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Soil Penetration Resistance Influenced by Eucalypt Straw Management under Mechanized Harvesting

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Abstract: This study aimed to evaluate the impacts of mechanized harvesting and soil tillage on soil penetration resistance (PR), influenced by the eucalypt straw management under sandy clay Oxisol in Southern Brazil. The study was conducted in a eucalyptus production area under Oxisol in Paraná State, Brazil. The treatments consisted of two harvesting systems: harvester + forwarder (HF) and feller + skidder (FS) both applied in areas under coppicing and stand renewal eucalypt cultivation systems. For stand renewal areas, eucalypt straw was managed on the soil surface at levels of 100, 50, and 0% before soil tillage. PR and soil moisture measurements were made in points distributed in regular grid for all treatments. This grid also was used to evaluate the geospatial behavior of PR in the stand renewal areas. During the measuring of PR, the averages ($\pm$ confidence interval) of soil moisture up to 0–0.60 m depth were 0.20 $\pm$ 0.01 and 0.24 $\pm$ 0.01 in coppicing and stand renewal areas, respectively. In areas under coppicing, the PR mean $\pm$ confidence interval at 0–0.05 m layer in HF (1.28 $\pm$ 0.24 MPa) was lower than in FS treatment (2.11 $\pm$ 0.44 MPa). However, the PR values were similar between treatments in stand renewal areas, regardless of the forest straw level on the soil surface. For both harvesting systems, there was a lack of spatial dependence of PR up to 0.40 m soil depth, indicating some physical and mechanical homogenization induced by the soil tillage in the layer. Eucalypt straw contributed to mitigating effects of harvest traffic on PR level in coppicing forest systems. However, different levels of eucalypt straw managed before soil tillage did not influence PR levels in stand renewal forest systems.

Keywords: coppicing system; geostatistics; forest soils; soil compaction; soil tillage

1. Introduction

Planted forests occupy 9.93 million hectares, approximately 1.2% of the Brazilian territory, and are responsible for 91% of the wood for the industry. Eucalyptus plantation has stood out for its yield average of 36.8 m^3 ha^{-1} $year^{-1}$ in 2021 [1], with a harvesting cycle lasting less than seven years, which has intensified the mechanization use in soils under forest production [2]. However, the practices used for harvesting and transporting operations frequently do not consider the potential risk of soil compaction [3] and its distribution in depth [4]. Monitoring the impact of the mechanized operations on soil physical quality could reduce the risk of its compaction and enhance planted forest production and environmental protection.

In planted forest production, soil physical quality degradation can be intensified by the mechanical cutting of trees and dragging and lifting logs, requiring machines with large masses and sizes [5]. In addition, the heterogeneous pattern of the machine traffic across the field increases the physical disturbance in the soil surface, which can also affect deeper soil layers [4,6]. Thus, these changes in soil physical properties increased bulk density and resistance to root penetration and decreased macroporosity, water infiltration, and airflow, resulting in non-uniform stands and lower yields of forest species [7,8].

Mainly in stand renewal areas, soil tillage is carried out to mitigate compaction and create a suitable physical environment for root development [9,10], succeeding the subsequent management practices. In areas with high forest straw production, it is necessary to remove part or total of the forest straw to facilitate the displacement of machinery equipment and, consequently, increase their operational performance [11]. Although the deposition of forest straw on the soil surface contributes to attenuating the impacts of machinery traffic, cumulative effects of removal practices before soil tillage are not well known yet [2,12,13].

Many soil physical properties such as those mentioned above have been used to characterize and quantify the effects of forest management practices. Between them, soil penetration resistance (PR) is widely used as an indicator of soil compaction due to the relatively easy measurement in the field and being correlated with dendrometric variables (e.g., wood volume, diameter at breast height, total height, etc.). Therefore, there is a critical PR value, above which roots growth is strongly limited, and can be used as an indicator of soil physical quality under forest management systems. PR > 3 MPa have been reported as restrictive for the growth of roots of *Pinus sp* [14] and may reach 4.5 MPa [15] for eucalyptus. PR values between 2 and 3 MPa have been considered limiting for other forest species (e.g., *Alnus cordata*, *Betula pendula*, and *Larix kaempferi*) [16]. Such variations occurred because of the differences between species and edaphic conditions [17,18]. However, it is known that root growth rate decreases exponentially with the increment in PR, and root development can be affected, depending on the magnitude and intensity with which plants are subjected to the effects of the resistance [19].

