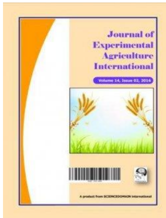

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Soil Attributes Related to Natural Succession in a Permanent Preservation Area– A Study for Brazilian Atlantic Forests

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Authors' contributions

This work was carried out in collaboration between all authors. The authors GS and MLC developed and implemented the study, performed the laboratory analyzes and wrote part of the manuscript. The authors DM and ESD collaborated data evaluation, statistical analysis and written part of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

The study of physical and chemical characteristics of associated to different vegetation cover is very important for understanding how the soil can influence the behavior of the forest.
Aims: This study aimed to relate soil attributes under pine cultivation and natural regeneration of vegetation in permanent preservation areas (PPA).
Methodology: For this purpose, a regenerated PPA (RA) and a non-regenerated PPA (NRA) had their vegetation and seed bank characterized, respectively. In different soil depths, chemical and physical attributes of the soil were analyzed.
Conclusion: Ca content and soil density (SD) were variables that can be best discriminated soils of both areas. High soil density (SD), poor soil drainage and lack of propagules of woody species

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determined the establishment of the herbaceous vegetation in the RA. Lower SD and better soil drainage allowed the establishment of arboreal and shrub species of the Mixed Ombrophilous Forest in the RA.

Keywords: Soil quality indexes; reforestation; recovery of degraded areas.

1. INTRODUCTION

Latin America is home for the Guarani Aquifer System (GAS), on Paraná Sedimentary Basin. It is an important subterranean water reservoir with an area of approximately 1.1 million km^2 [1]. In Brazil, it extends for about 840.000 km^2 through São Paulo, Minas Gerais, Goiás, Mato Grosso, Mato Grosso do Sul, Rio Grande do Sul, Paraná and Santa Catarina states [2].

With the disordered increase of the Brazilian agrosilvopastoral frontier, mainly during the Green Revolution, the modernization of agriculture, silviculture and livestock and the socioeconomic development have been intensified [3]. In contrast, this led to alterations of natural environments, degrading highly diversified areas like riparian forests. Thus, many forests of Mata dos Pinhais (Atlantic Mixed Ombrophile Forest - MOF), typical vegetation of the GAS of Southern Brazil, were replaced by *Pinus* sp. plantations, which were also stimulated by commercial exploitation of wood. This represented an increase on fragmentation and degradation of riparian forests areas and of other areas of permanent preservation [4].

There is a limit to the resilience of tropical forests, and their ability to recover from disturbances and reassemble all of their parts. In their traditional practice, forests would not be deforested until they are in climax, but the increasing pressure from the population forced many farmers to reduce their fallow periods by inducing a reduction in the forest regenerative capacity; and what makes a fragile forest ecosystem is not destruction, but rather what this causes in its resilience capacity [5]. The most widespread concept is that resilience is the ability of the ecosystem (intrinsically) to self-reorganize after a disturbance and to return to a situation like that which existed previously [6,7,8]. Resilience is part of the natural succession process of an area as well as the cycle of a forest, being it the evolutionary process of the plant community, from the initial stage to the phase in which the forest is considered mature. Many anthropogenic actions interfere on this resilience capacity [5].

In tropical and subtropical environments of natural occurrence in the Atlantic forest and high altitude fields, there is a predominance of weathered soils, where the soil organic matter (SOM) plays a fundamental role in its fertility [9] and contributes decisively to the soil texture [10], however, few published studies report the impacts of conversion to conifer plantations introduced in the subtropics [11]. The impacts of changing from one type of forest to another are unclear mainly in relation to uncertainties due to factors such as planting, age, type of planting and soil, besides the environmental factors and management [12].

The results of some studies on the effects of changes in soil use are generally variable in terms of their causes and magnitudes in the quantity and quality of SOM, depending on the soil type, planting age, forest species, geographic location and climate, between other factors [13].

Studies investigate, in contrast to ours, the impact of homogeneous plantations of exotic species on the natural environment, which may be natural fields, forests or pastures, which are limited to one or two soil characteristics.

When assessing the existence of changes in the quantity and proportion of the humic substances of a SOM in the state of Santa Catarina - Brazil, due to the substitution of natural vegetation by stands of *Pinus taeda* L., the authors [14] found that pasture substitution by homogeneous pine plantations may increase the soil organic carbon content and its stabilization, and that there is a greater accumulation with the aging of homogeneous plantations. This observation was similar to that found other authors when comparing areas of reforestation of Pinus with natural grassland [13] and when evaluating the total organic carbon content in a soil after the replacement of the natural field by homogeneous pine plantations, and the values they found were higher than areas of natural vegetation [15]. When evaluated the effects of soil compaction under forest machinery traffic on pine reforestation and observed that there was a decrease in total porosity, saturated hydraulic conductivity of the soil and stability of the aggregates, resulting in a higher soil compaction after the forest harvest [16]. It is worth mentioning [17] that this is one of the main effects of machine traffic on the soil particles, and several authors [17,18,19] report the negative effects of soil compaction under the development of the soil and vegetation.

