soil systems

Article

Soil Structure under Forest and Pasture Land-Uses Affecting Compressive Behavior and Air Permeability in a Subtropical Soil

Luis Eduardo Akiyoshi Sanches Suzuki [1,*], Dalvan José Reinert [2], Deonir Secco [3], Paulo Torres Fenner [4] and José Miguel Reichert [2]

1 Center of Technological Development, Federal University of Pelotas, Pelotas 96010-610, RS, Brazil
2 Soils Department, Federal University of Santa Maria, Santa Maria 97105-9000, RS, Brazil
3 Centro de Ciências Exatas e Tecnológicas, Universidade Estadual do Oeste do Paraná-UNIOESTE, Cascavel 85819-110, PR, Brazil
4 Department of Forest Sciences, UNESP Universidade Estadual Paulista, Botucatu 18610-307, SP, Brazil
* Correspondence: luis.suzuki@ufpel.edu.br

Abstract: Machinery traffic and animal trampling can deform the soil and, consequently, impair soil pore functioning. This study aimed to evaluate how soil structure affects the compressibility, physical properties and air permeability of a Typic Paleudalf under forest, pasture and eucalyptus. Soil samples with preserved structure were used to determine soil physical (bulk density, porosity, degree of water saturation at 33 kPa-tension, air permeability) and mechanical properties (soil deformation, precompression stress, compressibility index). After these evaluations, each soil sample was fragmented, sieved, and the metal rings filled with structureless soil, and underwent the same determinations as the samples with preserved structure. For loads greater than the precompression stress (load greater than 200 kPa), soil with non-preserved structure had the largest deformation. An increase in bulk density decreased macropores linearly (R^2 = 0.77 and 0.87, respectively, to preserved and non-preserved soil structure) and air flow exponentially. The soil with preserved structure was less susceptible to further compaction. Air flow was greatest in soils with lower bulk density, microporosity and water saturation degree, and a high volume of macropores. Soil structure (preserved and non-preserved) had more significative differences in microporosity, compressibility index, soil deformation, and bulk density at the end of the compression test.

Keywords: compressibility; precompression stress; soil compaction; soil permeability

check for updates

Citation: Suzuki, L.E.A.S.; Reinert, D.J.; Secco, D.; Fenner, P.T.; Reichert, J.M. Soil Structure under Forest and Pasture Land-Uses Affecting Compressive Behavior and Air Permeability in a Subtropical Soil. *Soil Syst.* **2022**, *6*, 98. https://doi.org/10.3390/soilsystems6040098

Academic Editor: Heike Knicker

Received: 1 November 2022
Accepted: 10 December 2022
Published: 15 December 2022

1. Introduction

Soils are responsible for many processes essential to life [1], serving as a substrate to support plant growth, a reservoir of nutrients [2,3], and the site for many biological processes involving the decomposition and cycling of animal and plant compounds [4–6]. Soil influences air and water quality through interactions with the atmosphere, and as a system for storing [7] and purifying water flowing through the soil profile [8].

Soil structural quality is essential for proper pore functioning for water and air flow and biological activity, all important for the maintenance of life. In cultivated soil, its structure is affected by machinery traffic, animal trampling and soil tillage, for example. Management practices that alter the classes of pores with larger diameters will directly affect flows of air and water in the soil [9]. Soil tillage alters the mechanical strength of soil aggregates, pore continuity, and hydraulic, gas and heat fluxes [10]. Soil as a three-phase system (solid–air–water) has limited resilience and sustainability and, when stress-supporting limits are exceeded, soil properties and functions are affected, particularly pore size and distribution, affecting the flux of water, gas and heat [11].

Soil precompression stress and the compression index are useful indicators to apprise, respectively, soil load bearing capacity and susceptibility to compaction [12,13]. When pressure applied to the soil is lower than the precompression stress, elastic (recoverable) deformation occurs in the soil, and physical properties undergo minor changes. However, with pressure greater than the load-bearing capacity of the soil, plastic deformation (non-recoverable) occurs, and soil physical properties change considerably [12,13].

A soil with good physical quality allows infiltration, retention and availability of water to plants, streams and subsurface; responds to management and resists degradation; allows exchange of heat and gases with the atmosphere and plant roots; and enables root growth [14]. Water, oxygen, temperature and root penetration resistance directly affect plant growth. These properties are affected by bulk density, aggregation, aggregate stability and pore size distribution, all indirectly related to crop growth and yield [15]. Precompression stress and compressibility index, soil mechanical parameters related to machinery traffic and to animal trampling, are associated with soil structure [16–18] and plants [18], and their knowledge may help maintain soil structure adequate for its functioning [19]. The knowledge on the transition from elastic to plastic properties and changes of function of the soil is essential to increase or at least maintain soil functions such as fluxes, root penetrability, filtering and buffering [4].

Some studies were conducted to understand the influence of soil tillage (no-tillage, plowing, chiseling) and land use (annual crops, forest, pasture) on the physical properties of soil [19–34]. However, the knowledge on soil structure, especially porosity (arrangement and continuity, for example), related to soil resistance to support loads and air flow is still incipient.

Thus, for soil physical, chemical and biological processes to contribute to improved environmental quality, soil structure must allow adequate aeration, infiltration and retention of water and exchanges of gases and heat with the atmosphere. Furthermore, field operations that involve soil rupture (e.g., by tillage) and/or machinery traffic and animal trampling can substantially change soil structure (soil loosening or compaction), modifying the conditions that determine root and plant growth and yield, and water and air flows [18,34–36]. Remolded soil or non-preserved structure has been used in compressibility tests, especially in engineering tests to demonstrate the soil supportability of buildings [37–42], but few studies [43] have focused on soil function.

Considering the importance of soil structure, this study aimed to evaluate the effect of soil structure on its compressibility, physical properties, and air permeability. Our hypothesis was that a loose soil has lower load bearing capacity and is more susceptible to soil compaction than a structured soil; and even with lower bulk density and greater macroporosity, the loose soil has lower air permeability due to decreased pore continuity. Therefore, this study contributes towards a better understanding of the relationship between soil structure, compressibility, and permeability.

2. Materials and Methods

2.1. Study Site and Treatments

The study area is located in the municipality of Butiá, in the physiographic region of the Southeast Mountain Range (Rio-Grandense Shield) of the Rio Grande do Sul State, southern Brazil, with geographic coordinates of 30°06′06″ south latitude and 51°52′18″ west longitude (Figure 1). According to the Köppen system of climatic classification, the climate in the region is "Cfa" type—subtropical, humid, without drought. Based on 30 years of data (1981 to 2020), the minimum and maximum temperature of the hottest (January) and least hot (July) month is, respectively, 19.4 and 30.8 °C and 9.4 and 19.2 °C, and the rainfall varies from 99.6 mm (March) to 149.7 mm (June), with an annual average of 124.37 mm [44].

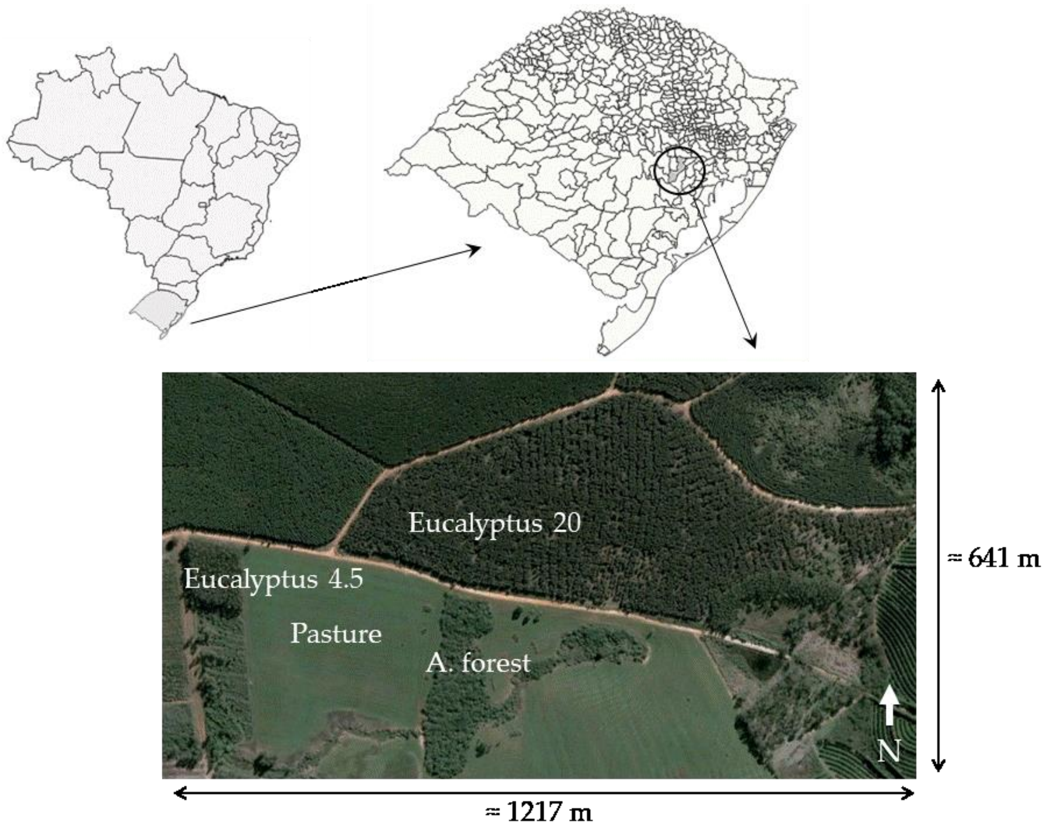

Figure 1. Map of Brazil, with Rio Grande do Sul State shown as hatched; map of Rio Grande do Sul State with Butiá shown as hatched; and image from Google Earth with the land uses studied. Image of Google Earth dated 5 September 2005.

The soil in the area is classified as Typic Paleudalf [45], Umbric Rhodic Acrisol [46] or "Argissolo Vermelho Distrófico" by the Brazilian Soil Classification System [47], with low-activity clays, moderate A horizon (i.e., not included in other categories of A horizon), medium texture in the horizon A/clay in the horizon B with gravel, smooth undulated and undulated relief, and the soil parent material is granite. The uses or treatments in this study were in contiguous areas and were as follows:

(1) Anthropized forest: forest composed by tree and shrub species with a height of approximately 4 m, used as shelter for cattle. Due to the possibility of cattle gaining access to this sampling point in the driest periods, this area was called anthropized forest;
(2) Pasture: 5-y-old pasture, consisting of brachiaria brizanta (*Brachiaria brizantha*) intercropped with Pensacola (*Paspalum lourai*) and clover (*Trifolium* sp.). The pasture was installed in an area of 1200 ha under conventional tillage (plowing and harrowing) in 2001. Before the pasture, there was natural forest and pasture, and soybean intermittently;
(3) Eucalyptus 20: a 20-y-old *Eucalyptus saligna* stand, with conventional tillage used to plant the stand in 1986. Before the eucalyptus, the area consisted of pasture;
(4) Eucalyptus 4.5: clonal *Eucalyptus saligna* in a second rotation, with 4.5 years of age. The original planting occurred in 1993, with soil tillage in strip and a three-stem chisel. The harvesting of eucalyptus in the first cycle, at 8.5 years of age, was performed manually with a chainsaw, and the wood extraction was carried out with a Forwarder Valmet 890 with a load capacity of 18 Mg, without burning the crop residue. The traffic for the harvesting of eucalyptus in the first cycle was at random, with number of passes reaching up to 16. The second planting of eucalyptus was carried out between the rows in 2002. Before the first planting in 1993, the area was used for soybean and pasture.

