CHARACTERIZATION OF THE SOIL FERTILITY AND ROOT SYSTEM OF RESTINGA FORESTS[1]

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SUMMARY

The Restinga vegetation consists of a mosaic of plant communities, which are defined by the characteristics of the substrates, resulting from the type and age of the depositional processes. This mosaic complex of vegetation types comprises restinga forest in advanced (high restinga) and medium regeneration stages (low restinga), each with particular differentiating vegetation characteristics. The climate along the coast is tropical (Köppen). Of all ecosystems of the Atlantic Forest, Restinga is the most fragile and susceptible to anthropic disturbances. Plants respond to soil characteristics with physiological and morphological modifications, resulting in changes in the architecture (spatial configuration) of the root system. The purpose of this study was to characterize the soil fertility of high and low restinga forests, by chemical and physical parameters, and its relation to the root system distribution in the soil profile. Four locations were studied: (1) Ilha Anchieta State Park, Ubatuba; (2) two Ecological Stations of Jureia-Itatins and of Chauás, in the municipality of Iguape; (3) Vila de Pedrinhas in the municipality of Ilha Comprida; and (4) Ilha do Cardoso State Park, Cananeia. The soil fertility (chemical and physical properties) was analyzed in the layers 0-5, 0-10, 0-20, 20-40 and 40-60 cm. In addition, the distribution of the root system in the soil profile was evaluated, using digital images and the Spring program. It was concluded that the root system of all vegetation types studied is restricted to the surface layers, 0-10 and 10-20 cm, but

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occupies mainly the 0-10 cm layer (70 %); that soil fertility is low in all environments studied, with base saturation values below 16 %, since most exchange sites are occupied by aluminum; and that restinga vegetation is edaphic.

Index terms: base saturation, root system, edaphic vegetation.

RESUMO: CARACTERIZAÇÃO DA FERTILIDADE DO SOLO E SISTEMA RADICULAR DE FLORESTA DE RESTINGA

A Restinga é um conjunto de comunidades vegetais em mosaico, determinadas pelas características de seus substratos resultantes de processos deposicionais e idades. Nesse complexo mosaico encontram-se as fitofisionomias de florestas de restinga em estádio de elevada regeneração (restinga alta) e em estádio de média regeneração (restinga baixa), cada qual com suas características vegetais que as diferenciam. O clima no litoral é do tipo tropical (Köppen). A Restinga, de todos os ecossistemas associados à Mata Atlântica, é o mais frágil e suscetível às perturbações antrópicas. As plantas respondem às características do solo por meio de modificações fisiológicas e morfológicas, de modo a alterar a arquitetura (configuração espacial) de seus sistemas radiculares. Este estudo teve por objetivo caracterizar a fertilidade do solo, por meio dos parâmetros químicos e físicos, sob floresta de restinga alta e baixa, com relação à distribuição do sistema radicular no perfil do solo. Foram estudados quatro locais: (1) Parque Estadual da Ilha Anchieta, município de Ubatuba; (2) Estação Ecológica Jureia-Itatins, Estação Ecológica dos Chauás, município de Iguape; (3) Vila de Pedrinhas, no município de Ilha Comprida; e (4) Parque Estadual da Ilha do Cardoso, município de Cananeia. Os estudos sobre fertilidade do solo foram feitos nas profundidades de 0-5, 0-10, 0-20, 20-40 e 40-60 cm, para as análises químicas e físicas. Também foi avaliada a distribuição do sistema radicular no perfil do solo, utilizando imagens digitais e o programa Spring. Conclui-se que o sistema radicular, para todas as fitofisionomias estudadas, encontra-se nas camadas mais superficiais, 0-10 e 10-20 cm, principalmente na primeira (80 %); que todos os ambientes estudados apresentaram baixa fertilidade do solo, com valores de saturação por bases inferiores a 16 %, em que a maior parte da CTC está ocupada por Al^{3+}; e que a vegetação de restinga é edáfica.

Termos de indexação: saturação por bases, sistema radicular, vegetação edáfica.

INTRODUCTION

According to Suguio & Tessler (1984), the term “restinga” is used in the Brazilian literature with different meanings; it can be used to designate various types of coastal deposits, as well as other coastal features, and even vegetation. The different vegetation types found in Brazilian restinga range from grasslands and shrublands to forests, with a maximum canopy height of 20 m (Silva, 1999). According to Rizzini (1997), restinga vegetation is a mosaic set of plant communities, defined by the characteristics of the substrates which, in turn, are determined by the type and age of the depositional processes (Araújo & Lacerda, 1987).