Removal of natural vegetation cover and cultivation of exotic species alter natural environment and cause decline of soil quality, which can contaminate water tables and both superficial and subterranean aquifers. In this way, studies on the adequacy of agricultural land use are necessary to analyse the vulnerability of natural resources of contamination of the Guarani Aquifer [20].

PPAs are of relevant importance in water dynamics. They present higher fragility and susceptibility to erosion due to its irregular topography and shallow soil depth. Therefore, restoration of native vegetation is indispensable in those areas, as they allow soil recovery and biodiversity and also serves as habitat for threatened animal and plant species [21].

In order to protect these areas of permanent preservation as well as other areas of native vegetation, there are three important laws in force on Brazil, the National Environmental Policy - Law nº 6938 [22], the Law on Environmental Crimes - Law nº 9605 [23] and the Brazilian Forest Code - Law nº 12651 [24]. The analysis of the Forest Code allows us to observe that there are contained purposes that go beyond the protection of forests, such as the fight against soil erosion and water protection, and in it are described the percentage of plant areas to be conversed as a function of size of the water reserve (superficial or not, natural or not) due to the relief (forests at high altitudes) or the effect that the vegetation can have on the soil. With the advent of this law, reforestation companies needed to adjust their properties and remove the plantations that were occupying areas of permanent preservation until then. The study area is an example of this case, where it is not known the real effect that the entrance of heavy machinery, for the removal of these permanent preservation areas vegetation, can generate in the soil. The enforcement of these laws is the best way to conserve the native vegetation that still exists in the country.

Given the need to understand the reestablishment process of native vegetation on a PPA degraded by exotic forest plantations, it is crucial to develop works that involve a broad environmental analysis and techniques that allow multiple relations between soil attributes and the progress of the vegetation.

The present study aimed to relate physical and chemical indicators of the quality of soils developed on Guarani Aquifer and previously explored by *Pinus* sp. plantation to regeneration of native vegetation in areas of permanent preservation in the city of Ponte Alta do Norte, SC.

2. MATERIALS AND METHODS

This work was carried out at Paredão Farm (belonging to Klabin S.A.), located in Ponte Alta do Norte, Planalto Sul Catarinense, under the central coordinates 27°15’38’’S and 50°20’43’’W at approximately 1,000 m of altitude (Fig. 1).

The study area is located on the Guarani Aquifer recharge system (GAS). This system is considered to be one of the largest groundwater reservoirs between international borders in the world, being located in the center-east portion of South America and irregularly distributed in four countries, Brazil, Paraguay, Uruguay and Argentina, where 90% of it is confined [25]; is composed of sediments from the Triassic-Jurassic period: sandstones of fluvial-lacustrine silty origin (Pirambóia Formation) and varied quartzite sandstones accumulated by wind processes under Botucatu Formation [26] 90% are covered by cretaceous basalts up to 1.5 km thickness in certain areas [27].

The granulometry of the sandstone changes within each formation for each position in the environment, and the Pirambóia Formation is characterized by thin sandstones in interdune areas, thin to medium sandstones deposited in the dunes and coarse grained sandstones on tops of hills while the Botucatu Formation is characterized by thin to medium sandstones, composed essentially of quartz sandstones, in contrast to the sandstones of the Pirambóia Formation, where the feldspathic ones predominate [28]. Although it is of great importance as a reservoir of drinking water for the south of Brazil, little is known about the basic characteristics of the GAS, mainly about the areas of recharge and discharges, which is where the water accesses the system.

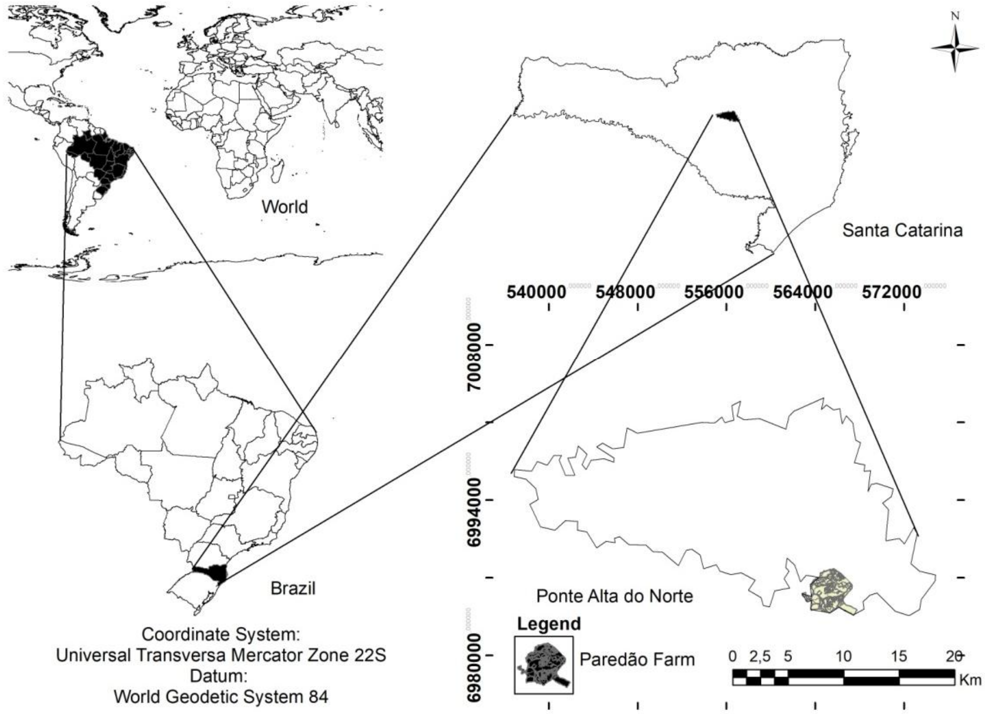

Fig. 1. Location of Ponte Alta do Norte City in the Santa Catarina state, Brazil, where the studied forest fragment is inserted