Soil particle size distribution and total organic carbon content in soils are presented in Table 1.

Table 1. Mean values of gravel, particle size distribution and total organic carbon for the studied land uses and six soil layers.

Layer (m)	Gravel (20–2 mm)	Sand Total (2–0.05 mm)	Sand Coarse (2–0.2 mm)	Sand Fine (0.2–0.05 mm)	Silt (0.05–0.002 mm)	Clay (<0.002 mm)	* Total Organic Carbon
	$g\ kg^{-1}$						$g\ dm^{-3}$
			Anthropized Forest				
0.00–0.05	8	407	245	162	191	402	34
0.05–0.10	12	385	210	175	193	422	21
0.10–0.20	12	379	213	166	187	434	17
0.20–0.40	23	345	198	147	179	476	14
0.40–0.60	48	293	171	122	165	542	14
0.60–1.00	47	277	167	110	144	579	11
			Pasture				
0.00–0.05	38	362	206	156	193	445	27
0.05–0.10	21	355	200	155	199	446	24
0.10–0.20	36	334	193	141	185	481	19
0.20–0.40	41	301	175	126	165	534	16
0.40–0.60	75	300	186	114	137	563	14
0.60–1.00	68	282	167	115	130	588	12
			Eucalyptus 20				
0.00–0.05	30	374	212	162	161	465	32
0.05–0.10	40	371	213	158	161	468	18
0.10–0.20	75	385	220	165	157	458	17
0.20–0.40	274	353	206	147	156	491	17
0.40–0.60	110	302	185	117	134	564	13
0.60–1.00	97	285	176	109	120	595	11
			Eucalyptus 4.5				
0.00–0.05	14	475	272	203	200	325	34
0.05–0.10	14	460	265	195	194	346	16
0.10–0.20	19	426	240	186	192	382	16
0.20–0.40	55	376	226	150	162	462	15
0.40–0.60	47	314	188	126	151	535	14
0.60–1.00	37	288	171	117	141	571	9

* Source: [48].

2.2. Soil Sampling and Analyses

Samples of soil with preserved or undisturbed structure, as it was in the field, were collected in September 2006. For this purpose, three trenches in each use were opened and, in each trench, two samples per soil layer were collected, totaling six replicates per layer. The samples were collected in metal cylinders of 2.5 cm height and 6.1 cm diameter, in the 0.025 to 0.05 m, 0.10 to 0.125 m, and 0.20 to 0.225 m soil layers. These were saturated by capillarity and, later, positioned on a tension table at 0.60 m of water column to determine the microporosity [49]. Soil macroporosity was calculated by the difference between the total porosity and the microporosity. The total porosity was calculated by the equation:

$$Tp = 1 - (Bd/Pd) \quad (1)$$

where Tp is the total porosity ($m^3\ m^{-3}$), Bd is the bulk density ($Mg\ m^{-3}$), and Pd is the particle density ($Mg\ m^{-3}$). Soil particle density was determined by the method proposed by Gubiani et al. [50], in soil samples with non-preserved structure collected in September 2006 in three trenches within each use, in the 0.00–0.05; 0.10–0.20 and 0.20–0.40 m soil layers.

The soil samples with preserved structure were re-saturated, equilibrated at a tension of 33 kPa using Richards pressure chambers [51] and, then, submitted to the air permeability test using an air permeameter. Permeability was calculated as:

$$K = \rho^* g^*[(\Delta v^* L)/(\Delta t^* \Delta p^* A)] \quad (2)$$

where K is the air permeability (m s^{-1}), ρ is the air density in the moment of measurement (kg m^{-3}), g is the acceleration of gravity (m s^{-2}), Δv is the reading on the flowmeter (m^3), L is the height of the cylinder (m), Δt is the time (minutes), Δp is the air pressure applied (hPa) and A is the area of the cylinder (m^2). We used ρ = 1.169 kg m^{-3}, g = 9.81 m s^{-2}, Δt = 1 min, and Δp = 1 hPa. Air density was calculated as:

$$\rho = \rho_n^*[(T_n^* p)/(p_n^* T)] \quad (3)$$

where ρ is the air density in the moment of measuring (kg m^{-3}), ρ_n is the standard air density (kg m^{-3}), T_n is the standard temperature (°K), p is the atmospheric pressure in the measurement (mbar), p_n is standard atmospheric pressure (mbar), and T is the temperature in the measurement (°K). We used: ρ_n (atmospheric pressure of 1013 mbar and temperature of 273.15 °K = 0 °C) = 1293 kg m^{-3}, T_n (0 °C) = 273.15 °K, p = 1000 mbar, p_n = 1013 mbar, and T (25 °C) = 298.15 °K.

After the air permeability test, the soil samples were submitted to a uniaxial compression test in the laboratory, with a five minutes application of successive static loads of 12.5, 25, 50, 100, 200, 400, 800 and 1600 kPa in the Terraload model S−450 (Durham Geo-Enterprises) consolidator, with pressure applied by compressed air. Maximum soil deformation was determined by following the methodology of Silva et al. [52], without considering pore water pressure changes during the test, since our apparatus had no such capability. Although this loading time might be considered a short interval in the multistep loading because of water pressure, as discussed in Rosa et al. [53], with the possibility of saturation and prevention, this loading time allows more than 99% of soil deformation. After the compression test, the soil samples were oven dried at 105 °C.

Before the compression test, soil bulk density (Bd) and degree of water saturation at 33 kPa matric tension (Sd) were calculated. Based on the vertical displacement measured in the laboratory by the consolidometer after the application of each load, the deformation (Def) of the soil at the end of the test was calculated. The compressibility index (Ci) and the precompression stress (Pcs) were calculated using Casagrande's method [54]. Soil compression curves were plotted relating the observed bulk density to the applied pressure in the uniaxial compression test.

After performing the determinations of macroporosity, microporosity, total porosity, air permeability, bulk density and compressibility with the soil samples with preserved structure, the samples from each ring were unstructured so that the particles passed through a 2 mm mesh sieve. Then the rings were filled with their respective soil (particles > and <2 mm), suffering a slight compaction so that all the soil filled the ring, maintaining the original bulk density of the soil sample. That soil was named non-preserved structure. The samples went through the same processes (saturated by capillarity, submitted at 0.60 m tension on a tension table and at 33 kPa tension using Richards pressure chambers, and oven dried at 105 °C) and determinations (bulk density, macroporosity, microporosity, total porosity, air permeability, degree of water saturation at 33 kPa matric tension and compressibility) of the samples with preserved structure.

A completely randomized design was used, comparing samples with preserved and non-preserved structure for each soil layer and land use. The analysis of variance and the Tukey test of means were performed considering 5% significance, as well as regression analysis considering the properties evaluated.

3. Results

Soil macroporosity, total porosity and initial bulk density were not significantly ($p > 0.05$) influenced by soil structure (Tables 2 and 3), whereas microporosity was significantly ($p < 0.05$) influenced by soil structure (preserved and non-preserved), with an increase in the soil with non-preserved structure in the eucalyptus areas. However, this increase in microporosity was not reflected in significant differences in total porosity ($p > 0.05$). The unstructured, sieving and reorganization of soil particles during sample accommodation in the cylinder with non-preserved structure may have contributed to the increase in the microporosity and decrease (not statistically significative) in the macroporosity.

Table 2. Coefficient of variation (cv) and mean values of macroporosity, microporosity and total porosity, for soil with preserved (Pres) and non-preserved (NPres) structure under different land uses and layers.

Layer, m	Macroporosity, $m^3\ m^{-3}$			Microporosity, $m^3\ m^{-3}$			Total Porosity, $m^3\ m^{-3}$		
	Pres	NPres	cv, %	Pres	NPres	cv, %	Pres	NPres	cv, %
					Forest				
0.025–0.05	0.109 a	0.149 a	41.73	0.367 a	0.337 b	5.93	0.475 a	0.486 a	7.54
0.10–0.125	0.159 a	0.183 a	17.10	0.347 a	0.335 a	6.42	0.506 a	0.518 a	2.64
0.20–0.225	0.150 a	0.146 a	18.66	0.336 a	0.348 a	5.06	0.486 a	0.495 a	2.54
					Pasture				
0.025–0.05	0.093 a	0.094 a	35.96	0.356 a	0.370 a	4.03	0.449 a	0.463 a	4.90
0.10–0.125	0.105 a	0.107 a	26.10	0.358 a	0.366 a	3.84	0.463 a	0.473 a	4.25
0.20–0.225	0.140 a	0.126 a	46.87	0.342 a	0.363 a	9.21	0.482 a	0.489 a	6.72
					Eucalyptus 20				
0.025–0.05	0.354 a	0.333 a	10.25	0.237 b	0.258 a	4.78	0.591 a	0.591 a	5.00
0.10–0.125	0.226 a	0.204 a	52.43	0.287 a	0.315 a	17.59	0.513 a	0.519 a	11.95
0.20–0.225	0.205 a	0.196 a	26.27	0.303 a	0.319 a	11.66	0.508 a	0.515 a	4.13
					Eucalyptus 4.5				
0.025–0.05	0.082 a	0.068 a	54.58	0.299 b	0.339 a	3.08	0.381 a	0.407 a	9.97
0.10–0.125	0.127 a	0.099 a	51.04	0.286 b	0.330 a	6.24	0.413 a	0.429 a	11.67
0.20–0.225	0.120 a	0.085 b	17.09	0.311 b	0.355 a	4.20	0.432 a	0.440 a	4.08

Means followed by same letters in a given line, for each physical property, do not differ statistically from each other by Tukey's test at 5% significance.

Although the initial bulk density was equal for soil with preserved and non-preserved structure, the latter soil reached the highest values at the end of the compression test and, consequently, the largest soil deformation (Table 3, Figures 2–5). As the initial bulk density increased, there was a decrease in soil deformation, and this decrease was more pronounced in soil with preserved structure (Figure 6a). Macropores decreased as bulk density increased ($R^2 = 0.77$ and 0.87, respectively, for preserved and non-preserved soil structure) (Figure 6b); therefore, the soil became less compressive, i.e., lower deformation occurred ($R^2 = 0.88$ and 0.32, respectively, for preserved and non-preserved soil structure) (Figure 6c). With an increase in the initial bulk density, there was an increase in the range of the final bulk density between soil with preserved and non-preserved structure ($R^2 = 0.46$ and 0.74, respectively, for preserved and non-preserved soil structure) (Figure 6d).

Table 3. Coefficient of variation (cv) and mean values of bulk density in the beginning and in the end of the uniaxial compression test, and deformation, for soil with preserved (Pres) and non-preserved (NPres) structure under different land uses and layers.