Although the RP measurement is relatively straightforward, the soil moisture variation across the areas can negatively affect its results due to an inverse relationship between these variables [20,21]. However, PR measurement should be performed under homogenous soil moisture conditions, preferentially close to the soil field capacity [21,22]. Additionally, the geospatial evaluation of PR can allow the identification of compacted sites for specific management operations [23,24]. Such detailed PR information can improve soil physical quality evaluation in mechanized planted forest areas [24–26].

In this study, we evaluate the impact of mechanized operations (harvesting and soil tillage) on soil compaction measured by PR in eucalypt plantation harvested using two different methods (harvester + forwarder and feller + skidder), both applied to coppicing and stand renewal with eucalypt straw managed on the soil surface. We hypothesized that eucalypt straw permanence on the soil surface can reduce the effect of the harvesting traffic and tillage on soil compaction measured by PR. The objective was to evaluate the impacts of the mechanized harvesting and soil tillage on PR, influenced by the eucalypt straw management under sandy clay Oxisol in Southern Brazil.

2. Materials and Methods

2.1. Experimental Area and Treatments

The experimental area under eucalyptus plantation was located at Monte Alegre Farm (Block BRM-J9A), belonging to the Klabin Company, in the Telêmaco Borba county, Paraná, Southern Brazil (24°18′15″ S, 50°36′39″ W, ~770 m above sea level) (Figure 1a). According to Köppen's classification, the climate of the region is Cfa and Cfb, a subtropical climate characterized by hot summers, infrequent frost, and a trend of rainfall concentration in the summer months. The average annual rainfall is between 1400 and 1600 mm, respectively [27]. The dominant soil is classified as an Oxisol, according to [28]. The relief is classified as gently undulating. The soil chemical and particle-size distribution characterization for the experimental area are shown in Table 1.

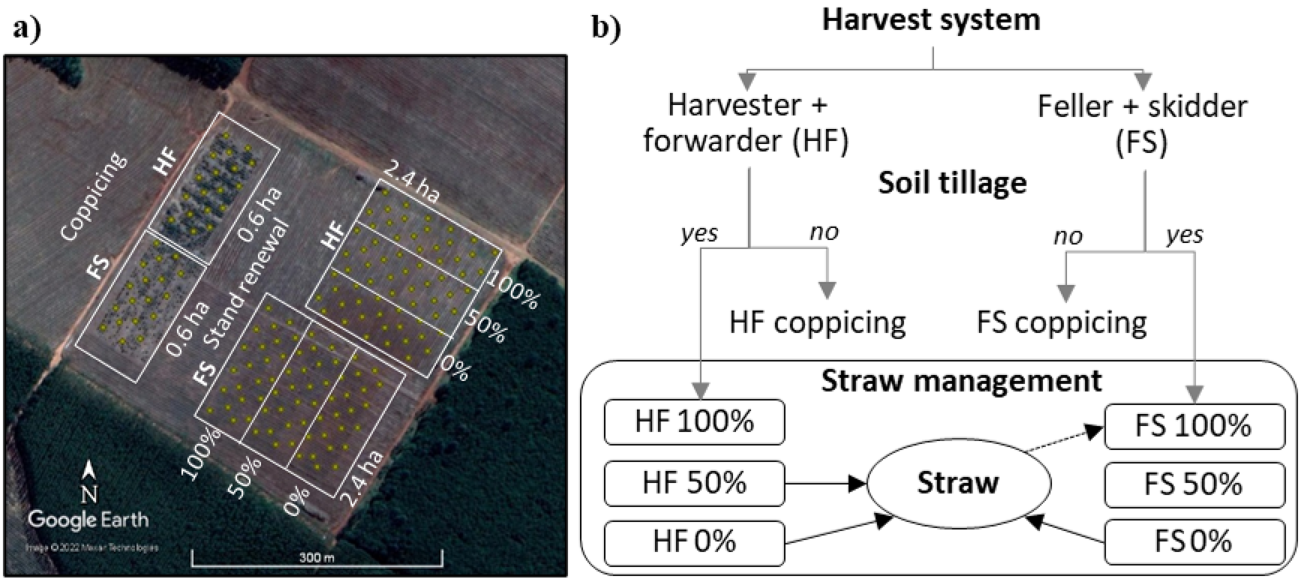

Figure 1. (**a**) Location of the harvester + forwarder (HF) and feller + skidder (FS) treatments in coppicing areas and stand renewed areas with different eucalypt straw levels (100, 50 and 0%). Yellow dots represent the place of soil penetration resistance measurements. (**b**) Flowchart illustrating the scheme of treatments. The solid and dashed black arrows indicate that the eucalypt straw was removed or added before soil tillage in renewal areas, respectively.