According to Köppen classification, the region has a mesothermic humid climate with mild summer (Cfb), well distributed rain during the year, mean annual precipitation of approximately 1,500 mm and mean annual temperature of 15.5°C according to Epagri data [29].

The studied areas represent an PPA, and had vegetation described as Mixed Ombrophiles Forest (MOF) according to IBGE [30]. They are rich in species such as *Araucaria angustifolia,* the first to be economically exploited until mid-1970s. From 1982, wood production chain started using exotic plants plantations largely represented by genera *Pinus* and *Eucalyptus*. In these areas, such activities occurred until May 2006 when recomposition of native vegetation was initiated through natural succession for compliance with environmental legislation.

Evaluation of regeneration of the natural vegetation was performed between August 2010 and May 2011. Presence of native tree and shrub species from MOF allowed distinction between PPAs in two classes: regenerated PPA (RA) and non-regenerated PPA (NRA).

Taxonomic classification of the soils was performed based on the Brazilian System of Soil Classification [31], through morphological, physical and chemical evaluation. This material was described and collected in two monoliths obtained from borehole and from reconstitution of the sequence of soil horizons and layers (on RA) and in an open trench (on NRA) in February 2011. Monolith construction on NRA occurred due to the proximity of the water table with the surface and to the shallow effective soil depth. Soil on RA is classified as a typical distrophic Latosol, while soil on NRA is classified as a typical hydromorphic quartzarenic Neosol.

For vegetation survey and soil analysis, sampling occurred along transects inside PPAs in adequacy process.

For floristic survey on RA, the quadrant-points method was used [32]. Points were marked along two transects and allocated within a distance of five meters between each other, totalizing 20 sampling points in each transect. Four trees and four shrubs that were closer to the central point and had its height greater than or equal to 1 meter were selected. Individuals were collected, identified [33] and herborized. To verify sampling adequacy, the rarefaction curve was used based on the Mao Tau index [34] using EstimateS v.8.0 programme [35].

Given the irregularities of the vegetation recomposition on NRA, botanical families were classified based on plants developed on seed banks. They were collected randomly on the soil litter along two transects, in eight sampling points and two depth (0-10 and 10-20 m). Plant development occurred in a climatized greenhouse with regulated temperature of 18 ± 2°C and 25 ± 3°C and air relative humidity between 35% and 75%.

For soil sampling, transects were allocated all over the study area through systematic disregarded method which is characterized by not having fixed distances between transects [36]. Four transects of approximately 100 m each were established. In these transects, soil samples were collected at intervals of 0–20 cm and 20-40 cm for chemical analysis and 0-10, 10-20, 20-30 and 30-40 cm for physical analysis, in 16 points for each of RA and NRA areas.

For chemical analysis, soil samples were collected with a Dutch auger, oven dried at 60ºC, rolled, milled and sieved in a 2 mm sieve. Afterwards, chemical attributes such as pH in water and SMP with a potentiometer [37], pH in KCl according to Embrapa [38] using a soil/solution ratio of 1:1, extractable P (phosphorous) and exchangeable K (potassium) and Na (sodium) through Mehlich-1 method [39]. and exchangeable Ca (calcium), Mg (magnesium) and Al (aluminium) extracted with a KCl 1 mol L^{-1} solution [37] were determined. The quantification of the Ca, and Mg contents was performed in an atomic absorption spectrometer, Al by neutralization tiltration, P by UV-visible at 660 nm, and K and Na by flame photometry. The determination of the clay, silt and sand contents followed a specific methodology [40,41].

Physical attributes were evaluated in two stages. In the first one, for granulometry analysis, samples with altered structure that were sampled with the Dutch auger were used, and the pipette method was used for determination [41]. Analysis of particle density was also performed on those samples [42].

In the second stage, the other attributes were analysed in samples with preserved structure, for which extraction and confinement were performed using metallic rings with cutting edges with volume corresponding to 70 cm^3(2.5 cm in height and 6.0 cm in diameter). These samples were weighted with field humidity and then saturated and submitted to tensions of 1, 6 and 10 kPa in a sand tension table and of 33, 100, 300, 500 and 1.500 kPa in a Richards chamber. Such procedure allowed determination of total porosity (TP) through difference between humidity of the saturated soil and the dry soil [38]. With the same procedure, it was possible to obtain soil density (SD) by drying samples at 105ºC and analysing them through the volumetric ring method [43].

In order to evaluate the association level between variables and the two studied environments, data obtained from chemical and physical analysis of the soil were submitted to canonical discriminant analysis (CDA) considering minimal significance level of 5% (P = 0.05). For this procedure, SAS (SAS Institute, Cary, NC, EUA) and R [44] programmes were used.