Layer, m	Bulk Density Initial, Mg m^{-3}			Bulk Density Final, Mg m^{-3}			Deformation, mm		
	Pres	NPres	cv, %	Pres	NPres	cv, %	Pres	NPres	cv, %
					Forest				
0.025–0.05	1.28 a	1.25 a	6.93	1.64 b	1.80 a	3.31	0.551 b	0.759 a	12.41
0.10–0.125	1.25 a	1.23 a	2.69	1.72 a	1.81 b	1.61	0.673 b	0.792 a	8.76
0.20–0.225	1.30 a	1.27 a	2.41	1.73 b	1.85 a	1.72	0.624 b	0.783 a	6.11
					Pasture				
0.025–0.05	1.38 a	1.32 a	3.39	1.73 b	1.89 a	3.03	0.513 b	0.744 a	7.91
0.10–0.125	1.36 a	1.33 a	3.77	1.72 b	1.88 a	3.61	0.538 b	0.728 a	6.24
0.20–0.225	1.29 a	1.27 a	6.67	1.69 a	1.78 a	6.14	0.593 a	0.711 a	17.38
					Eucalyptus 20				
0.025–0.05	1.03 a	0.99 a	6.33	Not determined			Not determined		
0.10–0.125	1.19 a	1.21 a	13.24	1.79 a	1.89 a	4.87	0.639 a	0.756 a	15.03
0.20–0.225	1.23 a	1.21 a	4.35	1.78 a	1.78 a	3.65	0.769 a	0.702 a	11.46
					Eucalyptus 4.5				
0.025–0.05	1.50 a	1.47 a	6.82	1.87 b	1.99 a	2.88	0.483 b	0.650 a	16.10
0.10–0.125	1.47 a	1.43 a	8.48	1.86 a	1.96 a	5.77	0.539 a	0.656 a	16.70
0.20–0.225	1.44 a	1.42 a	3.19	1.82 b	1.96 a	2.38	0.530 b	0.695 a	8.25

Means followed by same letters in a given line, for each physical property, do not differ statistically from each other by Tukey's test at 5% significance.

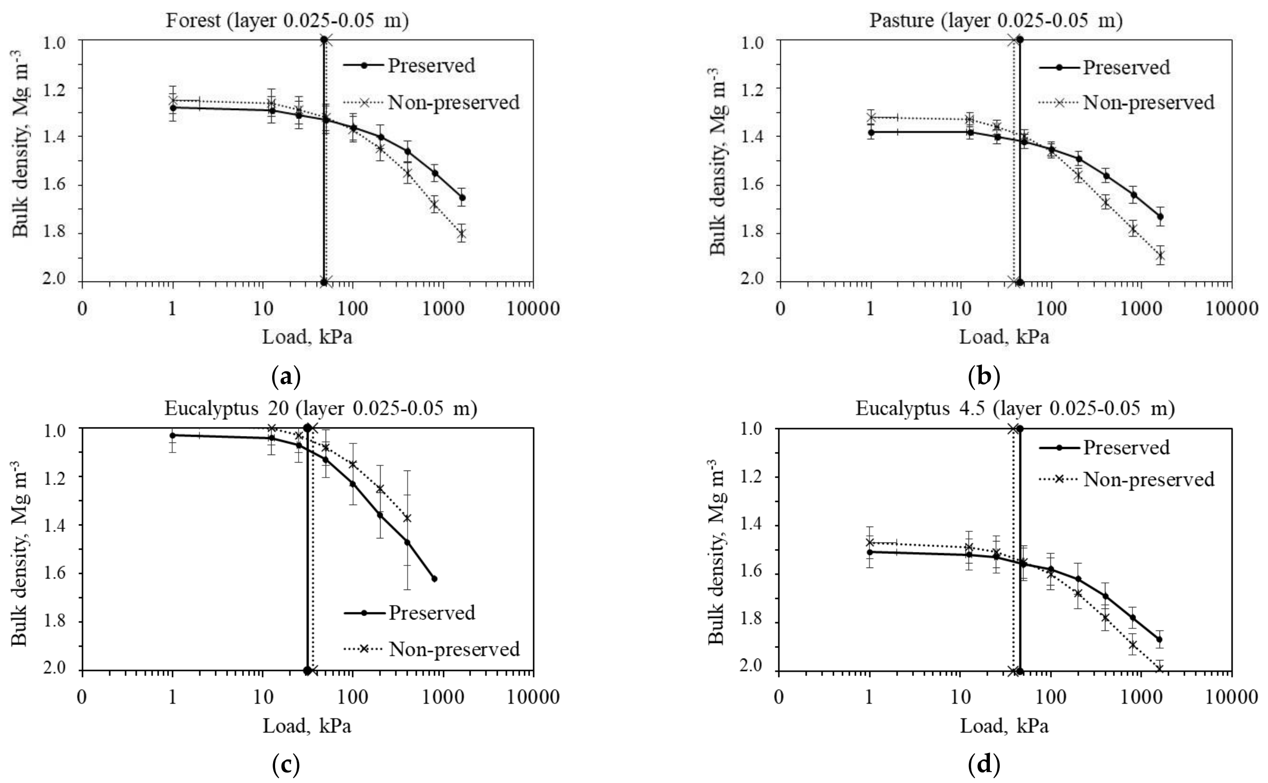

Figure 2. Soil compression curve for soil with preserved and non-preserved structure in the 0.025–0.05 m soil layer for four land uses. Vertical error bars for each pressure indicate the least significance difference, while vertical bars that accompany the superior and inferior axes in the figure indicate the precompression stress value for the preserved and non-preserved soil structures.

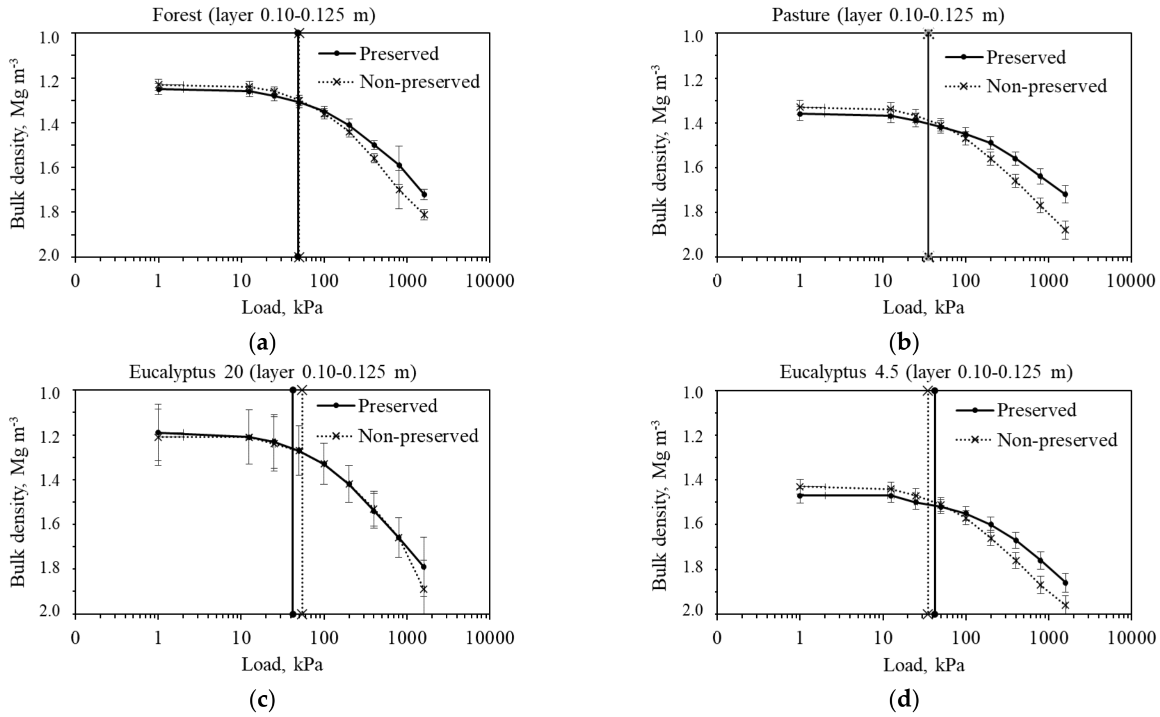

Figure 3. Soil compression curve for soil with preserved and non-preserved structure in the 0.10–0.125 m soil layer for four land uses. Vertical error bars for each pressure indicate the least significance difference, while vertical bars that accompany the superior and inferior axes in the figure indicate the precompression stress value for the preserved and non-preserved soil structures.

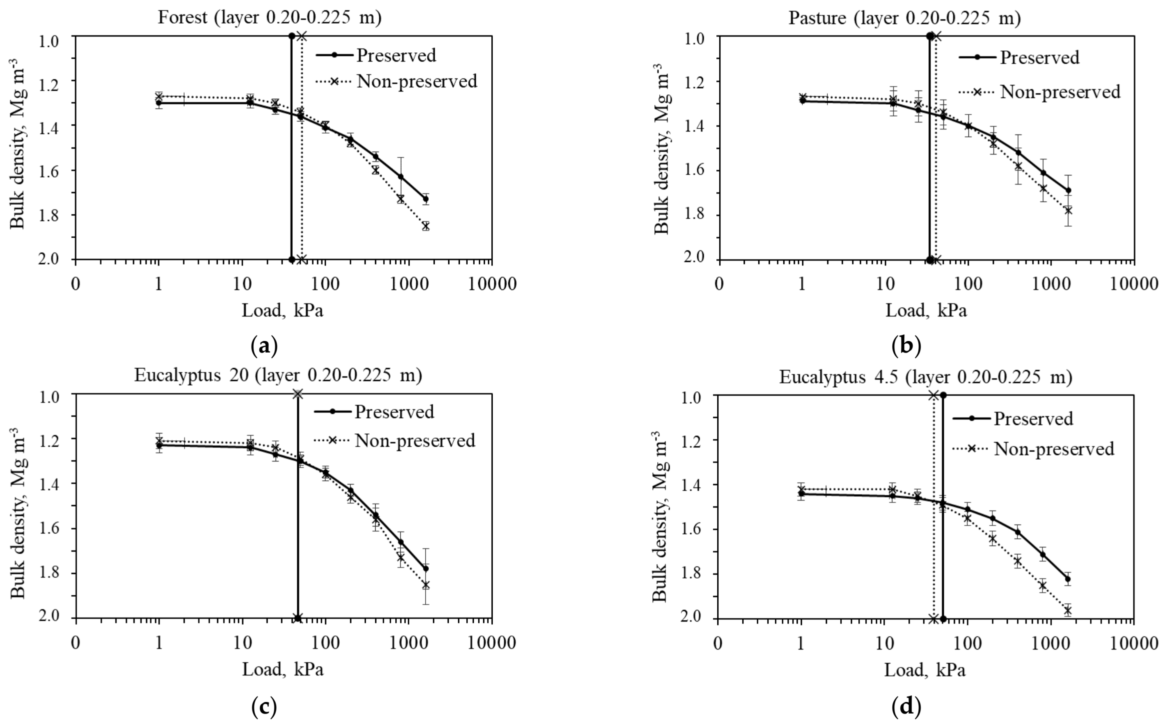

Figure 4. Soil compression curve for soil with preserved and non-preserved structure in the 0.20–0.225 m soil layer for four land uses. Vertical error bars for each pressure indicate the least significance difference, while vertical bars that accompany the superior and inferior axes in the figure indicate the precompression stress value for the preserved and non-preserved soil structures.