The experimental area has had a history of use with commercial stands of forests for approximately 30 years, with eucalyptus plantation with a cycle of 20 years and modified to eight-year cycles from September 2008. The last forest stand had been harvested in November 2016 and was composed of hybrids that originated from the cross between *Eucalyptus grandis x Eucalyptus urophylla*, clone 12/52. The spacing was 2.50 m between plants and 3.50 m between rows, totaling 1142 trees ha^{-1}. This stand had the following indicators: average canopy height of 19.50 m, average diameter at breast height of 0.16 m, and average annual increment at seven years of 65 m^3 ha^{-1} year^{-1}. Then, on March 16, 2017, a new planting was carried out using eucalyptus seedlings, clone I-144, at a spacing of 1.82 m between plants and 3.30 m between rows, totaling 1666 trees ha^{-1}.

The experiment was set up to represent two eucalypt harvesting systems: harvester + forwarder (HF) and feller + skidder (FS) applied to coppicing and stand renewal cultivation systems with straw management on the soil surface (Figure 1a). In the coppicing area, the soil tillage was not used and the level of eucalypt straw kept on the soil surface was the same as after harvesting. In the HF, there was an accumulation of eucalypt straw (bark, branches, leaves, tips, etc.), while for FS there was no accumulation of eucalypt straw on the soil surface. For stand renewal areas, the level of eucalypt straw was managed before the soil tillage considering differences in relation to the amount of straw, establishing the maintenance of approximately 100, 50, and 0% of forest straw on the soil surface (Figure 1b). For HF, 100% represents the eucalypt straw produced at harvest that was kept along with the remaining forest litter; 50% represents partial removal of straw produced at harvest along with the remaining forest litter; 0% refers to the total removal of eucalypt straw but keeping the remaining forest litter. In the FS, 100% refers to the eucalypt straw produced outside the plot (tips), which were returned to the area and spread on the remaining forest litter; 50% corresponded to the permanence of the remaining forest litter, and 0% represented the total removal of the forest litter (Figure 1b). After eucalypt straw management (removal or addition), the soil tillage was carried out by subsoiling down to 0.50 m depth using a bulldozer equipped with a subsoiler.

Table 1. Soil chemical characterization and particle-size distribution at the 0–0.20, 0.20–0.40 and 0.40–0.60 m layers, in eucalypt cultivation areas under coppicing and stand renewal with different straw levels (100, 50 and 0%), both harvested by harvester + forwarder (HF) and feller + skidder (FS) systems.

	Chemical Attributes ς								Particle Size Distribution			
Layers	**pH (H_2O)**	**P**	**K^+**	**Ca^{2+}**	**Mg^{2+}**	**Al^{3+}**	**H + Al**	**SOM §**	**Clay**	**Silt**	**Fine Sand**	**Coarse Sand**
(m)		**mg dm^{-3}**		**cmolc dm^{-3}**				**dag kg^{-1}**	**kg kg^{-1}**			
						Coppicing areas						
						harvester + forwarder						
0.00–0.20	4.4	2.2	23.0	0.31	0.39	2.06	10.20	3.63	0.32	0.11	0.30	0.26
0.20–0.40	4.2	1.3	8.0	0.00	0.12	1.67	6.30	1.75	0.32	0.11	0.29	0.25
0.40–0.60	4.2	1.1	4.0	0.02	0.12	1.47	6.00	1.48	0.30	0.12	0.31	0.27
						feller + skidder						
0.00–0.20	4.2	2.0	27.0	0.19	0.14	2.65	9.50	4.03	0.33	0.09	0.29	0.27
0.20–0.40	4.2	1.3	8.0	0.03	0.07	2.06	7.90	2.55	0.27	0.14	0.31	0.27
0.40–0.60	4.1	1.3	6.0	0.01	0.07	1.96	8.90	2.28	0.23	0.19	0.33	0.28
						Stand renewal areas δ						
						harvester + forwarder						
0.00–0.20	5.0	2.1	47.0	2.49	0.54	0.59	8.90	3.76	0.28	0.10	0.36	0.26
0.20–0.40	4.8	1.8	23.0	2.44	0.45	0.49	7.30	3.49	0.30	0.09	0.34	0.26
0.40–0.60	4.5	1.4	15.0	0.52	0.16	1.18	6.50	2.02	0.31	0.11	0.32	0.26
						feller + skidder						
0.00–0.20	4.3	1.6	15.0	0.23	0.13	1.76	9.10	3.09	0.35	0.06	0.27	0.32
0.20–0.40	4.2	1.4	12.0	0.18	0.09	1.76	8.60	2.42	0.37	0.07	0.27	0.29
0.40–0.60	4.1	1.0	6.0	0.02	0.06	1.57	7.90	2.28	0.39	0.07	0.26	0.28

ς Methods described in [29]. § SOM: Soil organic matter. δ The soil chemical and particle-size distribution characterization in stand renewal areas was done without considering the individual treatments of eucalypt straw level. Additionally, the complete soil particle-size distribution data considering the individual treatments of eucalypt straw level is available in the supplemental material (Table S1).

