

Article

Assessing Trail Erosion Through Soil Geochemical and Physical Characterization in Southern Ubatuba, São Paulo, Brazil

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Abstract

This study investigated the impact of recreational use on trails in the Atlantic Forest (Ubatuba Municipality, São Paulo State, Brazil) using physical, chemical and geochemical indicators. Five trails with different morphological characteristics were selected, and paired samples were collected from the trail surface (TR) and trail-side slope (TA). The statistical approach combined local analyses for each trail with global clustering ($n = 19$) using Student's t -test, along with multivariate modeling through Principal Component Analysis (PCA) and Pearson correlation. The analysis included physical attributes (bulk density, particle size and porosity), chemical attributes (pH, organic matter and macronutrients) and geochemical compositions (major oxides and trace elements determined by XRF). The overall results reveal systematic compaction in the trail surface (TR), with bulk density increasing from 1.32 g/cm³ (TA) to 1.37 g/cm³ (TR) ($p = 0.038$), and total porosity decreasing from 47.26% to 45.34% ($p = 0.016$). In contrast, the geochemical oxide composition (SiO₂, Al₂O₃, Fe₂O₃) remained stable ($p > 0.05$), indicating the resilience of the mineral matrix. However, significant local dynamics ($p < 0.05$) in K₂O and MgO were observed in more preserved trails, associated with surface compaction and fragmentation of the litter layer, and phosphorus showed strong dependence on organic matter ($r = 0.85$). Multivariate analysis indicates that degradation is predominantly physical and micromorphological at the local scale, with bulk density and porosity being the most sensitive indicators for environmental monitoring.

Keywords: soil degradation; trails; geochemistry; soil compaction; Atlantic Forest; Brazil



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1. Introduction

Trails are cultural features that have historically been present in human societies and have long been used as routes for communication, territorial exploration, and movement between different locations. In recent decades, trails have been increasingly used to access natural environments for nature appreciation, recreation, adventure sports, ecotourism [1–9], and, more recently, geotourism [10–13]. Although trails are essential for accessing natural areas, their use has generated several environmental impacts, leading to degradation [14].

One of the main consequences of inadequate trail management is soil degradation, defined as a reduction in soil quality and its capacity to function as an environmental regulator [15,16]. Research on the impacts of trail use has increased significantly in recent

decades, particularly regarding trampling, which can lead to soil compaction, erosion, nutrient loss, reduced organic matter and decreased soil biological activity [17–27].

The intensity of these impacts varies depending on environmental conditions and the type and frequency of trail use [28]. Several environmental indicators have been used to assess trail degradation, revealing changes in both biotic and abiotic conditions. Studies indicate that the opening and use of trails can alter temperature regimes, increase soil exposure to solar radiation, intensify wind exposure and facilitate the invasion of exotic species [29–31].

Vegetation responses to trampling have been extensively investigated through comparisons between areas near and far from trails. Experimental studies conducted in Tropical Forest environments in Conservation Units within São Paulo State have demonstrated that trampling affects vegetation cover, species richness and the extent of exposed soil, although responses may vary according to the resistance and resilience of ecosystems [32,33]. Vegetation with greater resistance and resilience to trampling tends to better withstand recreational use, exhibiting lower levels of degradation.

Recreational impacts can also differ between forest types due to variations in soil structure and nutrient availability, influencing soil and vegetation resilience [24,34]. Soil–plant interactions are fundamental to ecosystem functioning, as nutrient availability directly influences vegetation development and microbial activity. However, alterations in soil physical structure, particularly those caused by compaction, can reduce microbial activity and nutrient availability [5].

Trail morphology is another important factor influencing environmental degradation. Trail width, for example, can have ecological and esthetic implications, as well as intensify edge effects depending on vegetation structure and landscape fragmentation [35–37]. Furthermore, different forms of trail use, such as walking, cycling, horse trampling, and off-road vehicle use, produce distinct levels of soil compaction and erosion. Previous studies have shown that walking and cycling generally generate smaller impacts when compared to horse trampling and off-road vehicle use [38–40].