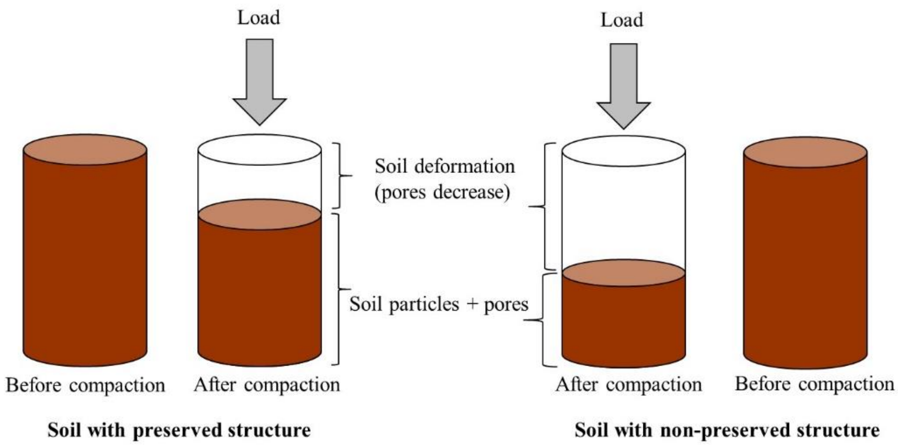

Figure 5. Soil with preserved and non-preserved structure with the same bulk density before the uniaxial compression test and the differences in soil deformation and pores decrease at the end of the test.

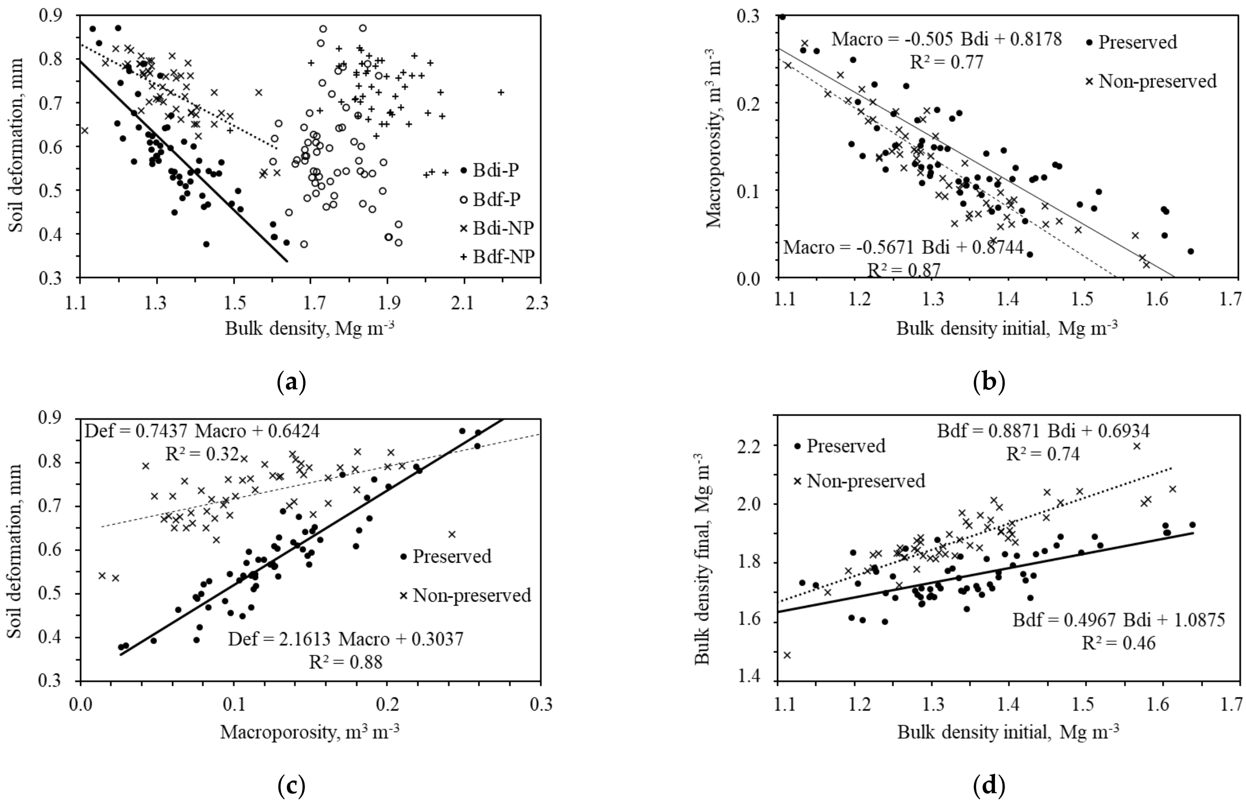

Figure 6. Regression between physical properties for soil with preserved (P) and non-preserved (NP) structure. Macro = macroporosity; Bdi and Bdf = bulk density in the beginning and in the final of the uniaxial compression test, respectively; Def = soil deformation in the final of the uniaxial compression test.

Soil precompression stress was similar for both types of soil structure ($p > 0.05$) (Table 4), while differences between soil structure occurred at loads greater than the precompression stress, i.e., greater than 200 kPa (Figures 2–4). Soil compressibility index was affected by soil structure ($p < 0.05$) for forest and pasture uses, where the non-preserved structure presented highest values (Table 4), i.e., the soil was more susceptible to compaction. The increase in bulk density (R^2 = 0.79 and 0.76, respectively, for preserved and non-preserved soil structure) (Figure 7a) and the degree of water saturation (R^2 = 0.78

and 0.65, respectively, for preserved and non-preserved soil structure) (Figure 6b) was associated with a decrease in the compressibility index.

Table 4. Coefficient of variation (cv) and average values of precompression stress, compressibility index, degree of water saturation and air permeability for soil with preserved (Pres) and non-preserved (NPres) structure under different land uses and layers.

Layer, m	Precompression Stress, kPa			Compressibility Index			Degree of Water Saturation, %			Air Permeability, mm h^{-1}		
	Pres	NPres	cv, %	Pres	NPres	cv, %	Pres	NPres	cv, %	Pres	NPres	cv, %
						Forest						
0.025–0.05	47.53 a	49.85 a	18.46	0.25 b	0.39 a	18.69	66.52 a	52.71 b	16.67	17.29 a	27.71 a	87.15
0.10–0.125	48.10 a	49.85 a	20.18	0.33 a	0.38 a	16.67	57.07 a	50.37 b	7.84	34.55 a	30.69 a	80.60
0.20–0.225	39.35 b	51.92 a	17.42	0.28 b	0.40 a	7.89	61.73 a	54.04 b	9.56	19.03 a	19.78 a	95.27
						Pasture						
0.025–0.05	44.56 a	38.47 a	20.31	0.21 b	0.34 a	10.51	69.62 a	64.21 a	6.74	26.09 a	10.07 a	69.75
0.10–0.125	35.53 a	35.50 a	22.58	0.22 b	0.32 a	9.83	67.39 a	62.34 a	11.93	15.09 a	10.21 a	53.41
0.20–0.225	34.42 a	40.76 a	39.80	0.25 a	0.33 a	21.35	61.94 a	60.04 a	17.74	16.10 a	14.75 a	65.28
						Eucalyptus 20						
0.025–0.05	31.24 a	35.85 a	28.57	0.60 a	0.58 a	16.43	36.65 a	33.92 a	8.58	Not determined		
0.10–0.125	42.20 a	54.40 a	32.70	0.43 a	0.45 a	26.76	45.87 a	47.98 a	29.49	192.70 a	110.99 a	78.48
0.20–0.225	46.47 a	46.62 a	27.51	0.38 a	0.45 a	15.23	50.33 a	47.42 a	13.60	66.33 a	119.39 a	67.66
						Eucalyptus 4.5						
0.025–0.05	46.00 a	38.65 a	18.27	0.18 a	0.25 a	24.57	68.45 a	67.83 a	15.84	19.16 a	7.37 a	117.84
0.10–0.125	42.27 a	34.85 a	28.26	0.21 a	0.28 a	24.41	63.23 a	59.95 a	18.08	27.53 a	17.18 a	107.33
0.20–0.225	50.92 a	39.33 a	25.42	0.21 b	0.29 a	12.01	62.02 a	61.27 a	5.11	26.35 a	9.67 a	78.51

Means followed by same letters in a given line, for each physical property, do not differ statistically from each other by Tukey's test at 5% significance.

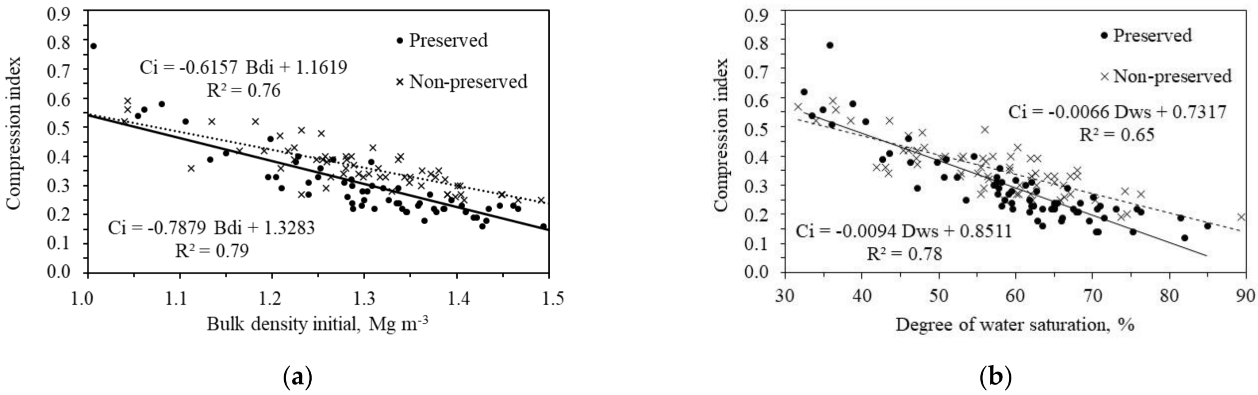

Figure 7. Regression between physical properties for soil with preserved and non-preserved structure. Bdi = bulk density in the beginning of the uniaxial compression test; Dws = degree of water saturation; Ci = compressibility index.

The degree of water saturation was affected by soil structure type (preserved and non-preserved) ($p < 0.05$) only in forest (Table 4). By decreasing macroporosity ($R^2 = 0.87$ and 0.91, respectively, for preserved and non-preserved soil structure) (Figure 8a) and increasing microporosity ($R^2 = 0.47$ and 0.71, respectively, for preserved and non-preserved soil structure) (Figure 8b), there was an increase in the degree of water saturation. Air permeability did not differ statistically ($p > 0.05$) between soil structure types (Table 4).