3. RESULTS AND DISCUSSION

3.1 Floristic Survey

Results from floristic survey in AR showed the occurrence of 11 species of tree and shrub plants belonging to eight botanical genera and six botanical families. The family with higher species richness was Asteraceae with six species. The other families had one species each. The floristic profile of this area is typical of araucaria forests at initial regeneration stage [45]. This pattern was also observed for the same given phytophysiognomy [46]. Table 1 lists tree and shrub species and their respective botanical families for vegetation.

As this area is in a process of natural regeneration, expressive quantities of pioneer species such as *Baccharis uncinella, Mimosa scabrella*, *Solanum variabile* and *Myrsine coriacea* were found in all transects. They are also characterized by their good adaptation to soil that lost their original properties [47], generating a permanent bank on the soil that, under light incidence, grow and recover the area efficiently.

Characterization of bank seed in NRA revealed the occurrence of four botanical families. The family with higher richness was Cyperaceae with

Table 1. List of arboreal and shrub species and related botanical families of the regenerated PPA (RA)

Species	Family
Baccharis uncinella DC.	Asteraceae
Baccharis trimera (Less) DC.	Asteraceae
Baccharis dracunculifolia DC.	Asteraceae
Baccharis semiserrata DC.	Asteraceae
Dicksonia sellowiana Hook.	Dicksoniaceae
Mimosa scabrella Bentham	Mimosaceae
Myrsine coriaceae (Sw.) R. Br.	Primulaceae
Piptocarpha angustifolia Dusén ex. Malme	Asteraceae
Sapium glandulosum (L.) Morong	Euphorbiaceae
Solanum variabille Mart.	Solanaceae
Vernonanthura discolor (Spreng.) H. Rob.	Asteraceae

43 individuals, followed by Asteraceae with 11 individuals, Melastomataceae with 4 individuals and Poaceae with 2 individuals. Seven species could not be identified. Some researches [48] registered Poaceae, Cyperaceae and Asteraceae families as the ones with the greatest species richness at Planalto Serrano wetlands; others also related abundance of these three families and also of Melastomaceae family in these areas [49].

The greatest number of individuals from Cyperaceae family in the NRA results from the high level of the water table, which provides a hydromorphic environment that enhances the development of these plants. At the lower sites of this area, several specimens of the genus *Sphagnum*, which are highly hydrophilic, were also found [50].

3.2 Soil Chemical and Physical Properties

Tables 2 and 3 shows the mean values of chemical and physical attributes, respectively, obtained at the sampled points in each analysed depth and in both RA and NRA. In order to evaluate the association level between chemical and physical variables and areas (RA and NRA), data was submitted to canonical discriminant analysis (CDA).

For both areas the pH value is considered very low (< 5.0) (Table 2) [51]. The release of organic acids by decomposing molecules and the higher cations absorption instead of anions are possible causes of soils acidification under *Pinus* sp. [52]. The acicles accumulation at the soil surface promotes the retention of considerable amounts of nutrients in the litter, which alters the balance of the soil-plant system [53].

For the average values of Al^{+3}, the highest observations of Al^{+3} (Table 2) in the RA are related to the clay content and the highest CEC of the soil because this is an older soil, being that at pH lower than 5,0, Al^{+3} is the cation that normally predominates in the CEC.

Higher values of Ca were found in NRA (Table 2). Ca concentrations in the soil less than or equal to 2.0 cmolc kg^{-1} are considered low and between 2.1 and 4.0 cmolc kg^{-1} are considered medium [51]. For Mg, higher levels were observed in the depth of 0-20 cm for NRA and in depth of 20-40 cm for RA (Table 2), considered high [51]. The highest levels of Ca and Mg available in the NRA area are related to poor drainage, because in reduced environments the availability of these nutrients is higher. However, this result does not reflect the differences between the source materials in relation to the amount of primary minerals that supply nutrients, since young soils derived from sandstone have very low amounts of intemperisable primary minerals.

The accumulation of Mg in the soil surface layers, similar to Ca, is due to the higher CEC, the superficial location of fertilizers and correctives and the mineralization of the residues of the cover plants [54]. These elements bind to the negative charges of clays and organic matter, reducing their leaching [55]. For the NRA, it is observed that the Mg content is lower than the Ca content in depth, since the leaching loss of Mg is usually higher [55]. However, this behavior was not observed in the RA, where Mg contents are higher than Ca in the two depths.

About the K contentes, the average values found on the two areas are classified as very low according to the criteria established [51].