Thus, the treatments established consisted of two harvesting systems: harvester + forwarder and feller + skidder, both applied in coppicing and stand renewal areas with eucalypt straw level (100, 50, and 0%) managed before soil tillage, as described in Figure 1b.

2.2. Soil Sampling

The sampling for soil penetration resistance (PR) measurements was performed between July 15 and 30, 2017, approximately 240 days after harvest and 120 days after soil tillage. Measurements of PR were taken by adopting a systematic sampling scheme with readings in quadruplicates of 22 sampling points defined by the vertices of isosceles triangles (15 m of height and 30 m of base) demarcated in the experimental area (Figure 2). Each triangle had an area of 225 m^2, and the sampling encompassed planting rows and between rows, alternately. In the areas of stand renewal, a grid of 66 points formed by the union of the 22 points of each one of the three straw levels (100, 50, and 0%), in both harvesting systems (HF and FS), was used to study the geospatial behavior of PR (Figure 1a).

Penetration resistance measurements were taken up to 0.60 m depth using a digital electronic penetrometer (penetroLOG/PLG1020) with a constant speed of approximately 30 mm s^{-1}. In 50% of the PR sampling points, alternately selected, disturbed samples were taken for the determination of soil moisture, chemical, and particle-size distribution characterization. The samples were collected from the center of the 0–0.20, 0.20–0.40, and 0.40–0.60 m soil depth layers, using a Dutch auger. The gravimetric soil water content was determined by drying disturbed samples in an oven at 105 °C for 48 h, according to [29]. The sampling points were georeferenced with a Leica GS14 GNSS receiver, set in the metric coordinate system (UTM), Zone 22s, and Datum Sirgas2000.

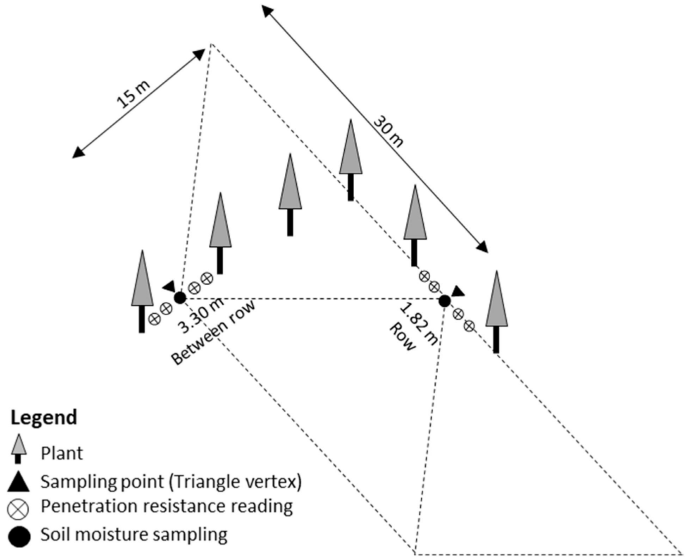

Figure 2. Sampling scheme for penetration resistance (PR) and soil moisture in coppicing and stand renewed with different straw levels 100, 50 and 0% areas, both preceded by eucalyptus harvest with Harvester + Forwarder (HF) and Feller + Skidder (FS). Sampling points are defined by the vertices of isosceles triangles (15 m of height and 30 m of base).

2.3. Statistical Analyses

All statistical analyzes were performed using R software [30]. The confidence intervals (CI) to means were calculated for the variables with a confidence level of 90% [31]. The coefficient of variation (CV%) was calculated and classified as: low (CV < 15%), medium ($15 \geq$ CV $\leq 50\%$), and high (CV > 50%) [32]. Data distribution normality was also tested using the Shapiro-Wilk test ($p > 0.05$). The correlation between PR and soil moisture was verified by the Student's t-test at a 95% confidence level using PR averages every 0.20 m in the profile.