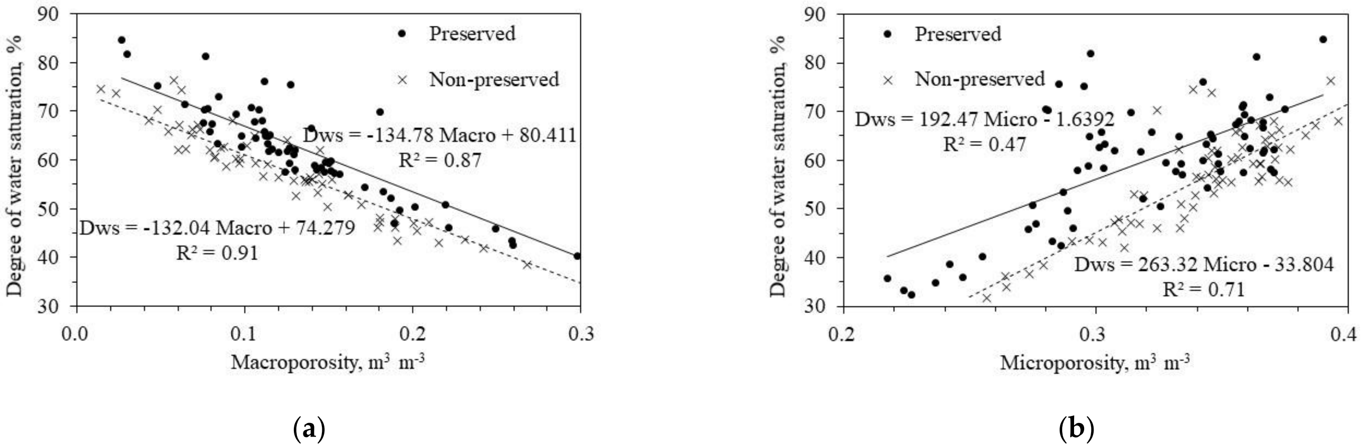

Figure 8. Regression between physical properties for soil with preserved and non-preserved structure. Macro = macroporosity; Micro = microporosity; Dws = degree of water saturation.

Increase in air permeability was associated with an exponential decrease in bulk density (Figure 9a), degree of water saturation (Figure 9b), microporosity (Figure 9d), and an increase in macropores (Figure 9c). This behavior shows that the air flow occurred mainly in the macropores. By increasing macroporosity (Figure 9c) and reducing the degree of water saturation (Figure 9b), more pores were available for air flow.

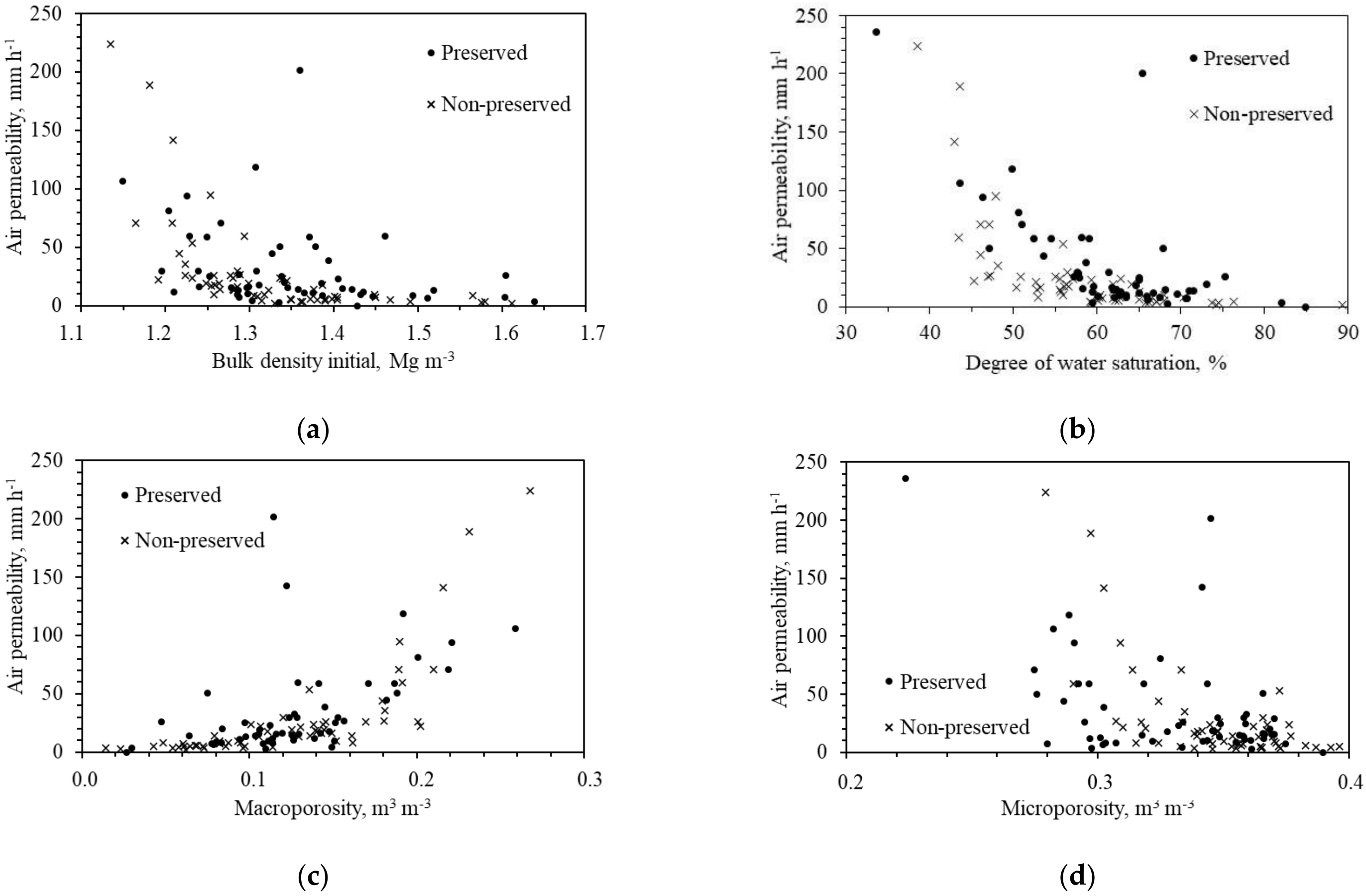

Figure 9. Regression between physical properties for soil with preserved and non-preserved structure.

Soil structure condition (preserved or not) had few influences on bulk density, macroporosity, total porosity, air permeability, and precompression stress ($p > 0.05$). However, for loads greater than the precompression stress (load greater than 200 kPa), the soil with non-preserved structure had greater deformation. The results show that compaction reduced macropores and air flow; as a consequence the soil experienced less deformation with further loading and was less susceptible to additional compaction.

4. Discussion

We observed that soil structure (preserved and non-preserved) had significant influence, especially on microporosity, compressibility index, soil deformation, and bulk density at the end of the compression test. Increasing bulk density and degree of water saturation decreased air permeability, soil deformation, macropores and compression index (Figure 10).

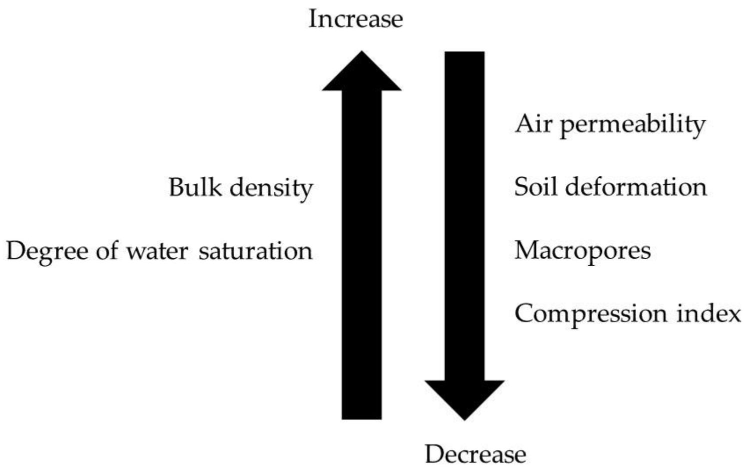

Figure 10. Scheme showing alterations on bulk density and degree of water saturation, with changes on physical and compressive properties and air permeability.

Chiseling and/or harrowing disaggregate the soil and modify the relation of mass/volume in the field [19,34,55]. In our case, in the laboratory the soil mass was the same for both preserved and non-preserved structure, justifying the similar values of bulk density and total porosity in both structural conditions. However, when the soil sample with non-preserved structure was disrupted, sieved and rearranged in the metal ring, the relation between microporosity and macroporosity was modified, with an increase in the microporosity and a decrease in the macroporosity. Pores in the soil with preserved structure were more continuous, formed by the decomposition of roots and biological activity [56,57], while pores in the soil with non-preserved structure were randomly distributed in the soil mass.

We expected greater values of precompression stress for undisturbed soil samples because of the history of loads applied by machinery traffic and animal trampling, and differences in the precompression stress values when comparing the soil structure (preserved and non-preserved), but our expectations were not confirmed. For instance, the pressure applied on the soil by forest machines and by horse-hoof can exceed 300 kPa [58]. When comparing soil tillage treatments (no-tillage, chisel plow, conventional tillage), Veiga et al. [43] obtained differences using undisturbed soil samples, but less difference in the precompression stress between treatments when using remolded soil samples, and suggested that remolding soil samples eliminates the effect of age hardening and soil aggregation.

Furthermore, in our study, we did not observe significative differences in the porosity and bulk density that could differently influence the precompression stress values when comparing preserved and non-preserved soil structure. For instance, Suzuki et al. [59] demonstrated the negative and positive correlation between precompression stress with, respectively, total porosity and bulk density, and Nunes et al. [18] showed correlation of precompression stress with macroporosity and bulk density.

Our precompression stress values (31.24 to 54.40 kPa) were low, suggesting a possible effect of mineralogy and contents of gravel and sand. The studied soil was derived from granite substrate and may have contained micas in its mineralogical composition, including in the clay fraction 1:1 clay minerals, such as kaolinite dominant in the clay fraction, and feldspars in the sand and silt fractions [60]. Horn and Lebert [61] stated that soil compressibility depends on soil strength, particle size distribution, type of clay mineral, content and type of organic substances, root distribution, soil bulk density, soil distribution, pore size and pore continuity in soil and simple aggregates, and water content and/or water potential. The resistance of the soil to decrease its volume when subjected to pressure is less pronounced in sandy soils and less aggregated. The increment in clay content increased the precompression stress, while the compression index decreased in denser soils and increased in clay soils and with higher void index, except in higher soil moisture [62]. Sandy soils retain less water on their surfaces [63–67], and present greater friction resistance between soil particles, which makes it difficult for particles to move to close-together positions [68].