Of all ecosystems belonging to the Atlantic Forest, Restinga is the most fragile and susceptible to anthropic disturbances, and has lost territory to urban infrastructure (Araújo & Lacerda, 1987; Silva et al., 1993). Due to its location, the degradation process of its natural features has been intense, ever since the time of the European colonization. This ecosystem was virtually the first to be affected by anthropic impacts which, almost four centuries after the country’s discovery, began to affect inland ecosystems. Few restinga areas have preserved natural characteristics and only a few are protected in Conservation Units (Lacerda & Esteves, 2000). The activity with greatest impact on these ecosystems is construction with removal of topsoil or depositions of clayey soil for earthwork, altering the soil water regime completely. Taking into account that the earth fill material is generally brought from nearby areas, the impact on neighboring areas is even greater.

The climate that characterizes much of the coast, according to the Köppen classification, is tropical type, with an average temperature of over 18 °C during the hottest month of the year, total rainfall of 60 mm during the driest month, and annual precipitation of approximately 2,200 mm. It does not have a dry winter season, only decreased rainfall, while summers are extremely humid (Rossi, 1999). According to the data registers (Embrapa, 2003), the municipalities of Cananeia, Iguape and Ubatuba, on the coastline of São Paulo, have average annual temperatures of 24.1/

24.3/21.9 °C, average annual rainfall of 2,261/1,900/ 2,519 mm, and water surplus of 939/551/1,460 mm, respectively. Ubatuba (SP) has water deficits, but for seven days per year only, i.e. the coastline of São Paulo is a region where water deficits practically never occur.

Restinga vegetation grows on sandy, chemically poor soils, with sea spray as the main source of nutrients (Araújo & Lacerda, 1987). Studies on the Brazilian coast have shown that the main soil classes underlying this vegetation are Spodosols and Quartzipsamments (Gomes et al., 2007), and that the latter are often in an initial process of podzolization, with intermediate characteristics of Spodosol. The base saturation (V%) of these soils is very low, mostly below 25 %.

The root system is exposed to spatial and temporal changes, in terms of concentrations of soil nutrients (Lainé et al., 1998); the plants respond to this heterogeneity by physiological and morphological modifications, resulting in changes in architecture (spatial configuration) of the root system. Typically, roots grow abundantly towards areas with higher nutrient concentrations (van Vuuren et al., 1996), most likely a compensatory, adaptive response to soil variability (Robinson, 1996). Among the restrictive chemical factors of acid soils that most affect the nutrient uptake are toxic elements (Al, especially) and the proper lack of nutrients, especially of P and Ca. The Al content in soil causes reduced root growth and varies according to the species, cultivars and soils. Roots do not grow in soils that are deficient in Ca, which is essential for cell division and cell membrane functionality. In quantitative terms, the demand is not high, but Ca must be present at the growth points, since there is no translocation from the phloem to the roots (Raij, 1991).

High rainfall combined with the sandy particle size of the soil leads to rapid leaching of salts with the water, which easily permeates the soil profile, so that these soils are not saline (Casagrande et al., 2006; Sato, 2007).

The purpose of this study is to characterize the soil fertility of high (advanced stage) and low (intermediate stage) restinga forests, by chemical and physical parameters, and to evaluate the distribution of the root system in the soil profile at four locations, developing knowledge about the limitations and capabilities of these soils as a guideline to the recovery of degraded areas.

MATERIAL AND METHODS

The study was conducted in the restinga ecosystem, in forest vegetation types in advanced (high restinga) and intermediate (low restinga) stages of regeneration, at four locations along the coastline of São Paulo: (1) Ilha Anchieta State Park, municipality of Ubatuba (23° 32' 24.58" S; 45° 4' 33.03" W); (2) Jureia-Itatins Ecological Station and Chauás Ecological Station, municipality of Iguape (24° 33' 2.16" S; 47° 13' 16.80" W); (3) Vila de Pedrinhas in the municipality of Ilha Comprida (24° 53' 52.38" S; 47° 47' 56.22" W); and (4) Ilha do Cardoso State Park, municipality of Cananeia (25° 04' 29.50" S; 47° 55' 41.10" W). The characterization of the restinga forest vegetation types was based on CONAMA Resolution No. 417/2009 (CONAMA, 2009).

Soil samples and analyses

The soil fertility studies (layers 0-5, 0-10, 0-20, 20-40 and 40-60 cm) addressed restinga forest in advanced and intermediate stages of regeneration, with five replications per vegetation type, each consisting of 12 subsamples from each study location. The data were statistically analyzed by means of variance analysis (ANOVA), and the averages compared by the Tukey test at 5 %, using the statistical software Assistat (Assis, 2011).