Several physical, chemical, and biological parameters have been used to assess soil degradation in trails, such as soil density, texture, porosity, pH, microbial biomass, enzymatic activities, and penetration resistance measured by penetrometer [3,8,10,40–45]. These indicators contribute to understanding the degree of soil degradation associated with recreational and tourist activities.

In addition to its ecological functions, soil is increasingly recognized as an important component of geodiversity and geoconservation. In this context, ref. [46] developed a guide for coastal trails in Anglesey, United Kingdom, based on soils exposed along the edges of cliffs, with the aim of raising awareness among trail users about the importance of soils and their relationship with geoheritage, biodiversity and land use. This perspective reinforces the importance of soil not only as a natural resource but also as part of the geoenvironmental heritage.

Since soils play essential ecological roles and represent one of the fundamental components of ecosystems, qualitative and quantitative analyses of chemical elements constitute important tools for soil management and conservation. These analyses help establish relationships between soils and potential natural and anthropogenic sources of elements by determining the concentrations of major and trace elements [47].

Among the analytical techniques available, X-ray fluorescence spectrometry (XRF) has been increasingly used in soil studies due to its efficiency in determining chemical and mineralogical composition. XRF is a non-destructive technique that allows qualitative and quantitative analyses by identifying elements based on wavelength measurements or

energy emission [48]. Qualitative analyses identify the elements present in a sample, while quantitative analyses determine the proportion of each element in the material.

The application of XRF in soil studies has been reported in different approaches, including fertility assessment [49,50]; rock, soil and sediment analysis [51]; contamination studies [52]; soil genesis and pedogenesis [53,54]; relationships between particle density and total chemical composition of the soil [55]; environmental analyses [56] and soil use and management [57]. These studies demonstrate the potential of XRF as an efficient tool for evaluating physical, chemical and mineralogical soil attributes.

Despite advances in studies on trail degradation, the application of XRF techniques in soil analysis on trails is still limited. Considering that the assessment of soil degradation requires the integration of multiple parameters related to soil quality, XRF can significantly contribute to the identification and quantification of chemical elements present in trail soils, broadening the understanding of nutrient availability and potential losses associated with erosion and reduced microbial activity.

Therefore, this study aims to evaluate the relationships between soil degradation in trail environments and their physical and chemical properties, soil density, pH, texture, organic matter, and chemical elements, through quantitative and qualitative analyses performed on trail surfaces and trail-side slope, seeking to understand the behavior and distribution of these attributes in the southern region of Ubatuba Municipality, São Paulo State, Brazil.

2. Materials and Methods

2.1. Study Area

Ubatuba Municipality is located between 23°26'13" South Latitude and 45°04'08" West Longitude. It has a territory of 712 km², and the total population is 92,981 inhabitants [58]. The study area is situated in the southern part of the Municipality (Figure 1) and its total area is 80 km². The main economic activities are tourism, house building and fishery. Its territory has an elongated form, with southwest–northeast direction, being 60 km long. Its width ranges from 5 to 17 km, from the coast to inland. According to [59], Serra do Mar Mountain range controls the coast configuration in Ubatuba, depending on how close the beaches are to the mountains.

Of the five trails selected for this research, two are surrounded by the beach and close to the rocky coast (Quilombo Trail—and Sete Praias Trail), two are further away from the seafront and are used for rural tourism activities (Sítio Lama Mole Trail and Sítio Recanto da Paz Trail), and the Água Branca Trail is the only one that is located within Serra do Mar State Park (Table 1).

Table 1. Physiographic characteristics of the trails studied in Ubatuba-SP.