Other studies [69,70] have shown higher precompression stress values (77 to 183 kPa for natural forest, annual crop and pasture areas in Oxisols, and values larger than 230 kPa for non-irrigated and irrigated grazing systems in Hapludalf) than those obtained in our study (31.24 to 54.40 kPa). However, Capurro et al. [71] showed similar values (35 to 47 kPa) in Vertissol under grazing cattle to those of our study, while Horn et al. [58] found values lower than 60 kPa in Inceptisol under forest. Suzuki et al. [59] verified precompression stress values ranging from 57.09 to 232.42 kPa depending on the sampling position (wheel line, interline planting, line planting and near the peach plant) and soil depth in a peach orchard, and that values were correlated positively with bulk density and negatively with total porosity.

As shown, there is a wide range of precompression stress values in the literature, in different soil types, use and management, and in our study the lower values may have been associated to mineralogy, gravel and sand influence. Corroborating with this suggestion, in the same site of the present study, Suzuki et al. [7] verified that soil texture (sand, silt and clay) and organic matter presented greater correlation with mean weight-diameter of aggregates than with properties related to soil structure, such as porosity and bulk density. The authors also found that, even in a small amount, gravel decreased the mean weight–diameter of aggregates because its low reactivity and greater diameter hindered the formation of stable aggregates.

A classification for precompression stress was proposed by Horn and Fleige [72], considering pF values of 1.8 and 2.5, (respectively, for soil when macropores are drained, and soil at field capacity), density and shear strength parameters. The authors classified precompression stress as very low (<30 kPa), low (30–60 kPa), medium (60–90 kPa), high (90–120 kPa), very high (120–150 kPa), and extremely high (>150 kPa). In our study, the range of precompression stress (31.24 to 54.40 kPa) was considered low according to the proposed classification.

Although the initial bulk density was equal for soil with preserved and non-preserved structure, the latter soil reached the highest values of bulk density at the end of the compression test and, consequently, the largest soil deformation. When the internal soil strength is high, the rigidity of the pore system will be more pronounced, and the more elastic the soil will be within the recompression load range [73]. As the initial bulk density increased, there was a decrease in soil deformation and macropores, making the soil less compressive. Suzuki et al. [17,59] also observed that soil with larger bulk density had smaller deformation and was less susceptible to soil compaction (larger load bearing capacity) when submitted to external loads. Powers et al. [74] observed that soil bulk density augmented with increased compaction, particularly in soils with low or moderate initial bulk density, while for soils with higher bulk density this increase was small. This behavior was attributed to the difficulty in compressing smaller pores, caused by high bulk density and pores filled with water. Soil deformation occurs when particles are able to separate and move towards each other, having their movements limited by friction and bonds between particles. Therefore, the more compact the soil and the closer the particles, the greater the friction forces, which are responsible for resistance [75].

With increasing bulk density, the soil becomes less compressive and less susceptible to compaction. Additionally, increasing the degree of water saturation increases moisture, firstly in micropores, resulting in the pore–pressure effect. Water in the micropores receives the applied load and, as the drainage of these pores is very slow, decreases soil susceptibility to compaction. Pore-pressure is the pressure exerted by water that occupies the pore space of the soil and corresponds to a force that can delay the consolidation of a cohesive soil [13].

When soil aggregates (from homogeneous via prismatic to subangular blocky and finally crumbly structure) are formed, the accessibility of particle and pore surfaces is better and maintains site productivity and biodiversity. However, soil compaction and deformation result in a platy rigid structure that is difficult for the roots to access water, ions and gas and change flux directions, and this occurs within the virgin compression stress range [4]. Mentges et al. [76] mention that the type of soil structure (prismatic, massive, for example) should be considered in studies that relate elastic parameters of soil.

Soil with non-preserved structure presented the highest values of compressibility index, while the increase in bulk density and degree of water saturation decreased the compressibility index. Other authors [17,59,77] also observed that the increase in bulk density decreased the compressibility index, while Reichert et al. showed that by increasing moisture, the compressibility index increased as well [77].

Although the types of soil structure did not show statistical differences for macroporosity and air permeability, a greater permeability was expected in samples with preserved structure due to greater pore continuity associated with the activity and root decomposition, while in samples with non-preserved structure there were possible less-continuous pores due to soil disruption and rearrangement. Mechanical deep-ploughing or soil loosening result in less dense soil layers, but they deprive soils of their internal strength and destroy pore continuity and the increased sensitivity to further soil settlement [78]. Even with lower total porosity than in conventional tillage, soil under no-tillage in agricultural areas generally conducts water more efficiently [79], due to bioporosity [57,80]. Mando et al. [56] found the efficiency of biological pores in increasing water infiltration.

We observed that increase in air permeability was associated with a decrease in bulk density, microporosity and degree of water saturation, and an increase in macropores, demonstrating that the air flow occurred mainly in the macropores; while increasing macroporosity and reducing degree of water saturation caused more pores to be available for air flow. During compaction, the larger pores responsible for soil aeration decreased and were replaced by smaller pores, mainly pores that retain water.

This decrease in aeration porosity can be 1.5–2 times greater than the decrease in total pore space. The decrease in the oxygen diffusion coefficient, however, will depend on the geometry and stability of aeration pore channels and deformation degree during compaction [81]. Horn et al. [58] found that soils with low bulk density generally have high air permeability. Soil compaction caused by a tractor changed the pore orientation that persisted two years after the traffic event in a Typic Argiudoll [82]. A long-term no-tillage (around 25 years old), increased soil bulk density and reduced air-filled porosity and macroporosity, but created a continuous and stable pore organization system, which is one of the most important properties for gas transport through soils [83].

With reduction in soil moisture, there was an increase in air permeability because of a greater amount of water-free and continuity of pores available for air flow [84,85]. Mentges et al. [84] also found that, in areas under no-tillage for annual crops, the increase in permeability is greater in sandy soils than in clayey ones. In an area with eucalyptus, the variation in soil saturated hydraulic conductivity and in air permeability was related to pore size distribution, especially for the >300 μm diameter pores [8]. When a load is applied to the soil surface, the stress is transmitted three-dimensionally through the solid, liquid and gas phases. If air permeability in the soil is high enough to allow the immediate deformation of the pores filled with air, the air flow can be interrupted by changes in water content or pore-pressure [13].

5. Conclusions

Our results contribute towards a better understanding of the relationship between soil structure, compressibility and air permeability in a Typic Paleudalf under forest, eucalyptus and pasture, with gravel and clay content ranging from 325 to 595 g kg^{-1}. Total porosity and initial soil bulk density were not influenced by soil structure (preserved and non-preserved), but the relation between macroporosity and microporosity was influenced; moreover, by increasing bulk density, there was a decrease in macropores and in deformation of soil under loading.

Precompression stress was low (<54.40 kPa) and similar between soil structure (condition preserved and non-preserved), refuting one of our hypotheses that preserved structure would have a larger precompression stress due to the history of loads applied by machinery traffic and animal trampling. Structure effect occurred for loads above the precompression stress (load larger than 200 kPa), where non-preserved structure presented a larger deformation. Compressibility index was highest for non-preserved soil under forest and pasture uses. With an increase in bulk density and degree of water saturation, the compressibility index decreased.

Air permeability was not affected by soil structure (preserved and non-preserved) in this soil with presence of gravel, and increase in air permeability was associated with a decrease in bulk density, microporosity and degree of water saturation, and increase of macropores, refuting our hypothesis since we expected lower air permeability in the loose soil due to the absence of pore continuity.

Soil structure (preserved and non-preserved) significantly influenced microporosity, compressibility index, soil deformation and bulk density at the end of the compression test.

In terms of farm management, both soil structures (preserved and non-preserved) require greater care in machinery traffic and animal trampling because of compaction susceptibility, especially for loads larger than the precompression stress, that can overcompact the soil, increasing bulk density and decreasing macroporosity and air flow. However, loose soil (non-preserved soil structure) requires more care, especially for loads greater than 200 kPa, when the soil becomes more compressive (greater deformation) than preserved structure.

Author Contributions: Conceptualization, L.E.A.S.S. and D.J.R.; formal analysis, L.E.A.S.S., D.J.R., D.S., P.T.F. and J.M.R.; investigation, L.E.A.S.S. and D.J.R.; methodology, L.E.A.S.S., D.J.R., D.S., P.T.F. and J.M.R.; resources, D.J.R.; writing—original draft, L.E.A.S.S. and D.J.R.; writing—review and editing, D.S., P.T.F. and J.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data available on request from the authors.