The chemical analyses were performed according to Embrapa (1997), determining pH, organic matter (OM), P, K, Ca, Mg, S, Al, H+Al, B, Cu, Fe, Mn, Zn, Al saturation (m%), sum of bases (SB), cation exchange capacity (CEC), base saturation (V%), as well as electrical conductivity (Camargo et al., 1986), sodium adsorption ratios (SAR) and exchangeable sodium percentage (ESP) which, together with the pH of the soil, are the criteria for classifying the soil as saline, sodic or saline-sodic. The physical analyses determined bulk density and particle size (Camargo et al., 1986). The analyses were performed at the Chemical Analysis Laboratory for Soils and Plants and the Soil Physics Laboratory of the Center for Agricultural Sciences, Araras Campus, of the Department of Natural Resources and Environmental Protection.

Distribution of the Root System

To analyze the root system distribution in the soil profile, trenches (width 80 cm and depth 70 cm) were opened, with three replications per vegetation type, at each study location. A species common to both vegetation types and at all study locations, *Psidium cattleyanum* (Araçá), was used as reference. After opening the trenches, the profile surface were vertically leveled to expose all roots. The soil particles on the roots were removed to avoid difficulties during the digital operations for root/soil differentiation and classification in the pictures. A wooden frame with a string grid (10 x 10 cm, vertically and horizontally) was then placed parallel to the soil profile. The frames were photographed using a high-resolution digital camera. The scheme/structure of the database was assembled by the program Spring (Camara et al., 1996), version 5.1.2. (Bonilha, 2012).

The images were processed (Spring) and automatically converted into three “RGB” (Red, Green and Blue) bands, allowing the histogram of the images to be viewed. Next, the RGB bands were transformed into IHS bands (Intensity, Hue and Saturation). Selecting the I (Intensity) band permits a "statistical analysis" of each image, providing the gray-level range in which the roots are found, the average of the values, variation coefficient, standard deviation and the asymmetry coefficient for each image. Thus, with the discrimination of the roots in the digital image, together with the vectorization of the quadrat (frame), the percentage of roots in the soil profile was calculated. By relating the quantity of roots per layer with the total amount of roots in the profile, the percentage of roots per layer was computed.

RESULTS AND DISCUSSION

Organic matter (OM) content was higher, in all vegetation types and at each location, in the surface layers (0-5, 0-10 and 0-20 cm), decreasing with increasing depth, and was statistically higher in the layers down to 20 cm (Table 1), as also noted for CEC. Due to the fact that restinga soils are very sandy, with only 2-4 % clay (Table 3), OM is even more essential in terms of nutrient retention and supply.

In the advanced restinga of the Jureia/Itatins Ecological Station and in the advanced (HR) and low (LR) restinga of Ilha Anchieta, that OM and CEC content were higher in 40-60 cm than the 20-40 cm layer (Table 1). As pointed out by Gomes et al. (2007), this can be explained by the occurrence of podzolization, with a spodic horizon in the 40-60 cm layer, characterized by the illuviation of humus acid, with or without Fe^{2+} and Al^{3+} oxyhydroxides and aluminosilicates. Spodosols are mineral soils, with horizon sequences of A-E-Bh, or Bs, or Bhs-C. They are mostly sandy, and there are few citations of other textural classes. In Ilha do Cardoso, in this study, to a depth of 60 cm, no spodic horizon was found, although it does occur at different depths below 60 cm (Gomes et al., 2007).

In all areas studied, for both high and low restinga, with the exception of the low restinga on Ilha do Cardoso, there was a significant decrease in P content in deeper layers (Table 1). The highest levels were found in the top layers, to a depth of 20 cm, with no difference between the layers 0-5, 0-10 and 0-20 cm. This P distribution in the soil profile of restinga forests, to a depth of 60 cm, is linked to the distribution of the OM content, with a correlation of 83 % (Table 1). Machado et al. (1993) evaluated samples of 44 soils in 11 major mapping units, and found that organic P accounted for 57 % of the total P and a significant correlation between organic P and OM in the soil. It should be noted that for restinga forest soils, with a very low clay content, the factors causing retention of P, Fe oxides and Al are present at low levels (Gomes et al., 2007). The work involving the characterization and classification of restinga vegetation soils on Ilha do Cardoso (Gomes et al., 2007) showed iron accumulation in depth, although the values were low. This finding indicates the importance of OM for P retention in the surface layers of these soils. In view thereof, nutrient cycling plays an essential role in maintaining P in the soil-plant system.

The sum of bases ranged from 2-12 $mmol_c\ dm^{-3}$, which are very low values from an agricultural standpoint, resulting in low V% values as well (2-20 % for all areas) (Table 1). As a reference value, soil remediation is recommended for mixed stands with typical Atlantic Forest species when V% is less than 40 % (Raij et al., 1997).