Trails	Extension Meters	Initial Altitude Meters	Final Altitude Meters
1. Sítio Recanto da Paz	907	17	182
2. Lama Mole	750	23	97
3. Sete Praias	4500	3	74
4. Água Branca	4550	70	560
5. Quilombo	9500	3	142

Regarding its geology, granite and gneiss support the crystalline basement (Proterozoic–Eopaleozoic and Mesozoic), and the Cenozoic sediments are distributed throughout the coastal plain [60]. The main soil orders identified in the region are Inceptisols, Oxisols, Entisols and Histosols. Among these, Entisols represent an important soil type in the study area, mainly associated with low hilly to mountainous reliefs and floodplains, where the

absence of well-defined horizons reflects recent geological deposition. On the other hand, Inceptisols occur mainly on the steep slopes of the Serra do Mar region [61], where active erosion in the accentuated topography limits the development of deeper soil profiles.

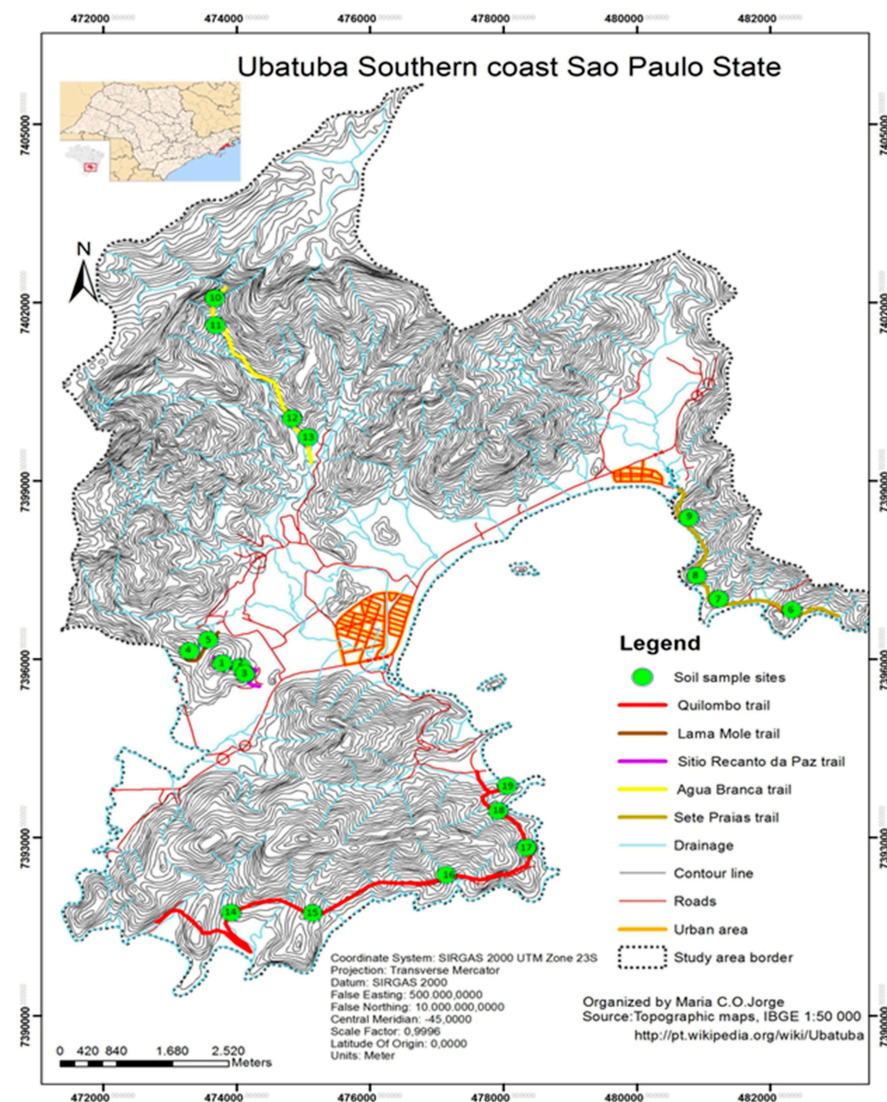


Figure 1. Study area, Maranduba drainage basin, Ubatuba Municipality.

