. In these

soils, the particle cohesion is higher, because the interaction between clay minerals (Reichert et al., 2016). For LV_{CN} and NB_{PA}, the critical limit of 2 MPa (Tormena et al., 1998; Silva et al., 2008; Lima et al., 2012) was achieved at DC 85 and DC 90, respectively, theoretically representing a limitation on root development. The NB_{SJ} shows less PR variance, but the critical limit occurs at DC 80 (Table 2). The gradual variation on PR over plant development can be less prejudicial than abrupt changes, as observed for clayey and very clayey soils. Even so, a PR increase can directly influence root and plant growth (Reinert et al., 2008).

Penetration resistance has less impact at CH_{LG}, exceeding the limit of 2 MPa only at DC 95, possibly related to its particle size distribution with less clay and higher sand content (Table 2). Bortolini et al. (2016) verified, in a Cambisol under integrated cattle raising and different grazing intensities, that PR varied mainly depending on soil moisture. Silva et al. (2016) evaluated a Ferralsol and reported higher PR at a no-tillage system in comparison to conventional tillage and native forest. These results show that this property depends on many factors, and it varies in space according to soil properties, and in time with the moisture.

The crop was not effectively compromised with the increase of DC, as only Cambisol crops presented a significant reduction in SDM. This reduction, which started from DC 80, shows that the crop is affected by the compaction effects, accentuating between DC 85 and DC 90 (Figure 2b). At this level, there were no PR restrictions. However, macroporosity and Ks may indicate physical restrictions (Table 2).

Considering that SDM production had an average of eight cuts performed during the evaluation period, in the end, production in DC 80 of CH_{LG} resulted in a total of 5.5 Mg ha^{-1}, higher than that found by Jochims et al. (2017) in an experiment conducted in west Santa Catarina region with different forage oat genotypes, which variated from 3.0 to 5.2 Mg ha^{-1}. Thus, plants show a potential to overcome the achieved yield in this experiment compared to other studies in which they achieved 7 Mg ha^{-1} yield in the Santa Catarina Plateau region (Rosa et al., 2008). The only significance in this attribute occurred in the CH_{LG}, which demonstrated a yield decrease of approximately 42 % from the lowest to the highest DC (Figure 2b). Overall, black oat did not respond with reduced SDM to soil compaction, corroborating the results of Silva et al. (2006), that evaluated the shoot growth of different plants in increasing DC of Ferralsol, and observed that, generally, grasses were little sensitive to the physical changes resulting from compaction.

Despite all physical restrictions observed in the most diverse DC of the soils, as previously discussed, no significant reduction of GR was observed, which oscillated between the DC and showed no direct relationship (Figure 3).

All soil fiber contents complied with the 60 % (van Soest, 1994) and 30 % (Mertens, 1994) limits, to NDF and ADF, respectively (Figure 4), which makes it possible to consider the forage having a good quality, despite the low yield.

The black oat in the present study may be considered tolerant to the compaction in most of the studied soils, considering that yield was affected only in CH_{LG}. However, it is important to note that the experiment was carried out under controlled moisture conditions. In a natural environment, soil moisture fluctuations can harm plants by anoxia in wet periods, and by increasing resistance to penetration in dry periods.

CONCLUSIONS

Soil physical properties are negatively affected by the increase of the degree of soil compaction, and they reach critical limits for crop development at bulk densities lower than maximum bulk density (DC 100). Compaction increases penetration resistance,

field capacity, permanent wilting point and microporosity, and it reduces total porosity, macroporosity, aeration capacity, and soil saturated hydraulic conductivity. However, available water is higher at an intermediary degree of compaction (DC 85 to DC 95).

Shoot dry mass of black oat decreased with increasing compaction only in the Humic Cambisol, but it is not affected in the other soils. The forage quality of black oat, represented here by the fiber content in acid and neutral detergent, is not altered by soil compaction.

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