Acknowledgments: We thank technicians and student helpers from the "Embrapa Clima Temperado" of Pelotas-RS, for their assistance in field and laboratory tasks. We also thank Capes for the scholarship during the first author's doctorate degree (finance code 001), CNPq for research productivity grants, and landowners for allowing access to the field sites.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wienhold, B.J.; Andrews, S.S.; Karlen, D.L. Soil quality: A review of the science and experiences in the USA. *Environ. Geochem. Health* **2004**, *26*, 89–95. [CrossRef] [PubMed]
2. Mengel, K.; Kirkby, E.A.; Kosegarten, H.; Appel, T. The soil as a plant nutrient medium. In *Principles of Plant Nutrition*; Mengel, K., Kirkby, E.A., Kosegarten, H., Appel, T., Eds.; Springer: Dordrecht, The Netherlands, 2001; pp. 15–110. [CrossRef]
3. FAO—Food and Agriculture Organization of the United Nations. *Soils for Nutrition: State of the Art*; FAO: Rome, Italy, 2022; 78p. [CrossRef]
4. Mary, B.; Recous, S.; Darwis, D.; Robin, D. Interactions between decomposition of plant residues and nitrogen cycling in soil. *Plant Soil* **1996**, *181*, 71–82. [CrossRef]
5. Piano, J.T.; Egewarth, J.F.; Frandoloso, J.F.; Mattei, E.; de Oliveira, P.S.R.; Rego, C.A.R.M.; de Herrera, J.L. Decomposition and nutrients cycling of residual biomass from integrated crop-livestock system. *Aust. J. Crop Sci.* **2019**, *13*, 739–745. [CrossRef]
6. Henneron, L.; Kardol, P.; Wardle, D.A.; Cros, C.; Fontaine, S. Rhizosphere control of soil nitrogen cycling: A key component of plant economic strategies. *New Phytol.* **2020**, *228*, 1269–1282. [CrossRef] [PubMed]
7. Suzuki, L.E.A.S.; Lima, C.L.R.; Reinert, D.J.; Reichert, J.M.; Pilon, C.N. Estrutura e armazenamento de água em um Argissolo sob pastagem cultivada, floresta nativa e povoamento de eucalipto no Rio Grande do Sul. *Rev. Bras. Ciênc. Solo* **2014**, *38*, 94–106. [CrossRef]
8. Cheng, K.; Xu, X.; Cui, L.; Li, Y.; Zheng, J.; Wu, W.; Sun, J.; Pan, G. The role of soils in regulation of freshwater and coastal water quality. *Philos. Trans. R. Soc. B* **2021**, *B376*, 20200176. [CrossRef]
9. Prevedello, J.; Vogelmann, E.S.; Kaiser, D.R.; Reinert, D.J. A funcionalidade do sistema poroso do solo em floresta de eucalipto sob Argissolo. *Sci. For.* **2013**, *41*, 557–566. Available online: https://www.ipef.br/PUBLICACOES/SCIENTIA/nr100/cap13.pdf (accessed on 31 October 2022).
10. Horn, R. Soil structure formation and management effects on gas emission. *J. Agric. Mach. Sci.* **2008**, *4*, 13–18. [CrossRef]
11. Horn, R.; Blum, W.E.H. Effect of land-use management systems on coupled physical and mechanical, chemical and biological soil processes: How can we maintain and predict soil properties and functions? *Front. Agric. Sci. Eng.* **2020**, *7*, 243–245. [CrossRef]
12. Holtz, R.D.; Kovacs, W.D. *An Introduction to Geotechnical Engineering*; Prentice-Hall: Hoboken, NJ, USA, 1981.
13. Reichert, J.M.; Reinert, D.J.; Suzuki, L.E.A.S.; Horn, R. Mecânica do solo. In *Física do Solo*; van Lier, Q.J., Ed.; Sociedade Brasileira de Ciência do Solo: Viçosa, Brazil, 2010; pp. 29–102.
14. Reichert, J.M.; Reinert, J.M.; Braida, J.A. Qualidade dos solos e sustentabilidade de sistemas agrícolas. *Ciência Ambiente* **2003**, *27*, 29–48.
15. Letey, J. Relationship between soil physical conditions and crop production. *Adv. Soil Sci.* **1985**, *1*, 277–293. [CrossRef]
16. Lima, C.L.R.; Reinert, D.J.; Reichert, J.M.; Suzuki, L.E.A.S. Compressibilidade de um Argissolo sob plantio direto escarificado e compactado. *Ciênc. Rural* **2006**, *36*, 1765–1772. [CrossRef]
17. Suzuki, L.E.A.S.; Reinert, D.J.; Reichert, J.M.; Lima, C.L.R. Estimativa da suscetibilidade à compactação e do suporte de carga do solo com base em propriedades físicas de solos do Rio Grande do Sul. *Rev. Bras. Ciênc. Solo* **2008**, *32*, 963–973. [CrossRef]
18. Nunes, M.R.; Pauletto, E.A.; Denardin, J.E.; Suzuki, L.E.A.S.; van Es, H.M. Dynamic changes in compressive properties and crop response after chisel tillage in a highly weathered soil. *Soil Tillage Res.* **2019**, *186*, 183–190. [CrossRef]
19. Suzuki, L.E.A.S.; Reinert, D.J.; Fenner, P.T.; Secco, D.; Reichert, J.M. Prevention of additional compaction in eucalyptus and pasture land uses, considering soil moisture and bulk density. *J. S. Am. Earth Sci.* **2022**, *120*, 104113. [CrossRef]
20. Collares, G.L.; Reinert, D.J.; Reichert, J.M.; Kaiser, D.R. Compactação de um latossolo induzida pelo tráfego de máquinas e sua relação com o crescimento e produtividade de feijão e trigo. *Rev. Bras. Ciênc. Solo* **2008**, *32*, 933–942. [CrossRef]
21. Flores, C.A.; Reinert, D.J.; Reichert, J.M.; Albuquerque, J.A.; Pauletto, E.A. Recuperação da qualidade estrutural, pelo sistema plantio direto, de um Argissolo Vermelho. *Ciênc. Rural* **2008**, *38*, 2164–2172. [CrossRef]
22. Suzuki, L.E.A.S.; Lima, C.L.R.; Reinert, D.J.; Reichert, J.M.; Pilon, C.N. Condição estrutural de um Argissolo no Rio Grande do Sul, em floresta nativa, em pastagem cultivada e em povoamento com eucalipto. *Ciênc. Florest.* **2012**, *22*, 833–843. [CrossRef]
23. Kunz, M.; Gonçalves, A.D.M.A.; Reichert, J.M.; Guimarães, R.M.L.; Reinert, D.J.; Rodrigues, M.F. Compactação do solo na integração soja-pecuária de leite em Latossolo argiloso com semeadura direta e escarificação. *Rev. Bras. Ciênc. Solo* **2013**, *37*, 6. [CrossRef]
24. Prevedello, J.; Kaiser, D.R.; Reinert, D.J.; Vogelmann, E.S.; Fontanela, E.; Reichert, J.M. Manejo do solo e crescimento inicial de Eucalyptus grandis Hill ex Maiden em Argissolo. *Ciênc. Florest.* **2013**, *23*, 129–138. [CrossRef]
25. Prevedello, J.; Vogelmann, E.S.; Kaiser, D.R.; Fontanela, E.; Reinert, D.J.; Reichert, J.M. Agregação e matéria orgânica de um Argissolo sob diferentes preparos do solo para plantio de Eucalipto. *Pesq. Florest. Bras.* **2014**, *34*, 149–158. [CrossRef]
26. Reichert, J.M.; Bervald, C.M.P.; Rodrigues, M.F.; Kato, O.R.; Reinert, D.J. Mechanized land preparation in eastern Amazon in fire-free forest-based fallow systems as alternatives to slash-and-burn practices: Hydraulic and mechanical soil properties. *Agric. Ecosyst. Environ.* **2014**, *192*, 47–60. [CrossRef]
27. Suzuki, L.E.A.S.; Reichert, J.M.; Reinert, D.J.; de LIMA, C.L.R. Degree of compactness and mechanical properties of a subtropical Alfisol with eucalyptus, native forest, and grazed pasture. *Forest. Sci.* **2015**, *61*, 716–722. [CrossRef]
28. Reichert, J.M.; Brandt, A.A.; Rodrigues, M.F.; da Veiga, M.; Reinert, D.J. Is chiseling or inverting tillage required to improve mechanical and hydraulic properties of sandy clay loam soil under long-term no-tillage? *Geoderma* **2017**, *301*, 72–79. [CrossRef]

29. Holthusen, D.; Brandt, A.A.; Reichert, J.M.; Horn, R. Soil porosity, permeability and static and dynamic strength parameters under native forest/grassland compared to no-tillage cropping. *Soil Tillage Res.* **2018**, *177*, 113–124. [CrossRef]
30. Holthusen, D.; Brandt, A.A.; Reichert, J.M.; Horn, R.; Fleige, H.; Zink, A. Soil functions and in situ stress distribution in subtropical soils as affected by land use, vehicle type, tire inflation pressure and plant residue removal. *Soil Tillage Res.* **2018**, *184*, 78–92. [CrossRef]
31. Reichert, J.M.; Fontanela, E.; Awe, G.O.; Fasinmirin, J.T. Is cassava yield affected by inverting tillage, chiseling or additional compaction of no-till sandy-loam soil? *Rev. Bras. Ciênc. Solo* **2021**, *45*, e0200134. [CrossRef]
32. Reichert, J.M.; Morales, C.A.S.; Lima, E.M.; Bastos, F.; Sampietro, J.A.; Araújo, E.F.; Srinivasan, R. Best tillage practices for early-growth of clonal eucalyptus in soils with distinct granulometry, drainage and profile depth. *Soil Tillage Res.* **2021**, *212*, 105038. [CrossRef]
33. França, J.S.; Reichert, J.M.; Holthusen, D.; Rodrigues, M.F.; Araújo, E.F. Subsoiling and mechanical hole-drilling tillage effects on soil physical properties and initial growth of eucalyptus after eucalyptus on steeplands. *Soil Tillage Res.* **2021**, *207*, 104860. [CrossRef]
34. Suzuki, L.E.A.S.; Reinert, D.J.; Alves, M.C.; Reichert, J.M. Medium-term no-tillage, additional compaction, and chiseling as affecting clayey subtropical soil physical properties and yield of corn, soybean and wheat crops. *Sustainability* **2022**, *14*, 9717. [CrossRef]
35. Nunes, M.R.; Denardin, J.E.; Pauletto, E.A.; Faganello, A.; Pinto, L.F.S. Effect of soil chiseling on soil structure and root growth for a clayey soil under no-tillage. *Geoderma* **2015**, *259–260*, 149–155. [CrossRef]
36. Suzuki, L.E.A.S.; Reinert, D.J.; Alves, M.C.; Reichert, J.M. Critical limits for soybean and black bean root growth, based on macroporosity and penetrability, for soils with distinct texture and management systems. *Sustainability* **2022**, *14*, 2958. [CrossRef]
37. Habibbeygi, F.; Nikraz, H.; Verheyde, F. Determination of the compression index of reconstituted clays using intrinsic concept and normalized void ratio. *Int. J. Geotec. Const. Mat. Env.* **2017**, *13*, 54–60. [CrossRef]
38. Ma, J.; Qian, M.; Yu, C.; Yu, X. Compressibility evaluation of reconstituted clays with various initial water contents. *J. Perform. Constr. Facil.* **2018**, *32*, 04018077. [CrossRef]
39. Xu, B.; Zhang, N. Determination of compression curve of in-situ soil considering soil disturbance. *Adv. Eng. Res.* **2018**, *162*, 213–216. [CrossRef]
40. Oluwaseun, A.A.; Yinusa, A.A.; Siyan, M. Compressibility characteristics of remoulded residual soils under loading. *J. Appl. Geol. Geophys.* **2018**, *6*, 52–57. [CrossRef]
41. Zhang, C.; Liu, E.; Tang, Y. Investigation on mechanical properties of artificially structured soils under different stress paths. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *267*, 042089. [CrossRef]
42. Zheng, J.; Yang, Z.; Gao, H.; Lai, X.; Wu, X.; Huang, Y. Experimental study on microstructure characteristics of saturated remolded cohesive soil during consolidation. *Sci. Rep.* **2022**, *12*, 18378. [CrossRef]
43. Veiga, M.; Horn, R.; Reinert, D.J.; Reichert, J.M. Soil compressibility and penetrability of an Oxisol from southern Brazil, as affected by long-term tillage systems. *Soil Tillage Res.* **2007**, *92*, 104–113. [CrossRef]
44. Somar Meteorologia. Médias Climatológicas de Butia. Available online: https://irga.rs.gov.br/medias-climatologicas (accessed on 5 May 2022).
45. Soil Survey Staff. *Keys to Soil Taxonomy*, 12th ed.; USDA-Natural Resources Conservation Service: Washington, DC, USA, 2014. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/taxonomy/?cid=nrcs142p2_053580 (accessed on 8 December 2021).
46. IUSS Working Group WRB. *World Reference Base for Soil Resources 2014, Update 2015 International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*; World Soil Resources Reports No. 106; FAO: Rome, Italy, 2015.
47. Santos, H.G.; Jacomine, P.K.T.; Anjos, L.H.; Oliveira, V.A.; Lumbreras, J.F.; Coelho, M.R.; Almeida, J.A.; Araujo Filho, J.C.; Oliveira, J.B.; Cunha, T.J.F. *Sistema Brasileiro de Classificação de Solos*; E-book: Il. Color; Embrapa: Brasília, Brazil, 2018; Available online: https://www.embrapa.br/solos/sibcs (accessed on 5 October 2022).
48. Pilon, C.N.; Santos, D.C.; Lima, C.L.R.; Antunes, L.O. Carbono e nitrogênio de um Argissolo Vermelho sob floresta, pastagem e mata nativa. *Ciênc. Rural* **2011**, *41*, 447–453. [CrossRef]
49. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. (Eds.) *Manual de Métodos de Análise de Solo*, 3rd ed.; e-Book: Il. Color.; Embrapa: Brasília, Brazil, 2017; 212p. Available online: http://www.infoteca.cnptia.embrapa.br/infoteca/handle/doc/1085209 (accessed on 10 November 2021).
50. Gubiani, P.I.; Reinert, J.; Reichert, J.M. Método alternativo para a determinação da densidade de partículas do solo—Exatidão, precisão e tempo de processamento. *Ciênc. Rural* **2006**, *36*, 664–668. [CrossRef]
51. Klute, A. Water retention: Laboratory methods. In *Methods of Soil Analysis: Physical and Mineralogical Methods*, 2nd ed.; Klute, A., Ed.; American Society of Agronomy and Soil Science Society of America: Madison, WI, USA, 1986; pp. 635–660.
52. Silva, V.R.; Reinert, D.J.; Reichert, J.M. Suscetibilidade à compactacão de um latossolo vermelho-escuro e de um podzólico vermelho-amarelo. *Rev. Bras. Ciênc. Solo* **2000**, *24*, 239–249. [CrossRef]
53. Rosa, D.P.; Reichert, J.M.; Lima, E.M.; Rosa, V.T. Chiselling and wheeling on sandy loam long-term no-tillage soil: Compressibility and load bearing capacity. *Soil Res.* **2021**, *59*, 488–500. [CrossRef]
54. Casagrande, A. The determination of the pre-consolidation load and its practical significance. In Proceedings of the International Conference on Soil Mechanics and Foundation Engineering; Harvard University: Cambridge, MA, USA, 1936; pp. 60–64.