The typical climate is the Tropical humid and warm, with average temperatures of 19 °C and highest annual rainfall around 4000 mm, with 2500 mm average [62,63]. These high rainfall indices, according to [62], are caused by the humidity brought by the winds originating from the Atlantic Ocean, which condense when they reach the orographic barrier caused by Serra do Mar Mountain range. Under these physical characteristics, there is the Atlantic Forest, where it is possible to encounter associated ecosystems. This forest is considered one of the 36 world hotspots, being a priority for its conservation, due to its high biodiversity and the great number of endemic species.

2.2. Soil Sample Collection

Both disturbed and undisturbed soil samples were collected at a depth of 10 cm from the trail surface (TR) and the adjacent trail-side slope (TA), which served as comparative controls. Sampling was conducted along five trails: Sítio Recanto da Paz Trail (TA1/TR1; 1–3), Sítio Lama Mole Trail (TA2/TR2; 4–5), Sete Praias Trail (TA3/TR3; 6–9), Água Branca Trail (TA4/TR4; 10–13), and Quilombo Trail (TA5/TR5; 14–19) (Figure 1). In total, 19 trail-

side slope (TA) sites and 19 trail-surface (TR) sites were sampled. Each site was sampled in triplicate to ensure statistical representativeness and reduce sampling error, resulting in 114 samples ($38 \text{ sites} \times 3 \text{ replicates}$).

Samples collected from the trail-side slope (TA) served as control samples, representing the original and undisturbed soil conditions (Figure 2). Because the trail-side slope shares the same parent material, climate and soil formation as the trail surface (TR), it isolates anthropogenic trampling as the main driver of soil alteration.



Figure 2. Sampling sites on trail-side slope (TA) and trail surface (TR). (a) Sitio Lama Mole (site 5); (b) Sete Praias (Site 6); (c) Quilombo (site 16). Soil samples (red triangle). Different inclinations can be seen in the position of the trail-side slope, trail surface and bare soil, exposed to the direct actions of the relief carving agents. Photos by Maria Jorge.

During sampling of the adjacent trail-side slope, environmental variables such as slope angle, vegetation type and natural moisture regimes were kept as uniform as possible. The selection of the 0–10 cm depth layer was based on the vulnerability of the topsoil to direct mechanical compaction from pedestrian traffic. This surface horizon also concentrates the highest levels of organic matter, where changes in physical attributes (e.g., soil bulk density) are more pronounced in tropical forest soils. This sampling depth aligns with routine procedures recommended by the Brazilian Agricultural Research Corporation (EMBRAPA, 2017) for fertility and organic matter assessments in the topsoil layer.

2.3. Laboratory Analysis

Bulk density was determined using the volumetric cylinder method, proposed by [64], in which soil samples were collected in a 100 cm^3 steel cylinder. In the laboratory, the samples were removed from the cylinder and dried in the oven at 105°C for 24 h. After drying, the samples were weighed and bulk density was calculated by dividing the mass by the cylinder volume (100 cm^3).

Soil texture was determined using the method described by [64], in which 20 g of soil were weighed and mixed with 10 mL of dispersant and 100 mL of distilled water. The

mixture was then shaken for 15 min and passed through a 0.053 mm sieve, where sand is retained, and the fractions silt + clay are filtered into a 1000 mL beaker. After a fixed settling time, 50 mL of the suspension was pipetted, where the clay fraction is collected, which is then taken to the oven for 24 h, at 105 °C. Finally, the sample is sieved on a 0.20 mm sieve to separate the fine and coarse sand. After all these procedures, the results are plotted on the textural triangle.

Organic matter was determined by wet oxidation using potassium dichromate and diphenylamine as an indicator. The procedure included subsequent titration steps as described by [61]. Organic matter content was expressed in g/kg, calculated as $C \text{ (g/kg)} \times 1.724$.

Soil pH was determined by weighing 10 g of soil and adding 25 mL of distilled water. The mixture was shaken and allowed to stand for 1 h. The soil pH was measured using a digital pH meter [64].