Base saturation, in turn, is an index number that compares K, Ca and Mg content with CEC, which represents the soil base saturation (BS) in relation to CEC (BS+H+Al). Their values indicated that the quantities of cations (K^+, Ca^{2+} and Mg^{2+}) are present in the same proportion in each area, as reported by Casagrande et al. (2010), and observed by Pinto (1998), Reis-Duarte (2004), Sato (2007), and Martins (2010). According to Schoenholtz et al. (2000), for acidic forest soils, CEC is less important than V%, as a parameter of soil fertility to indicate the nutrient supply from the soil. This shows that, although CEC, as well as the OM content, are higher in the topsoil, the percentage of cations present is always low, resulting in low V% values and low fertility throughout the profile, since most exchange sites are occupied by aluminum, as indicated by Al saturation (Table 1).

These considerations show that restinga is a type of edaphic vegetation, in that the soil plays a decisive role in the forest development. On the other hand, as also observed by Martins (2010) in an altitudinal gradient of the Atlantic Forest, it was noted that the agronomic concept of low natural fertility may not apply to the study of soil-vegetation interaction in natural ecosystems, since the very low nutrient contents, m% around 60-91 % and V% below 24 %, would not explain the exuberance of low and high restinga forests. The concepts of ecological succession groups can most likely be applied to the situation of high and low restinga, where species with lower nutrient requirements have come to constitute the majority of the population.

The Al content (Table 1) was high in all soil layers of all areas and vegetation types, with a statistical difference between the layers, mainly between those between the surface and a depth of 20 cm and the deeper layers. The Al content was higher at 40-60 cm compared than in the layer above, in the cases of spodic horizon in the high restinga forest on Ilha Anchieta and at the Ecological Station of Jureia-Itatins. As a result, Al saturation values were very high for all

Table 1. Results of the chemical analyses of restinga forest soils in advanced (high restinga) and intermediate (low restinga) stages of regeneration, at four locations along the coast of the state of São Paulo