The PR average of each 0.20 m soil depth layer was also used for the geospatial evaluation in the stand renewal areas. The data distribution asymmetry was calculated and classified according to the coefficient of asymmetry (As): asymmetric ($|As| < 0.15$), moderate ($0.15 < |As| < 1.0$), and strong ($|As| > 1.0$). As for the shape of the distribution curve (tailedness), it was classified according to the coefficient of kurtosis (Ks): mesokurtic (Ks = 0), platykurtic (Ks< 0), and leptokurtic (Ks > 0) [33]. Geostatistical analysis was performed using the R functions available in the gstat package. The semivariances were calculated according to the equation [31]: $\gamma(h) = 1/2N(h)\sum_{i=1)}^{N(h)}[\{Z(x_i+h) - Z(x_i)\}]^2$; where $\gamma(h)$ is the semivariance for the interval class h; $N(h)$ is the number of experimental pairs of observation; and $Z(x_i)$ and Z $(x_i + h)$ are the values of attributes measured at the positions x_i and $xi + h$, separated by a vector h (distance between samples). From the semivariances analysis, the following parameters were obtained: range (A_o), nugget effect (C_o), and sill (C), which were used to evaluate the degree of spatial dependence of the variable, by calculating the index of spatial dependence (SD), according to the expression: SD = $[C_o/(C + C_o)] * 100$, being classified as strong (SD $\leq$ 25%), moderate (25% < SD $\leq$ 75%), and weak (SD > 75%) [34].

3. Results and Discussion

3.1. Soil Moisture Conditions for Penetration Resistance Sampling

In coppicing areas, during the measure of PR the soil moisture averages ($\pm$ confidence interval) were 0.21 ± 0.02 and 0.20 ± 0.01 kg kg^{-1} in the soil profile (0–0.60 m depth layer), for harvester + forwarder (FS) and feller + skidder (FS) treatments, respectively; being statistically similar (Table 2). The averages of soil moisture (0–0.60 m depth layer) were also similar between the harvest treatments in the stand renewal areas, being equal to

0.23 ± 0.01 and 0.25 ± 0.01 kg kg^{-1}, for HF and FS treatments, respectively (Table 2). The CVs were classified as medium and low (15.92 and 9.60%) in the areas of coppicing and stand renewal, respectively (Table 2). Similar moisture conditions between treatments were due to the period of rainfalls before the sampling in the areas. Precipitation data is available in the supplementary material (Figure S1). The correlations between PR and soil moisture were not significant ($p > 0.05$), regardless of the cultivation system (coppicing and stand renewal), harvesting method (HF and FS), and eucalypt straw level (100, 50, 0%) (Table 2), indicating that the differences in PR are due to the effects of treatments.

Table 2. Soil moisture averages (θ_m) in the 0–0.20, 0.20–0.40 and 0.40–0.60 m layers, in eucalypt cultivation areas under coppicing and stand renewal with different straw levels (100, 50 and 0%), both harvested by harvester + forwarder (HF) and feller + skidder (FS) systems.

Layers	**Average** ς	**CV** §	**Normality Test** ¥		**PR = f(θ_m)** δ	
(m)	**(kg kg^{-1})**	**(%)**	**W**	***p*-Value**	**R**	***p*-Value**
Coppicing areas						
harvester + forwarder						
0.00–0.20	0.21 ± 0.03	22.88	0.95	0.62_{ns}	−0.007	0.98_{ns}
0.20–0.40	0.21 ± 0.02	15.94	0.85	0.05_{ns}		
0.40–0.60	0.22 ± 0.02	16.5	0.85	0.05_{ns}		
feller + skidder						
0.00–0.20	0.20 ± 0.02	15.24	0.96	0.84_{ns}	−0.07	0.85_{ns}
0.20–0.40	0.20 ± 0.01	12.84	0.95	0.65_{ns}		
0.40–0.60	0.21 ± 0.01	12.11	0.95	0.69_{ns}		
Stand renewal areas						
harvester + forwarder with straw level 100%						
0.00–0.20	0.20 ± 0.01	13.54	0.88	0.12_{ns}	−0.093	0.80_{ns}
0.20–0.40	0.20 ± 0.01	12.67	0.97	0.90_{ns}		
0.40–0.60	0.20 ± 0.01	8.14	0.95	0.59_{ns}		
harvester + forwarder with straw level 50%						
0.00–0.20	0.21 ± 0.01	9.7	0.96	0.72_{ns}	0.597	0.54_{ns}
0.20–0.40	0.22 ± 0.01	9.39	0.9	0.15_{ns}		
0.40–0.60	0.21 ± 0.01	12.86	0.95	0.69_{ns}		
harvester + forwarder with straw level 0%						
0.00–0.20	0.26 ± 0.02	13.05	0.89	0.15_{ns}	0.23	0.52_{ns}
0.20–0.40	0.26 ± 0.01	11.19	0.92	0.32_{ns}		
0.40–0.60	0.26 ± 0.01	9.75	0.89	0.15_{ns}		
feller + skidder with straw level 100%						
0.00–0.20	0.23 ± 0.01	8.71	0.94	0.48_{ns}	0.54	0.09_{ns}
0.20–0.40	0.23 ± 0.01	10.08	0.94	0.48_{ns}		
0.40–0.60	0.25 ± 0.01	7.81	0.93	0.37_{ns}		
feller + skidder with straw level 50%						
0.00–0.20	0.25 ± 0.01	7.07	0.88	0.09_{ns}	−0.061	0.85_{ns}
0.20–0.40	0.26 ± 0.01	10.49	0.94	0.53_{ns}		
0.40–0.60	0.27 ± 0.01	7.1	0.94	0.56_{ns}		
feller + skidder with straw level 0%						
0.00–0.20	0.25 ± 0.01	6.63	0.94	0.53_{ns}	−0.07	0.36_{ns}
0.20–0.40	0.26 ± 0.01	10.53	0.85	0.05_{ns}		
0.40–0.60	0.27 ± 0.01	4.01	0.91	0.23_{ns}		