Table 2. Chemical properties of soil at different depths of regenerated PPA (RA) and non-regenerated PPA (NRA)

Depth	Variables	Unit	RA		NRA	
			Average	Standard deviation	Average	Standard deviation
0-0.20 m	pH in water		4.6481	0.2189	4.2486	0.2269
	pH in KCl		3.8531	0.0865	3.8581	0.1912
	pH in SMP		4.8300	0.2568	5.3131	0.3067
	Ca	$cmol_c\ kg^{-1}$	1.0539	0.3176	2.5282	0.4840
	Mg	$cmol_c\ kg^{-1}$	1.3474	0.2849	2.1680	0.1676
	Al	$cmol_c\ kg^{-1}$	13.3000	2.6250	4.2469	3.2474
	K	$cmol_c\ kg^{-1}$	0.1259	0.0826	0.0359	0.0232
	Na	$cmol_c\ kg^{-1}$	0.0156	0.0148	0.0200	0.0087
	P	$mg\ kg^{-1}$	7.8625	4.3246	12.4346	8.1160
0.20-0.40 m	pH in water		4.6938	0.2270	4.3269	0.2517
	pH in KCl		3.8900	0.0912	4.0540	0.1548
	pH in SMP		4.9256	0.2708	5.5100	0.2751
	Ca	$cmol_c\ kg^{-1}$	0.9282	0.3641	2.5920	0.5903
	Mg	$cmol_c\ kg^{-1}$	1.9104	0.6582	1.8354	0.4189
	Al	$cmol_c\ kg^{-1}$	13.0306	2.4001	4.9686	4.1246
	K	$cmol_c\ kg^{-1}$	0.0654	0.0427	0.0312	0.0131
	Na	$cmol_c\ kg^{-1}$	0.0116	0.0068	0.0224	0.0155
	P	$mg\ kg^{-1}$	4.4244	3.1982	4.3414	4.3336

Ca: Calcium. Mg: Magnesium. Al: Aluminum. K: Potassium. Na: Sodium. P: Phosphorus.

Phosphorus presented a higher concentration on lower depth (Table 2). According to the Soil Chemistry and Fertility Comission [51] which considers the clay content present in the soil for interpretation of the P values, the AR soils shows low content of the reffered element while the NRA soils presents very low to low P contents. The Na values were similar for the two studied areas (Table 2), which were very low.

Although most soils have nutritional deficiencies, natural forests generally do not show symptoms of deficiency due to nutrient cycling that is in balance with the demand. The replacement of natural forests by short-cycle forest plantations or any type of crop changes the natural processes of cycling and storage of nutrients, mainly due to changes in the quality of organic matter caused by management practices. This impairs the sustainability of the sites by the important role of organic matter in the chemical, physical and biological attributes of the soil [56].

The mean clay, silt and sand contents found for the soil indicate that the textural class of the RA area is sandy clay loam and the NRA is sandy loam (Table 3), and this texture difference is a reflection of the differences in the clay content of these areas soils; being that the higher clay content of the RA explains the higher Al^{+3} content and the higher effective CEC.

In Table 3 it is also possible to see that soil SD was low in both environments. There was a gradual increase in this in-depth variable for both areas; This was expected, since there was heavy machinery traffic in the area when it contained homogeneous Pinus plantations. The mean value of SD in the NRA at depth 0-10 is higher than RA, but in depth the SD of the two environments resemble each other. Sandy soils have naturally higher density values in relation to clay soils [57]. On the other hand, the total pore volume is smaller in these soils when compared to those of clay texture, where the formation of microaggregates by the clay particles increases, because they have larger particles, they present porous space constituted by pores of larger diameter (macropores) microporosity [58]. Corroborating with the presented, other author [59], when evaluating the compaction of the soil produced by the traffic of a forest cart used to transport wood from the fields to the industry, found that, for soils with more than 80% sand, in terms of density the effects of cart traffic were more pronounced up to 10 cm deep and another one [60] found an increase in soil bulk density for a clay Oxisol when using a forwarder.

For soils of sandy texture the critical SD is between 1.7 and 1.8 $mg.m^{-3}$ [61]. Physical attributes such as density and humidity are indicators of soil quality, being understandood as soil quality the capacity of the soil to maintain biological productivity [62], environmental quality and healthy plant and animal life on the face of the earth [63].

In a study was determined a SD value of 1.43 g cm^{-3} in an area under native vegetation, at a depth of 0-20 cm from the soil for an Argisol [64], as well as for an Oxisol [65]. It can be seen that the SD values, at the established depth, independent of the cultural tract and the sampling site, are above the means values considered ideal for SD, which are in the range of 1, 0 and 1.2 $g.cm^{-3}$ for clay soils [66]. These higher values for density may result in greater soil degradation in the study areas, which indicates a possible soil compaction and/or soil densification.

The porosity of the soil is a direct reflection of the soil structure and texture, being the pores determined by the arrangement and geometry of the particles, differing in shape, length, width and tortuosity. Sandy soils, such as those in the NRA area, have pore space constituted by larger pores (macropores), on the other hand the total pore volume is lower in these soils when compared to the clay ones, where the formation of microaggregates by clay particles increases microporosity [67].

3.3 Discriminate Functional Analysis

The number of canonical discriminant functions (CDF) in this analysis is determined by the lowest value, according to the number of analysed groups (in the present study, environments formed by combination between analysed areas and sampling depths) minus one, and the number of studied variables [68]. In this way, three CDFs were obtained or each group of variables (chemical and physical) of the soil.

Only the first two significatives CDFs ($p < 0.01$) were used, as they represent 85.15% and 9.44% of the total discrimination potential for the chemical variables and 82.99% and 12.73% for the physical variables for CDF_1 (discrimination between areas) and CDF_2 (discrimination between depths), respectively (Tables 4 and 5).