Depth	Pres		OM		pH		K^+		Ca^{2+}		Mg^{2+}		H+Al		Al^{3+}		SB		CEC		V		m		S	
cm	mg dm^{-3}		g dm^{-3}		$CaCl_2$								mmol$_c$ dm^{-3}								%				mg dm^{-3}	
													Ilha Anchieta															
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
0 - 5	11aB	22aA	49aA	61aA	3.2bC	3.2bC	0.8aA	0.4bB	2aC	3aB	2aB	7aA	112aB	177 aA	25aA	20aB	4aB	11aA	116aB	188aA	4 bB	6 bB	85bA	66bB	14aA	12aA
0 - 10	11aB	20aA	49aA	55aA	3.2bC	3.2bC	0.8aA	0.5aB	2aB	2bB	2aB	7aA	113aB	153 aA	24aA	18aB	4aB	9aA	115aB	161aA	3 bC	5 bC	87aA	70bC	15aA	10aB
0 - 20	11aA	20aA	42bA	29bB	3.2bC	3.2bC	0.6bA	0.3cC	1bC	1cC	1bB	2bA	108aA	68 bB	24aA	13bB	3bC	4bC	111aA	72bB	2 bC	5 bC	90aA	78aB	11aA	3 bC
20 - 40	4bA	2bC	8dA	5cB	3.9aA	3.9aA	0.3cB	0.1dD	1bB	1cB	1bB	1bB	14cB	12 bB	6bB	3cC	3bB	2bB	17cB	14cB	15aA	15aA	69cA	60cB	1 bC	1 bC
40 - 60	2bC	2bB	20cA	29bA	3.9aA	3.9aA	0.3cB	0.1dD	1bB	1cB	1bB	1bB	76bA	10.5bD	23aA	3cD	2bB	2bB	79bA	34cD	3 bC	17aA	91aA	65bB	3 bC	2 bD
													Ilha do Cardoso															
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
0 - 5	10aB	3aD	47aA	34aB	3.4bB	3.1bC	0.5aB	0.2bC	1aC	2aC	4aA	2aB	54aC	116aB	13aC	13aC	6aB	4aB	61aC	119aB	11cB	5 bB	66aB	77aA	7 aB	7 aB
0 - 10	8aC	3aD	43aA	28aB	3.4bB	3.2bC	0.4aB	0.2bC	1aC	2aB	4aA	2aB	47aC	92 aB	12aC	11aC	5aB	3aB	52aD	95aC	10cB	5 bC	69aC	78aB	7 aC	7 aC
0 - 20	2bC	4aC	31bB	26aB	3.3bC	3.5aB	0.3aC	0.4aB	1aC	2aB	2bA	2aA	38aC	49 bC	11aB	7bC	4bB	4aB	42aC	53bC	10cB	9 aB	73aB	61bD	6 aB	8 aB
20 - 40	1bD	3aB	9cA	11bA	3.6bB	3.5aB	0.1bD	0.1bD	1aB	2aA	1bB	1aB	12bB	23 bA	5bB	6bB	2bB	3aA	14bB	26bA	15bA	14aA	70aA	62bB	3 bB	5 aA
40 - 60	1bD	3aA	4cB	8bB	3.9aA	3.6aB	0.1bD	0.1bD	1aB	1bB	1bB	1aB	10bD	21 bC	2bD	4bC	3bB	3bB	13bD	24bC	19aA	9 aB	47bC	61bB	2 bD	5 bA
													Ilha Comprida															
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
0 - 5	7aC	3aD	29aB	31aB	3.2cC	3.6bA	0.4aB	0.5aB	4aA	5aA	5.4aA	5aA	65aC	50 aC	13aC	9aD	12aA	10aA	76aC	61aC	16aA	19aA	54bC	45cC	12aA	11aA
0 - 10	7aC	4aD	30aB	29aB	3.2cC	3.6bA	0.4aB	0.5aB	4aA	4aA	4.5aA	4bA	67aC	42 bC	13aC	9aD	9aA	9bA	76aC	58aD	12bB	17aA	60bD	49cE	14aA	11aB
0 - 20	7aB	2bC	25aB	16bC	3.2cC	3.6bA	0.4aB	0.4bB	1bC	2cA	2.6bA	3cA	64aB	29 bC	12aB	8aC	4bB	5cA	68aB	35bC	6 bC	18aA	76aB	59bD	14aA	8 aB
20 - 40	3bC	2bD	9bA	4cB	3.4bC	3.9aA	0.2bC	0.3cB	1bB	1dB	1.4dB	1dB	23bA	12 cB	7bA	4bB	3bB	2dB	25bA	15cB	10bB	16aA	74aA	65ab	5 bA	4 bB
40 - 60	3bB	1cD	5bB	1cB	3.6aB	4.0aA	0.2bC	0.3cB	3aA	1dA	1.6cA	1dB	15bD	13 cD	4cC	6bB	5bA	2dB	20bC	16cD	24aA	15aA	49cC	70aB	4 bB	3 bC
													Jureia-Itatins															
	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low
0 - 5	4aD	3aD	16aB	24aB	3.3bB	3.3cB	0.5aB	0.4aB	1aC	1aC	2aB	3aB	38bC	49aC	9aD	8aD	4aB	4aB	42bC	53aC	9bB	8cB	70aB	66aB	4aB	3aB
0 - 10	4aD	3aD	15aB	20aB	3.3bC	3.3cC	0.5aB	0.4aB	1aC	1aC	2aB	2bB	37bC	43aC	9aD	7aD	3aB	4aB	40bD	46aD	9bC	8cC	73aC	67aC	3aD	3aD
0 - 20	3aC	2aC	13aC	13bC	3.4bC	3.3cC	0.5aA	0.4aB	1aC	1aC	1aB	2bA	35bC	26bC	9aC	6aC	3bC	3bC	37bC	29bC	7bC	11bB	79aB	67aC	3aC	4aC
20 - 40	2bC	1bD	4bB	3cB	3.6aB	3.8bA	0.4aA	0.3bB	1aB	1aB	2aA	1cB	16cB	11cB	8aA	2bC	3aA	2cB	19cB	13cB	16aA	18aA	72aA	39bC	1bC	1bC
40 - 60	1bD	1bD	15aA	2cB	3.6aB	4.1aA	0.5aA	0.3bB	1aB	1aB	1aB	1cB	66aB	9cD	11aB	1bD	2bB	2cB	69aB	12cD	4cC	20aA	77aB	33bC	3aB	2bD

High: restinga in advanced regeneration. Low: restinga in medium regeneration. Averages followed by the same letter do not differ statistically by the Tukey test at 5 %. Small letters refer to layers of the same single location, and capital letters to the same layer in all locations.

areas and vegetation types, reaching 90 % saturation, even when the horizon was not spodic. Other authors also found high Al contents in the surface layer: Sugiyama (1993), on Ilha do Cardoso; Guedes-Silva (2003), in Bertioga; Carrasco (2003), on Ilha Comprida, and Casagrande & Soares (2009), in Picinguaba. In 63 % of these restinga soil samples, Al was higher than 10 $mmol_c$ dm^{-3} and 11 % exceeded 20 $mmol_c$ dm^{-3}. These values indicate that the exchangeable Al content in the restinga surface layer was higher than the values in the *cerrado* (Brazilian savannah-like ecosystem): Lopes (1984) found that most of 518 *cerrado* surface samples from Minas Gerais and Goiás had Al contents of 2.5-10.0 $mmol_c$ dm^{-3} and only 15 % exceeded 10.0 $mmol_c$ dm^{-3}.