ς Average ± confidence interval (90% of confidence); § Coefficient of variation (CV); ¥ Normality test: Shapiro-Wilk test for normal distribution, where: (ns) not significant; δ Indexes of the correlation between soil moisture and penetration resistance (PR) in the 0–0.60 m soil depth layer: Coefficient of linear correlation (R) and Student's *t*-test, where: (ns) not significant.

3.2. Soil Penetration Resistance in Coppicing Areas

Under coppicing areas, the harvester + forwarder (HF) treatment showed a PR average significantly lower (1.28 ± 0.24 MPa) than the feller + skidder treatment (FS) (2.11 ± 0.44 MPa) at 0–0.05 m depth layer (Figure 3). The lower PR value in HF was associated with the physical effect of eucalypt straw kept on the soil surface, which attenuates the soil compaction. For the underlying layers, regardless of the treatments, the confidence interval (CI) limits of PR were superposed, suggesting no significant differences between them. These results suggest that only the superficial layer (0–0.05 m) was affected by the eucalypt straw management as also found by other studies [12,35] reporting positive effects of forest straw kept on the soil surface, promoting reduced soil compaction. According to [35], plant straw act as a protective layer that reduces the contact pressure of machine wheels on the soil surface, dissipating the applied load and reducing the risks of soil compaction.

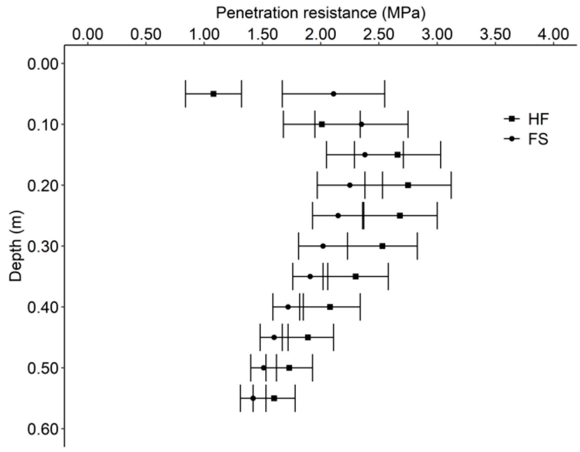

Figure 3. Soil penetration resistance (PR) up to 0.60 m depth in eucalypt cultivation areas under coppicing harvested with harvester + forwarder (HF) and feller + skidder (FS) systems. Bars refer to the confidence interval (90%) of the average (n = 22).

Figure 3 shows also that PR averages in both harvest systems were below 3 MPa, which was established as critical for eucalyptus roots development based on [16]. Less intense machinery traffic for harvesting in areas of coppicing possibly contributed to maintaining PR < 3 MPa. In forest soils, other studies have suggested that significant increments in PR only occur after several events of heavy traffic [36,37]. Besides that, the Oxisols are characterized by their stable structure and well drainage, which result in a higher deformation resistant [35,38]. These structure characteristics may have contributed to lower soil compaction during mechanized harvesting operation in the investigated Oxisol. Well drained soils have higher load support capacity, which reduces the risks of compaction [39].