Table 3. Physical properties of soil at different depths of regenerated PPA (RA) and non-regenerated PPA (NRA)

Depth	Variables	Unit	RA		NRA	
			Average	Standard deviation	Average	Standard deviation
0-0.10 m	Clay	%	27.9196	10.2291	10.8985	0.8515
	Sand	%	56.9212	14.2174	84.7866	1.0420
	Silte	%	15.1592	5.5492	4.3149	1.7324
	SD	$g\ cm^{-3}$	0.9903	0.1025	1.2567	0.1701
	PD	$g\ cm^{-3}$	2.3703	0.1058	2.4442	0.1570
	TP	$m^3\ m^{-3}$	0.5817	0.0442	0.4856	0.0654
0.10-0.20 m	Clay	%	29.0906	10.9793	11.7481	0.1034
	Sand	%	54.8304	15.9624	83.0204	1.3577
	Silte	%	16.0790	6.3673	5.2315	1.2543
	SD	$g\ cm^{-3}$	1.2005	0.1588	1.3075	0.1565
	PD	$g\ cm^{-3}$	2.3994	0.0739	2.4822	0.0831
	TP	$m^3\ m^{-3}$	0.5002	0.0603	0.4742	0.0532
0.20-0.30 m	Clay	%	29.1030	11.5055	11.1830	0.6952
	Sand	%	54.8514	15.3777	85.2626	0.8817
	Silte	%	16.0457	6.0896	3.5544	0.1935
	SD	$g\ cm^{-3}$	1.2156	0.2038	1.3438	0.1825
	PD	$g\ cm^{-3}$	2.4031	0.0452	2.5014	0.0722
	TP	m^3m^{-3}	0.4944	0.0830	0.4637	0.0649
0.30-0.40 m	Clay	%	29.7901	12.7460	9.4651	1.2882
	Sand	%	54.8921	14.8941	86.2711	1.3970
	Silte	%	15.3178	4.1495	4.2637	1.5375
	SD	$g\ cm^{-3}$	1.3061	0.1166	1.3499	0.1647
	PD	$g\ cm^{-3}$	2.4232	0.0768	2.4778	0.1224
	TP	$m^3\ m^{-3}$	0.4604	0.0515	0.4559	0.0559

SD: Soil density. PD: Particle Density. TP: Total Porosity

CDF_1 showed a canonical correlation coefficient of 0.93 for chemical analysis and 0.71 for physical analysis, which indicates a high association level between variables and the studied areas.

Standard canonical coefficient (SCC) indicates the relative influence of each variable for separation of the environments in the presence of other variables, thus representing a measure of multivariate behaviour. The *r* value expresses the influence of each variable independent of the others, that is, it reveals a view of the univariate behaviour [69]. The parallel discrimination rate (PDR) is the result of the product between the SCC value and the *r* value. Higher and positive values of PDR indicate more weight on environment separation, while negative values indicate the presence of supressing variables that mask their effect.

In the evaluation of the soils in the present study, there was a significant difference ($p<0.001$) of the mean vectors of chemical and physical attributes between groups (combination of areas *vs.* depth), tested by Wilks' lambda and Pillai's trace statistics. Such behaviour can be seen in Figs. 2 (chemical attributes) and 3 (physical attributes). It was possible to verify the separation between areas and sampling depths for both attributes. However, the discrimination is more evident between the areas.

The chemical attributes with more weight on CDF_1 were Ca (*PDR=1.2275*) and Al (*PDR=0.8499*) contents. For CDF_2. the greatest weights were observed for P (*TDP=0.5713*) and pH in KCl (*TDP=0.4042*) attributes (Table 4).

Discrimination of areas related to Ca and its high contents in NRA (Table 2) for both depths can be explained based on distinct processes. In this area, soil saturation with water is recurrent and can remain for prolonged period. It favours the reduction of compounds that have oxygen in their molecule by anaerobic or facultative anaerobic organisms. Such reduction causes release of hydroxyls and consequent increase in pH in a phenomenon called auto-liming [70]. As a result of the dissolution of Fe oxides and Fe^{+2} ions competition for exchange sites, Ca^{+2} is released to the soil solution.

Table 4. Linear correlation coefficients (*r*), standardized canonical coefficients (SCC) and parallel discrimination rate (PDR) in the first two canonical axes, for the chemical properties of soil at different depths in the regenerated PPA (RA) and non-regenerated PPA (NRA)

Variables	Canonical Discriminating Function 1			Canonical Discriminating Function 2		
	r	**SCC**	**PDR**	***r***	**SCC**	**PDR**
pH in water	-0.6808	-0.3790	0.2580	0.1395	0.1039	0.0145
pH in KCl	0.2371	-0.0479	-0.0114	0.6280	0.6436	0.4042
pH in SMP	0.7120	0.1333	0.0950	0.3058	0.1202	0.0368
Ca	0.9214	1.3322	1.2275	0.1399	1.0976	0.1536
Mg	0.4253	0.3737	0.1590	-0.3470	-0.4409	0.1530
Al	-0.8819	-0.9637	0.8499	0.0125	0.8568	0.0107
K	-0.5775	-0.5417	0.3128	-0.0480	0.2535	-0.0122
Na	0.3960	0.1233	0.0488	0.1336	0.0976	0.0130
P	0.1492	0.0674	0.0100	-0.6668	-0.8567	0.5713
Eigenvalues		8.16			0.90	
% Acum Var		85.15			9,43	