Low pH levels are common in restinga soils, since these soils develop beneath sandy sediments, originally poor in bases (Gomes et al., 2007). In all areas and depths studied, the pH values were very low (3.2-3.9), with decreasing acidity in deeper layers (Table 1). This high acidity helps the nutrient cycling process, by slowing down the nutrient release from leaf litter to the extremely sandy soil (< 5 % clay). According to Pires et al. (2006), in a study on Ilha do Mel, annual leaf litter production in restinga forests corresponds to the lower limit of the amount obtained in tropical forests (5.5 ton ha^{-1} $year^{-1}$). However, together with the relatively low annual decomposition rate, this high acidity represents an adaptative advantage of the ecosystem, by minimizing leaching losses and enhancing nutrient use. These pH values also indicate that 60-80 % of the Al in these soils is found in the form of Al^{3+}. Furthermore, the concentrations or activities of the ionic forms of the micronutrients that are preferentially absorbed from the soil solution by plants, under well-aerated soil conditions, are pH-dependent (Abreu et al., 2007).

Boron, under acidic conditions (pH<7), mainly in the form of undissociated boric acid (H_3BO_3), is highly soluble and easily permeable to the cell membrane (Mengel & Kirkby, 1987). According to et al. (1997), high boron values were observed (Table 2) for all areas in the 0-5, 0-10 and 0-20 cm layers, and average values in the deeper layers (20-40 and 40-60 cm). Under high rainfall, with a high degree of leaching losses, particularly in sandy soils, boron availability is reduced (Abreu et al., 2007). The available boron is mainly associated with organic matter, which explains its higher content in the topsoil.

The contents of copper (Cu), whose high acidity increases its availability, were medium in the surface layers (down to 20 cm) (Table 2) under high restinga forest in Ilha Anchieta, and low, according to the classification proposed by Raij et al. (1997), in all other areas and layers. These contents are related to organic material, which also decreases with depth. Of all micronutrients, Cu interacts most with the soil organic compounds, forming stable complexes, and some of these complexes are so stable that most Cu deficiencies were associated with organic soils (Abreu et al., 2007).

The availability of manganese (Mn), similarly to boron and copper, is enhanced by higher soil acidity and also interacts with the soil OM, forming organic complexes, albeit with lower affinity than Zn and Cu. The values obtained for Mn were high, according to Raij et al. (1997) (Table 2), in the high and low restingas on Ilha Comprida and Ilha do Cardoso, in the 0-5 and 0-10 cm layers, and average in the other layers and areas. At the Ecological Station of Jureia-Itatins, despite a low OM content, average values were registered for Mn, due to the fact that Mn availability is reduced in sandy soils with high rainfall and low cation exchange capacity (CEC) (Abreu et al., 2007). As shown in table 1, the CEC values at the Ecological Station of Jureia-Itatins were in the range of 40 - 53 $mmol_c$ dm^{-3} for high and low restinga, whereas for Ilha Anchieta they were in the range of 115 - 188 $mmol_c$ dm^{-3} for high and low restinga, respectively.

The iron (Fe) contents were high (Raij et al., 1997) in the surface layer (0-5, 0-10 and 0-20 cm) for all areas, with average values in the deeper layers (20-40 and 40-60 cm) (Table 2). With the exception of the contents in the high restinga forest of the Ecological Station of Jureia-Itatins, the Fe contents were higher in the 40-60 cm layer, with average values in the surface layer (0-20 cm) and lower values in the intermediate layer (20-40 cm), in line with the distribution of OM in the surface and deeper layers, which is typical of Spodosols.

The values for Zn decreased with increasing depth, in all areas under study, and were considered low, according to Raij et al. (1997) (Table 2). The reason is that Zn availability increases when acidity is high and the clay content low, resulting in severe leaching.

The extremely sandy texture results in excessive drainage due to high macroporosity and low water holding capacity (Table 3). Nevertheless, there is no water deficit throughout the year because the level of precipitation along the coastline of São Paulo is significantly higher than in the other regions of the State, with an annual average of 2,200 mm (Sanchez et al., 1999). However, the combination of sandy texture and exposure to high precipitation leads to intense leaching of nutrients that are essential for plant development (Casagrande & Soares, 2008). These conditions characterize soils with a low support potential for biomass production, making forest regeneration a very slow process, especially when deforestation was followed by a long period of losses exceeding the additions.

Therefore, the highly sandy texture, high rainfall and soils with low support potential for biomass production result in a low capacity of the vegetation to overcome critical situations (degradation) and regain the natural state of excellence (low resilience). These characteristics reduce the nutrient-retention capacity, indicating that the nutrient availability for

Table 2. Micronutrient contents in the different layers of soils under restinga forests in advanced (high) and intermediate (low) stages of regeneration, at four locations