Soil porosity, defined as the total volume of voids occupied by air and/or water, was calculated using the technique [64].

X-ray Fluorescence (XRF) was used to determine the chemical composition of the samples by Energy Dispersive X-ray Fluorescence (EDXRF) using a PANalytical Epsilon 3X spectrometer with an analytical range from Sodium (Na) to Uranium (U) (Malvern Panalytical, Malvern, UK). The soil samples were ground and sieved through a 0.0125 mm mesh and subjected to ignition in a muffle furnace at 375 °C for 12 h. Subsequently, 8.5 g of soil were mixed with 1.5 g of Licowax, homogenized, and pressed in a hydraulic press to produce pellets for spectrometric analysis.

Data processing and concentration calculations (ppm to 100%) were performed using the instrument's integrated software, based on Fundamental Parameter (FP) algorithms, allowing for automatic correction of matrix effects and overlapping spectral peaks. Of the 32 quantified elements, the analysis focused on the major oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , and TiO_2) and macronutrients (K_2O , MgO , and P_2O_5), selected for their 100% detection frequency in the analyzed trails and for representing > 90% of the soil's mineralogical matrix. The selection of these elements ensured greater statistical robustness ($n = 19$) and comparability between the trail-side slope and trail surface environments, minimizing uncertainties associated with trace elements near the equipment's detection limit.

2.4. Statistical Analysis of the Data

Statistical analyses were performed using Jamovi software (Version 2.6). Data normality was assessed using the Shapiro–Wilk test on the complete sample set ($n = 19$), justifying the use of parametric statistics. To assess the impact of recreational use, mean values for the trail-side slope (TA) and trail surface (TR) were compared using a paired-samples *t*-test, given the paired design at each sampling point.

The analysis was conducted at two scales: a regional scale (global cluster, $n = 19$), aimed at identifying overall patterns of degradation, and a local scale examining individual trails. At the local scale, trails with the larger sample sizes were evaluated independently, while data from the Lama Mole Site ($n = 2$), limited by its short length, were interpreted in conjunction with the global cluster ($n = 19$), which provides sufficient statistical support for the observed compaction trends.

3. Results

3.1. Bulk Density and Porosity

Soil porosity and bulk density values show a systematic contrast between the TA and TR environments (Tables 2 and 3). The global analysis ($n = 19$) confirms this regional pattern, indicating a significant increase in soil bulk density from 1.32 to 1.37 (g/cm^3) and

($p = 0.038$) (Table 2), accompanied by a reduction in total porosity from 47.26% to 45.34% ($p = 0.016$) in the trail surface (TR) compared to the adjacent trail-side slope (TA).

Table 2. Average bulk density (g/cm^3).

Trails	<i>n</i> (TA/TR)	TA (Mean $\pm$ CV%)	TR (Mean $\pm$ CV%)	t-Value	p-Value
1. Recanto da Paz	3/3	1.15 $\pm$ 17.48%	1.24 $\pm$ 7.90%	−0.55	0.624
2. Sítio Lama Mole	2/2	1.41 $\pm$ 16.01%	1.58 $\pm$ 2.53%	−1.02	0.414
3. Sete Praias	4/4	1.31 $\pm$ 13.20%	1.53 $\pm$ 9.29%	−1.82	0.137
4. Água Branca	4/4	1.08 $\pm$ 2.66%	1.19 $\pm$ 4.66%	−3.28	0.017 *
5. Quilombo	6/6	1.31 $\pm$ 9.05%	1.39 $\pm$ 6.67%	−1.25	0.239
Global Pool	19/19	1.32 $\pm$ 14.39%	1.37 $\pm$ 15.33%	2.15	0.038 *

Note. TA = Trail-side slope (control); TR = Trail surface (impacted). For Global Pool (comparison between (TA) and (TR) $n = 19$). * Significant at the 5% probability level ($p < 0.05$).

Table 3. Porosity (%).