Table 5. Linear correlation coefficients (*r*). standardized canonical coefficients (SCC) and parallel discrimination rate (PDR) in the first two canonical axes, for the physical properties of soil at different depths, in the regenerated PPA (RA) and non-regenerated PPA (NRA)

Variables	Canonical Discriminating Function 1			Canonical Discriminating Function 2		
	r	**SCC**	**PDR**	***r***	**SCC**	**PDR**
Clay	0.8947	0.3384	0.3028	-0.0202	0.1445	-0.0029
Silte	0.9710	0.7595	0.7375	-0.0675	0.0909	-0.0061
SD	-0.3983	-4.2710	1.7012	0.8858	-7.0057	-6.2053
PD	-0.4370	1.0805	-0.4722	0.3028	2.2830	0.6914
TP	0.3021	-4.0539	-1.2245	-0.9072	-7.4419	6.7516
Eigenvalues		2.48			0.38	
% Acum Var		82.99			12.73	

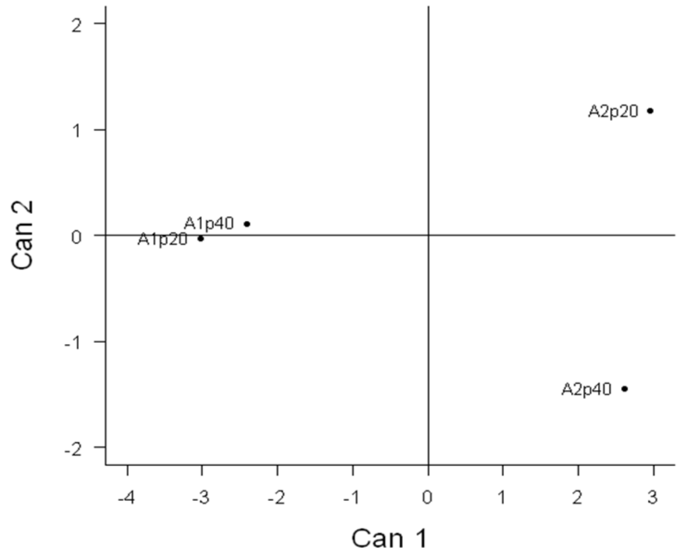

Fig. 2. Average values of the canonical discriminant function 1 (Can 1) and canonical discriminant function 2 (Can 2) in relation to chemical properties of soil at the depths of 0-20 cm (P20) and 20-40 cm (P40) in the RA (A1) and NRA (A2)

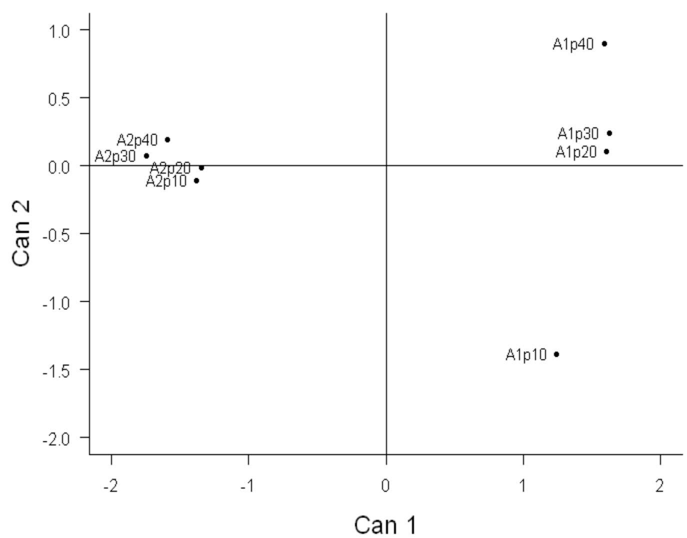

Fig. 3. Average values of the canonical discriminant function 1 (Can 1) and canonical discriminant function 2 (Can 2) in relation to physical properties of soil at the depths of 0-0.10 m (p10), 0.10-0.20 m (p20), 0.20-0.30 m (p30) and 0.30-0.40 m (p40) in the RA (A1) and NRA (A2)

Increase in pH caused by soil saturation by water can also increase the thickness of the double electric layer on the external surfaces of the solid components of the soil. In this way, there is greater diffusion of the basic cations towards the soil solution including Ca [71].

As Ca, exchangeable Al also explains great part of the variation between areas due to chemical processes in the soil. Lower values found in NRA (Table 2) are due to lower clay and organic material content to lower soil ability to exchange cations (AEC) and thus to the capacity of fixing exchangeable Al under the RA soil [71]. This can also be explained by the increase in pH due to the auto-liming caused by periodic saturation of the soil with water, which can increase Al precipitated with hydroxyls ($Al(OH)_3$) and diminish exchangeable Al.