Depth	B		Cu		Fe		Mn		Zn	
cm	mg dm^{-3}									
Ilha Anchieta										
	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.
0 – 5	2.17 aA	1.72 aB	0.4 aA	0.1 bB	175 aA	10 bC	0.8 aC	0.4 bC	0.5 aA	0.2 cB
0 – 10	1.97 aA	1.36 aB	0.4 aA	0.1 bC	180 aA	30 aC	0.9 aC	0.7 aC	0.5 aA	0.4 aA
0 – 20	1.94 aA	0.95 bB	0.5 aA	0.2 aB	175 aA	30 aC	0.7 aB	0.6 aB	0.5 aA	0.3 bB
20 – 40	0.53 bA	0.38 cA	0.2 bA	0.1 bB	58 bA	4 cC	0.3 bB	0.2 bB	0.3 bA	0.2 cA
40 – 60	0.52 bA	0.27 cB	0.1 bA	0.1 bA	38 bB	3 cC	0.2 bB	0.3 bB	0.2 cC	0.2 cC
Ilha do Cardoso										
	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.
0 – 5	1.13 aC	0.66 aC	0.1 bB	0.1 aB	13 aC	30 aC	1.2 aB	1.2 aB	0.5 aA	0.2 bB
0 – 10	1.22 aB	0.55 aC	0.2 aC	0.1 aC	12 aC	30 aC	0.8 bC	1.1 aB	0.4 aA	0.2 bB
0 – 20	0.87 aB	0.55 aC	0.2 aB	0.1 aB	11 aC	26 aC	0.7 bB	0.8 aB	0.4 aB	0.3 bB
20 – 40	0.42 bA	0.23 bB	0.1 bB	0.1 aB	5 bC	19 aB	0.2 cB	0.8 aA	0.2 bA	0.2 bA
40 – 60	0.44 bA	0.29 bB	0.1 bA	0.1 aA	5 bC	22 aB	0.3 cB	0.8 aA	0.3 bB	0.5 aA
Ilha Comprida										
	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.
0 – 5	0.87 aC	1.39 aB	0.2 aB	0.1 aB	28 aC	50 aB	1.5 aB	4.0 aA	0.6 aA	0.5 aA
0 – 10	0.93 aC	1.34 aB	0.2 aB	0.1 aC	27 aC	44 aB	1.5 aB	2.9 aA	0.5 aA	0.5 aA
0 – 20	0.84 aB	0.83 bB	0.1 bB	0.1 aB	34 aC	30 aC	0.9 bB	1.2 bA	0.5 aA	0.3 bB
20 – 40	0.37 bA	0.53 bA	0.1 bB	0.1 aB	16 bB	8 bC	0.3 cB	0.2 bB	0.2 bA	0.2 cA
40 – 60	0.17 bB	0.45 bA	0.1 bA	0.1 aA	9 bC	12 bC	0.2 cB	0.2 bB	0.2 bC	0.2 cC
Jureia-Itatins										
	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.
0 - 5	0.53 aC	0.41 aC	0.2 aB	0.2 aB	52 bB	28 aC	0.4 aC	0.7 aC	0.3 aB	0.3 bB
0 - 10	0.59 aC	0.37 aC	0.1 bC	0.2 aB	52 bB	27 aC	0.5 aC	0.6 aC	0.3 aB	0.3 bB
0 - 20	0.66 aC	0.18 bD	0.1 bB	0.1 bB	81 bB	22 aC	0.4 aB	0.6 aB	0.2 aB	0.5 aA
20 - 40	0.34 bA	0.10 bB	0.1 bB	0.1 bB	50 bA	8 bC	0.3 bB	0.4 bB	0.1 bB	0.2 bA
40 - 60	0.56 aA	0.21 bB	0.1 bA	0.1 bA	186 aA	5 bC	0.6 aA	0.3 bB	0.2 aC	0.1 cC

High R.: advanced regeneration. Low R.: intermediate regeneration. Small letters refer to depths at the same location, and capital letters to the same depth at all locations. Averages followed by the same letter do not differ statistically by the Tukey test at 5 %.

vegetation is sustained by leaf litter decomposition, since the nutrient levels in the soil are very low. The soil fertility levels corroborate this assumption, since the soil acts more as nutrient support than as reservoir. These facts lead to the conclusion that the restinga forest ecosystem is edaphic.

In these soil profiles with high and low restinga vegetation along the coastline of São Paulo, the distribution of the root system was also evaluated, generating important information to better understand the soil-plant interactions of an ecosystem considered edaphic (Table 4).

In both vegetation types, the distribution of the root system was concentrated in the surface layers down to 20 cm (0-10 and 10-20 cm), with on average 92 and 94 % of the roots under high and low restinga, respectively. In the top 10 cm of soil, 69 and 68 % of the roots were concentrated, under high and low restinga, respectively. In other words, almost 70 % of the root system was found in top 10 cm of soil (Table 4).