3.3. Soil Penetration Resistance in Stand Renewal Areas

In areas under stand renewal and harvested by harvester + forwarder (HF) method with three eucalypt straw levels (100, 50, and 0%) kept on the soil surface, the averages of PR at 0–0.60 m were 1.09 ±0.18, 1.21 ± 0.17, and 1.25 ± 0.18 MPa for areas with straw levels of 100%, 50%, and 0%, respectively; in areas harvested with feller + skidder (FS) method, RP averages were 1.14 ±0.16, 1.16 ± 0.15, and 1.24 ± 0.18 MPa for areas with straw levels of 100%, 50%, and 0%, respectively. There were no significant differences in PR between soil layers (Figure 4) in both HF and FS, regardless of the amount of eucalypt straw on the soil surface, suggesting that maintenance or removal of eucalypt straw prior to soil tillage does not significantly affect PR values.

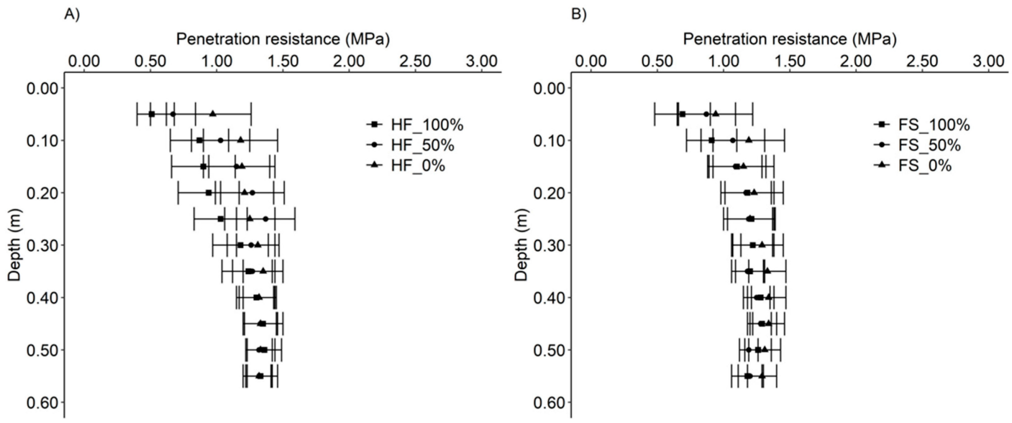

Figure 4. Soil penetration resistance (PR) up to 0.60 m depth in eucalypt cultivation areas under stand renewal with different straw levels (100, 50, and 0%) and harvested with (**A**) harvester + forwarder (HF) and (**B**) feller + skidder (FS) systems. Bars refer to the confidence interval (90%) of the average (n = 22).

Despite the lack of differences between treatments (Figure 4), it should be considered that in areas where the eucalypt straw was completely removed, the subsequent renewals will be carried out on an increasingly smaller amount of straw on the soil surface, especially in areas harvested by feller + skidder method in which the trees are processed outside the plots. For this harvesting system, the practice of returning the eucalypt straw after harvest (represented here by the treatment FS with 50% of a straw level) leads to higher operational costs as well as a reduction of raw material as a source of energy for the industry. As already mentioned, the presence of harvest straw deposited on the soil surface can attenuate the effects of machinery traffic on PR, so that under stand renewal with subsequent cycles, much more attention should be paid to monitoring soil compaction where the eucalypt straw was removed before soil tillage.

The decreased values of PR, as well as its relative homogeneity between HF and FS treatments, are consequences of the current soil tillage, which was carried out shortly after the operations of harvest and straw management. It is well known that, in forest soils, soil tillage is usually carried out up to 0.50 m depth [9] and can reach up to 1 m depth in situations where there are impeding layers for root growth [40]. The soil physics conditions promoted by tillage can increase forest stand uniformity in renewal areas by decreases in root resistance to penetration [9] and improvements in water storage capacity [41]. Besides that, there is evidence that the effect of soil tillage on soil physical properties may persist for decades in forest soils [42].