Regarding the association between soil depths and evaluated variables, P presents relative importance. For both areas, soil litter deposition during *Pinus* cultivation period and low mobility of P in the soil contributed to its accumulation in its organic form on the superficial layer. NRA presented higher levels of P than RA in this layer (Table 2), as saturation by water occur in this area, which allows dissociation of Fe oxides through reductive organisms and thus releasing P from these minerals [70], pH in KCl also contributes to variation between soil depth specially in NRA, setting a pH-dependent charge gradient between the analysed depths (Table 2). Variable loads or pH dependent vary the change soil pH, when the pH increases there is an increased amount of pH dependent negative charges in the soil that are primarily formed by dissociation of H+ from the side surfaces (OH-), and organic compounds such as carboxylic acids (R-COOH), when the pH of the soil tends to rise, if the pH reduces, the process is reversed; being that this type of charge is predominant in soils of countries of warm climate, as in Brazil [71].

Soil litter supply, its decomposition and incorporation to nutrients are part of a dynamic process that gives a distinct character for the soils under vegetal cover: nutrients are rapidly released and can be transported to lower layers where roots can recover them [72]. Therefore, native plant species in forests usually do not have limitations about nutritional deficiencies as cycling in the soil-plant system tend to ease the effects of low nutrients concentration in the soil. Thus, it is not surprising that the low content of Ca, K and P and the high content of exchangeable Al (Table 2) (element whose toxic effect can cause reduction of root growth) were not limiting for the development of tree and shrub species in RA.

Higher values of Ca content and lower values of exchangeable Al at 0-20 and 20-40 cm, as well as higher Mg, K and P contents at 0-20 cm in NRA (Table 2) are an indicative that the effectiveness of the regeneration of the native vegetation can be related to other variables other than soil chemistry.

The physical attributes with higher weight on CDF_1 were SD (*TDP=1.7012*), silt content (*TDP=0.7375*), while for CDF_2 the highest weights were observed for TP (*TDP=6.7516*) and PD (*TDP=0.6914*) (Table 5).

The high contents of silt and clay on the typical distrophic Latosol in RA (Table 3) indicates its characterization as sandy-clay loam texture, while the hydromorphic quartzarenic Neosol typical of NRA fits in sandy loam texture, as the silt and clay fractions are less representative comparing to the previous soil. Both attributes showed relative importance in discrimination since they affect the soil texture, density and porosity. The textural classification fits all evaluated depths since silt and clay contents did not reveal significant variation between depths in each area.

A gradual reduction of Total Porosity (TP) according to depth was observed in both areas due to the action of compacting forces in the soil. However, the main discriminant between areas was SD, with higher values in the NRA (Table 3), according to the literature [73], sandy soils of forests present maximum density of 1.25 mg m^{-3}, which is lower than the values in all depths in NRA.

Although both areas have sandy soil (Table 3), reduction in TP according to soil depth occurred more intensively in NRA once the effect of compaction is potentialized under high water content [74] and shallow soil depth conditions. Reduction of total porosity after eucalyptus harvest, suggesting that machine traffic in reforestation causes decrease in pore volume due to soil compaction [75]. This effect is evidenced when the entrance of these machines in the area do not respect the soil humidity conditions, as some similar results have shown for the Red Yellow Latosol after the eucalyptus harvest [76].

High values of soil density and reduction of total porosity influenced the water retention capacity and thus hindered the establishment of the vegetation, even though the soil presents good chemical conditions as observed in NRA (Tables 2 and 3).

Soil density can be altered by its use and management therefore, monitoring values over time can provide important information about the influence of soil use and management on exploitation sustainability to which the soil is submitted [77].

Soil density value reflects characteristics of the soil porous system. As roots develop on those pores, any significative alteration on this system can result in interference on root development and on water availability for the plants [78]. With higher retention of water, water percolation in the soil profile is reduced drastically [79]. The presence of a water table next to the surface and the high soil density hinders soil drainage in the NRA, providing high humidity conditions.

Therefore, even though NRA offers better conditions of soil fertility than AR, the natural situation of hydromorphism associated with high SD impair soil aeration, reducing seed germination rates and root growth of forest species [80]. A presumable low quantity of propagules, indicated by the seed bank survey, also contributes to the inefficiency of the spontaneous regeneration of these species in the area.

On the other hand, species that have root system on the superficial layers of the soil and are adapted to low oxygen concentration and SD gain importance in floristics from periodically flooded environments. Herb species include Cyperaceae, Asteraceae, Melastomataceae and Poaceae families, which are predominant in the NAR.

Lower SD values, allied to better drainage and low level of the water table help to avoid restrictions of the root development in woody species in the NRA soil. In this way, tree and shrub species at the Mixed Ombrophilous Forest are predominant in the area.

4. CONCLUSION

The attributes that better describe soils in the RA and NRA are Ca content and total porosity.

High soil density values, poor drainage and lack of propagules from tree and shrub species favoured the establishment of herbaceous vegetation in the NRA.

Low soil density values and good drainage conditions of the soil were sufficient for establishment of tree and shrub species at the Mixed Ombrophilous Forest in the RA.

5. RECOMMENDATIONS

The maintenance of these fragments in the middle of Pinus reforestation plantations assists in the formation of ecological corridors which will promote the successional progression of natural regeneration areas and that due to the identified differences between the soils of the two studied areas, the vegetation that will reestablish during the process of environmental succession will have characteristics inherent to its development over each environment, and the restoration techniques to be used should be in function of the results obtained in this work.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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