Trails	<i>n</i> (TA/TR)	TA (Mean $\pm$ CV%)	TR (Mean $\pm$ CV%)	t-Value	p-Value
1. Recanto da Paz	3/3	53.31 $\pm$ 16.04%	49.51 $\pm$ 7.58%	0.58	0.609
2. Sítio Lama Mole	2/2	44.13 $\pm$ 21.50%	34.58 $\pm$ 8.08%	1.37	0.377
3. Sete Praias	4/4	47.42 $\pm$ 10.33%	42.38 $\pm$ 13.97%	1.31	0.239
4. Água Branca	4/4	55.51 $\pm$ 5.37%	49.78 $\pm$ 5.85%	2.75	0.033 *
5. Quilombo	6/6	49.73 $\pm$ 6.71%	46.26 $\pm$ 10.05%	1.49	0.171
Global Pool	19/19	47.26 $\pm$ 12.57%	45.34 $\pm$ 12.75%	2.53	0.016 *

Note. TA = Trail-side slope (control); TR = Trail surface (impacted). For Global Pool (Comparison between (TA) and (TR) $n = 19$). * Significant at the 5% probability level ($p < 0.05$).

At the local level, this structural divergence is driven primarily by the Água Branca trail. It stands out as the only individual trail to exhibit statistically significant differences for both parameters, such as bulk density (TA 1.08 vs. TR 1.19 g/cm^3 , $p = 0.016$) and porosity (TA 55.51% vs. TR 49.78%, $p = 0.033$).

Conversely, although the highest bulk density and lowest porosity were recorded along Lama Mole trail, the high internal dispersion of the data limited the statistical significance for this specific point. For the other trails, although the numerical trends align with the global pattern, the differences were not statistically significant.

The difference in mean values is invariably lower than in the trail surface (TR). The differences in means did not reach the threshold for statistical significance ($p > 0.05$). Notably, the Coefficient of Variation (CV%) was lower in the trail surfaces (TR) than in the trail-side slope (TA), with the exception of the Água Branca trail.

3.2. Texture

Particle size analysis showed no statistically significant differences were detected in the coarse sand, fine sand, silt, or clay fractions between (TA) and (TR), both in the overall analysis ($n = 19$; $p > 0.05$) and in the individual evaluations of each trail (Table 4).

Despite the stable regional average values, the spatial distribution of these fractions shows localized variability, as indicated by the CV%. At the Recanto da Paz site, the variability of the clay fraction increased sharply from 18.84% (TA) to 54.46% (TR). On the Água Branca trail, a numerical trend of enrichment of coarse sand from 45.05% (TA) to 50.05% (TR) was observed, accompanied by a reduction in clay from 14.83% (TA) to 11.09% (TR).

The Quilombo trail, the only trail with a finer textural classification (clay loam), showed high heterogeneity in the (TR) for the silt (CV = 48.15%) and fine sand (CV = 43.59%) fractions compared to its respective TA (38.01% and 49.07%, respectively). Regarding Lama

Mole trail, although local statistical tests did not indicate significance ($p > 0.05$), the absolute numerical data revealed the greatest textural change in (TR), with a perceptible increase in the coarse sand fraction, from 36.40% (TA) to 44.79% (TR). This sandy enrichment was accompanied by a significant reduction in clay content, which fell from 31.95% (TA) to 24.98% (TR).

Table 4. Average texture (%).