55. Alves, M.C.; Suzuki, L.E.A.S.; Hipólito, J.L.; Castilho, S.R. Propriedades físicas e infiltração de água de um Latossolo Vermelho Amarelo (Oxisol) do noroeste do estado de São Paulo, Brasil, sob três condições de uso e manejo. *Cad. Lab. Xeolóxico Laxe* **2005**, *30*, 167–180. Available online: https://ruc.udc.es/dspace/bitstream/handle/2183/6311/CA-30-10.pdf?sequence=1&isAllowed=y (accessed on 31 October 2022).
56. Mando, A.; Stroosnijder, L.; Brussaard, L. Effects of termites on infiltration into crusted soil. *Geoderma* **1996**, *74*, 107–113. [CrossRef]
57. Abreu, S.L.; Reichert, J.M.; Reinert, D.J. Escarificação mecânica e biológica para a redução da compactação em argissolo franco-arenoso sob plantio direto. *Rev. Bras. Ciênc. Solo* **2004**, *28*, 519–531. [CrossRef]
58. Horn, R.; Vossbrink, J.; Becker, S. Modern forestry vehicles and their impacts on soil physical properties. *Soil Tillage Res.* **2004**, *79*, 207–219. [CrossRef]
59. Suzuki, L.E.A.S.; Reisser Júnior, C.; Miola, E.C.C.; Rostirolla, P.; Strieder, G.; Scherer, V.S.; Pauletto, E.A. Variabilidade da compressibilidade e do grau de compactação de um Argissolo cultivado com pessegueiro. *Sci. Rural* **2021**, *23*, 60–75. Available online: http://www.cescage.com.br/revistas/index.php/ScientiaRural/article/view/1642 (accessed on 31 October 2022).
60. Castro, P.P.; Curi, N.; Furtini Neto, A.E.; Resende, Á.V.; Guilherme, L.R.G.; Menezes, M.D.; Araújo, E.F.; Freitas, D.A.F.; Mello, C.R.; Silva, S.H.G. Química e mineralogia de solos cultivados com Eucalipto (*Eucalyptus* sp.). *Sci. For.* **2010**, *38*, 645–657. Available online: http://www.bibliotecaflorestal.ufv.br:80/handle/123456789/16762 (accessed on 31 October 2022).
61. Horn, R.; Lebert, M. Soil compactability and compressibility. In *Soil Compaction in Crop Production*; Soane, B.D., van Ouwerkerk, C., Eds.; Elsevier: Amsterdam, The Netherlands, 1994; pp. 45–69.
62. Braga, F.V.A.; Reichert, J.M.; Mentges, M.I.; Vogelmann, E.S.; Padrón, R.A.R. Propriedades mecânicas e permeabilidade ao ar em topossequência Argissolo-Gleissolo: Variação no perfil e efeito de compressão. *Rev. Bras. Ciênc. Solo* **2015**, *39*, 1025–1035. [CrossRef]
63. Vaz, C.M.P.; Freitas Iossi, M.; Mendonça Naime, J.; Macedo, Á.; Reichert, J.M.; Reinert, D.J.; Cooper, M. Validation of the Arya and Paris water retention model for Brazilian soils. *Soil Sci. Soc. Am. J.* **2005**, *69*, 577–583. [CrossRef]
64. Klein, V.A.; Reichert, J.M.; Reinert, D.J. Água disponível em um Latossolo Vermelho argiloso e murcha fisiológica de culturas. *Rev. Bras. Eng. Agrícola Ambient.* **2006**, *10*, 646–650. [CrossRef]
65. Awe, G.O.; Reichert, J.M.; Timm, L.C.; Wendroth, O.O. Temporal processes of soil water status in a sugarcane field under residue management. *Plant Soil* **2015**, *387*, 395–411. [CrossRef]
66. Reichert, J.M.; Albuquerque, J.A.; Kaiser, D.R.; Reinert, D.J.; Urach, F.L.; Carlesso, R. Estimation of water retention and availability in soils of Rio Grande do Sul. *Rev. Bras. Ciênc. Solo* **2009**, *33*, 1547–1560. [CrossRef]
67. Reichert, J.M.; Albuquerque, J.A.; Solano Peraza, J.E.; Costa, A. Estimating water retention and availability in cultivated soils of southern Brazil. *Geoderma Reg.* **2020**, *21*, e00277. [CrossRef]
68. Lima, C.L.R.; Silva, A.P.; Imhoff, S.; Lima, H.V.; Leão, T.P. Heterogeneidade da compactação de um Latossolo Vermelho-Amarelo sob pomar de laranja. *Rev. Bras. Ciênc. Solo* **2004**, *28*, 409–414. [CrossRef]
69. Kondo, M.K.; Dias Junior, M.S. Compressibilidade de três Latossolos em função da umidade e uso. *Rev. Bras. Ciênc. Solo* **1999**, *23*, 211–218. [CrossRef]
70. Lima, C.L.R.; Silva, A.P.; Imhoff, S.; Leão, T.P. Compressibilidade de um solo sob sistemas de pastejo rotacionado intensivo irrigado e não irrigado. *Rev. Bras. Ciênc. Solo* **2004**, *28*, 945–951. [CrossRef]
71. Capurro, E.P.G.; Secco, D.; Reichert, J.M.; Reinert, D.J. Compressibilidade e elasticidade de um Vertissolo afetado pela intensidade de pastejo bovino. *Ciênc. Rural* **2014**, *44*, 283–288. [CrossRef]
72. Horn, R.; Fleige, H. A method for assessing the impact offload on mechanical stability and on physical properties of soils. *Soil Tillage Res.* **2003**, *73*, 89–99. [CrossRef]
73. Horn, R. Effect of land-use management systems on coupled hydraulic mechanical soil processes defining the climate-food-energy-water nexus. *Bulg. J. Soil Sci.* **2019**, *4*, 3–15. Available online: https://www.bsss.bg/issues/Issue1_2019/BJSS_2019_1_1.pdf (accessed on 31 October 2022).
74. Powers, R.F.; Scott, D.A.; Sanchez, F.G.; Voldseth, R.A.; Page-Dumroese, D.; Elioff, J.D.; Stone, D.M. The North American long-term soil productivity experiment: Findings from the first decade of research. *For. Ecol. Manag.* **2005**, *220*, 31–50. [CrossRef]
75. Guérif, J. Effects of compaction on soil strength parameters. In *Soil Compaction in Crop Production*; Soane, B.D., van Ouwerkerk, C., Eds.; Elsevier: Amsterdam, The Netherlands, 1994; pp. 191–214.
76. Mentges, M.I.; Reichert, J.M.; Gubiani, P.I.; Reinert, D.J.; Xavier, A. Alterações estruturais e mecânicas de solo de várzea cultivado com arroz irrigado por inundação. *Rev. Bras. Ciênc. Solo* **2013**, *37*, 221–231. [CrossRef]
77. Reichert, J.M.; Mentges, M.I.; Rodrigues, M.F.; Cavalli, J.P.; Awe, G.O.; Mentges, L.R. Compressibility and elasticity of subtropical no-till soils varying in granulometry organic matter, bulk density and moisture. *Catena* **2018**, *165*, 345–357. [CrossRef]
78. Horn, R.; Mordhorst, A.; Fleige, H.; Zimmermann, I.; Burbaum, B.; Filipinski, M.; Cordsen, E. Soil type and land use effects on tensorial properties of saturated hydraulic conductivity in northern Germany. *Eur. J. Soil Sci.* **2020**, *71*, 179–189. [CrossRef]
79. Wu, L.; Swan, J.B.; Paulson, W.H.; Randalla, G.W. Tillage effects on measured soil hydraulic- properties. *Soil Tillage Res.* **1992**, *25*, 17–33. [CrossRef]
80. Costa, F.S.; Albuquerque, J.A.; Bayer, C.; Fontoura, S.M.V.; Wobeto, C. Propriedades físicas de um Latossolo Bruno afetadas pelos sistemas plantio direto e preparo convencional. *Rev. Bras. Ciênc. Solo* **2003**, *27*, 527–535. [CrossRef]
81. Boone, F.R.; Veen, B.W. Mechanisms of crop responses to soil compaction. In *Soil Compaction in Crop Production*; Soane, B.D., van Ouwerkerk, C., Eds.; Elsevier: Amsterdam, The Netherlands, 1994; pp. 237–264.

82. Soracco, C.G.; Lozano, L.A.; Villarreal, R.; Palancar, T.C.; Collazo, D.J.; Sarli, G.O.; Filgueira, R.R. Effects of compaction due to machinery traffic on soil pore configuration. *Rev. Bras. Ciênc. Solo* **2015**, *39*, 408–415. [CrossRef]
83. Talukder, R.; Plaza-Bonilla, D.; Cantero-Martínez, C.; Wendroth, O.; Castel, J.L. Soil gas diffusivity and pore continuity dynamics under different tillage and crop sequences in an irrigated Mediterranean area. *Soil Tillage Res.* **2022**, *221*, 105409. [CrossRef]
84. Mentges, M.I.; Reichert, J.M.; Rodrigues, M.F.; Awe, G.O.; Mentges, L.R. Capacity and intensity soil aeration properties affected by granulometry, moisture, and structure in no-tillage soils. *Geoderma* **2016**, *263*, 47–59. [CrossRef]
85. Ambus, J.V.; Reichert, J.M.; Gubiani, P.I.; Carvalho, P.C.F. Changes in composition and functional soil properties in long-term no-till integrated crop-livestock system. *Geoderma* **2018**, *330*, 232–243. [CrossRef]