The root system, under all vegetation types and at all locations (Table 4), was not significantly developed below the depth of 20 cm (8 and 6 %, respectively, for high and low restinga). The only exception was the high restinga of Ilha Comprida, where 24 % of the roots were found below 20 cm. The root system is exposed to spatial and temporal changes, in terms of concentrations of soil nutrients (Lainé et al., 1998); the plants respond to this heterogeneity by physiological and morphological modifications, resulting in changes in architecture (spatial configuration) of the root system. Typically, roots grow abundantly towards areas with higher

Table 3. Results of the physical analyses of soil under restinga forest in advanced (high) and intermediate (low) stages of regeneration at four locations

Depth	Ilha Anchieta				Ilha do Cardoso				Ilha Comprida				Jureia-Itatins			
	Clay	Sand	Silt	Ds	Clay	Sand	Silt	Ds	Clay	Sand	Silt	Ds	Clay	Sand	Silt	Ds
cm	%			kg dm^{-3}	%			kg dm^{-3}	%			kg dm^{-3}	%			kg dm^{-3}
								High Restinga								
0-5	2	96	3	0.80	1	90	9	0.61	2	97	1	0.99	1	92	7	0.99
0-10	2	96	3	0.90	2	91	8	0.74	2	97	2	1.03	2	91	8	1.04
0-20	2	94	4	1.12	2	94	4	1.07	2	97	1	1.12	2	94	4	1.14
20-40	2	96	2	1.32	2	93	5	1.44	2	97	1	1.31	1	94	5	1.21
40-60	2	96	2	1.38	1	96	3	1.51	1	98	1	1.32	1	95	4	1.14
								Low Restinga								
0-5	3	95	2	0.92	2	90	8	0.99	2	96	2	0.94	2	94	4	1.06
0-10	3	96	2	1.01	2	91	8	1.27	2	97	2	1.01	2	95	4	1.12
0-20	4	95	1	1.23	2	92	6	1.66	2	95	3	1.06	2	95	3	1.19
20-40	3	95	2	1.44	1	93	6	1.78	1	98	1	1.30	1	93	6	1.34
40-60	2	97	1	1.41	1	91	7	1.67	1	97	2	1.27	2	91	7	1.31

High Restinga: advanced regeneration; Low Restinga: medium regeneration; Ds: soil density.

Table 4. Percentage of the root system distribution of restinga forest in the soil profiles at four study locations

Depth	Ilha Anchieta		Ilha do Cardoso		Ilha Comprida		Jureia-Itatins	
	High R.	Low R.	High R.	Low R.	High R.	Low R.	High R.	Low R.
cm	%							
0-10	67 a	86 a	77 a	59 a	50 a	52 a	81 a	77 a
10-20	31 b	14 b	21 b	38 a	26 ab	35 ab	14 b	16 b
20-30	2 c	0 c	1 bc	3 b	21 ab	5 b	3 b	2 b
30-40	0 c	0 c	0 c	0 b	3 b	8 ab	2 b	5 b

High R.: advanced regeneration. Low R.: medium regeneration. Averages followed by the same letter do not differ statistically in depth by the Tukey test at 5 %.

nutrient concentrations (van Vuuren et al., 1996), most likely a compensatory, adaptive response to soil variability (Robinson, 1996). Taking into account that approximately 70 % of the restinga forest root system was concentrated in the 0-10 cm layer, it can be concluded that this layer would provide the best soil sample to determine fertility.

Thus, the more superficial development of the root system can be explained, in all areas (Table 4), by the low calcium content and high aluminum saturation (Table 1), which may be reflected in a slowdown, limitation or even the failure of revegetation (Reis-Duarte & Casagrande, 2006).

Therefore, it can be concluded that the main parameters of restinga forest soil fertility are linked to high acidity, organic matter content, which is responsible for CEC, since the clay content is very low, and the low nutrient reserve. Hence, the removal of vegetation is critical in these environments, especially due to the elimination of nutrient cycling, leading to intense leaching and the destruction of organic matter. In this context, in spite of the seed bank available, the natural conditions for the recovery of vegetation are not given, particularly where anthropization caused the severe degradation of the soil by removal of the surface layer.

Soil fertility management in degraded restinga areas must focus on increasing the capacity to retain nutrients, as well as the permanent availability of nutrients during the early years of revegetation. The supply of organic matter is critical for the success of the more complex initial phases, since OM represents an important source of nitrogen and micronutrients and establishes a regime of slower and more gradual nutrient release. The kinetics of nutrient release can also be slowed down by the use of rocks that take longer to dissolve. The use of legumes is always adequate as alternative for nitrogen supply and organic matter production in the early revegetation stage.

CONCLUSIONS

1. The main limitations of soil fertility of restinga forest are low nutrient availability and high aluminum saturation;

2. Approximately 70 % of the root system is concentrated in the 0-10 cm layer and more than 90 % is found in the 0-20 cm layer;

3. Soil fertility should be determined in samples from the 0-10 cm layer;

4. Restinga vegetation is edaphic.

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