The analysis of the PR spatial distribution in the harvesting systems HF and FS were done without considering the individual treatments of eucalypt straw level. The PR data showed moderate asymmetric ($0.15 < |As| < 1.0$) with right and platykurtic distribution curves ($Ks < 0$), which reflects frequencies close to the mean value (Table 3). According to the parameters obtained in the geostatistical analysis of PR, the layers 0–0.20 and 0.20–0.40 m showed a pure nugget effect ($C = C + Co$) for both harvesting systems (HF and FS) (Table 3). In contrast, in the 0.40–0.60 m soil depth layer, there was a weak (SD = 90.50%) and moderate (SD = 72.77%) spatial dependence of PR for HF and FS, respectively. This lack of spatial dependence of PR up to 0.40 m soil depth did not allow the fitting of any semivariance model, as well as the PR mapping by the kriging method. According to [43], the existence of spatial dependence is a prerequisite for applying the kriging method. For the 0.40–0.60 m layers, a linear model was fitted with a coefficient of determination (R^2) of 0.14 and 0.69 for HF and FS, respectively, which indicated the weakness of the semivariance model to estimate the PR spatial variability in the studied area. Besides that, the large spatial dependence ranges ($\geq$139.96 m) found for both linear models (HF and FS) do not have any practical application to justify the PR mapping in this soil depth layer.

Table 3. Geostatistical parameters for soil penetration resistance (PR) at the 0–0.20, 0.20–0.40 and 0.40–0.60 m soil depth layers, in eucalypt cultivation areas under stand renewal and harvested by systems harvester + forwarder (HF) and feller + skidder (FS).

Parameter	Harvester + Forwarder			Feller + Skidder		
Layer (m)	0.00–0.20	0.20–0.40	0.40–0.60	0–0.20	0.20–0.40	0.40–0.60
Average (MPa)	0.99	1.27	1.32	1.05	1.24	1.25
Median	0.60	0.46	0.30	0.58	0.37	0.23
CV (%) §	60.51	35.97	22.66	54.97	29.45	18.58
Asymmetry	0.50	−0.01	0.30	0.29	−0.20	0.25
Kurtosis	−0.81	−0.65	−0.51	−1.30	−0.57	−0.12
Sill	0.00	0.00	0.01	0.00	0.00	0.02
Nugget	0.34	0.20	0.09	0.35	0.14	0.04
Sill + Nugget	0.00	0.00	0.09	0.00	0.00	0.06
Range (m)	0.00	0.00	163.22	0.00	0.00	139.96
SD (%) ς	0.00	0.00	90.50	0.00	0.00	72.77
Model	no	no	linear	no	no	linear
R^2 ¥	no	no	0.14	no	no	0.69

§ CV: coefficient of variation; ς SD: index of spatial dependence; ¥ R^2: coefficient of determination.

Furthermore, these results indicated that the soil tillage reduced the spatial dependence of PR by increasing the soil's physical and mechanical homogenization, especially up to 0.40 m soil depth. The occurrence of some spatial dependence only in the layer less influenced by the management (0.40–0.60 m) corroborates the observations made. According to [34], the weak spatial dependence is related to the external factors (e.g., soil tillage and agricultural machinery traffic), while the well-defined spatial dependence is more related to intrinsic factors associated with the natural soil structure. In other similar studies [24,26,44], the authors found spatial dependence of PR in areas under eucalyptus production. However, in these studies, the PR readings were carried out in eucalyptus stands before harvesting and soil tillage. Even under these conditions, [26] also observed a decrease in the PR spatial dependence from the bottom to the soil's top layer. In the present study, the geospatial assessment allowed inferences about the spatial distribution of the PR measured after soil tillage.

4. Conclusions

We found in this investigation that the eucalypt straw kept on the soil surface contributed to mitigating the effects of machinery traffic on the penetration resistance of the 0–0.05 m layer depth during harvesting operations applied in areas under coppicing cultivation system. However, the harvesting operations did not increase the PR up to the critical (3 > MPa) limit to eucalypt roots development regardless of the harvest method (HF and FS) applied.

In stand renewal areas, the PR measured was not influenced by the different levels of eucalypt straw managed on the soil surface before soil tillage, regardless of the harvesting method used. The geospatial analysis of PR indicated that the soil tillage caused physical and mechanical homogenization of the soil, leading to uniform PR conditions for eucalyptus roots development. Additionally, future investigations may explore other physical indicators also related to plant development to monitor the short and long term changes in physical quality promoted by the forest straw management on the soil surface.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12061482/s1, Figure S1: Precipitation and temperature between 1 June and 31 July 2017, measured by the nearest (38 km) whether station from the experimental areas. The weather station belongs to the National Institute of Meteorology (INMET), located in Ventania, Parana, Brazil, lat: −24.28027777; long: −50.21027777; level: 1093.41 m. Data are available on the INMET website: https://bdmep.inmet.gov.br/ (accessed 27 May 2022); Table S1:

Particle-size distribution at the 0-0.20, 0.20-0.40, and 0.40-0.60 m layers in eucalypt cultivation areas under coppicing and stand renewal with different straw levels (100, 50 and 0%) both harvested by harvester + forwarder and feller + skidder systems.

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