Trails/Parameters	Position	Coarse Sand (Mean $\pm$ CV%)	Fine Sand (Mean $\pm$ CV%)	Silt (Mean $\pm$ CV%)	Clay (Mean $\pm$ CV%)	Textural Class	t-Value (TA/TR)	p-Value (TA/TR)
1. Sítio Recanto da Paz	TA	36.92 $\pm$ 18.48%	12.10 $\pm$ 25.40%	29.89 $\pm$ 34.47%	20.94 $\pm$ 18.84%	Loam	0.21	0.846
	TR	35.84 $\pm$ 16.01%	16.19 $\pm$ 54.86%	27.23 $\pm$ 28.64%	20.39 $\pm$ 54.46%	Loam		
2. Sítio Lama Mole	TA	36.40 $\pm$ 23.55%	9.17 $\pm$ 15.03%	22.20 $\pm$ 33.74%	31.95 $\pm$ 16.48%	Sandy clay loam	−1.02	0.414
	TR	44.79 $\pm$ 17.43%	9.68 $\pm$ 13.87%	20.97 $\pm$ 14.64%	24.98 $\pm$ 22.79%	Sandy clay loam		
3. Sete Praias	TA	42.48 $\pm$ 20.72%	15.40 $\pm$ 33.02%	16.70 $\pm$ 45.83%	25.42 $\pm$ 45.50%	Sandy clay loam	0.31	0.770
	TR	40.90 $\pm$ 12.75%	14.80 $\pm$ 33.48%	20.48 $\pm$ 27.77%	23.83 $\pm$ 52.75%	Sandy clay loam		
4. Água Branca	TA	45.05 $\pm$ 18.03%	13.39 $\pm$ 26.29%	26.73 $\pm$ 29.88%	14.83 $\pm$ 43.44%	Sandy loam	−0.88	0.414
	TR	50.05 $\pm$ 15.98%	11.99 $\pm$ 23.36%	26.87 $\pm$ 34.21%	11.09 $\pm$ 28.05%	Sandy loam		
5. Quilombo	TA	30.01 $\pm$ 23.09%	8.73 $\pm$ 49.07%	24.44 $\pm$ 38.01%	36.82 $\pm$ 33.48%	Clay loam	0.51	0.621
	TR	27.83 $\pm$ 28.15%	7.85 $\pm$ 43.59%	20.66 $\pm$ 48.15%	37.01 $\pm$ 33.80%	Clay loam		
Global Pool	TA	39.03 $\pm$ 17.81%	11.93 $\pm$ 25.02%	23.62 $\pm$ 17.23%	24.73 $\pm$ 34.82%	—	—	—
	TR	39.58 $\pm$ 18.34%	11.93 $\pm$ 32.86%	22.56 $\pm$ 36.75%	25.86 $\pm$ 33.02%	—		

Note. Values in parentheses indicate the Coefficient of Variation (CV%). TA = Slope (Control); TR = Trail Surface (Impacted). The *t*-test did not reveal significant differences ($p > 0.05$) on the global scale for any fraction. Global pool: Coarse Sand ($t = -0.23$; $p = 0.818$); Fine Sand ($t = -0.01$; $p = 0.999$); Silt ($t = 0.33$; $p = 0.740$); Clay ($t = 0.45$; $p = 0.654$).

3.3. Organic Matter and pH

The chemical attributes of the soil showed a pattern of homogeneity between the evaluated environmental positions (TR and TA). The pH values remained stable, without statistically significant differences between the trail-side slope (TA) and the trail surface (TR), both in the joint analysis and at the individual scale of each trail (Table 5). On the Água Branca trail, the averages recorded were 3.71 in TA (CV% = 3.72%) and 3.69 in TR (CV% = 4.35%). On the other hand, the Quilombo site presented the highest absolute average pH values, registering 4.75 in TA and 4.74 in TR, although it showed the greatest dispersion of data in TA (CV% = 16.87%).

Table 5. Average organic matter content (%).

Trails	n (TA/TR)	TA (Mean $\pm$ CV%)	TR (Mean $\pm$ CV%)	t-Value	p-Value
1. Recanto da Paz	3/3	6.47 $\pm$ 20.29%	6.25 $\pm$ 11.78%	0.25	0.816
2. Sítio Lama Mole	2/2	2.44 $\pm$ 12.02%	3.27 $\pm$ 21.92%	−1.52	0.325
3. Sete Praias	4/4	2.72 $\pm$ 44.30%	2.55 $\pm$ 50.67%	0.19	0.854
4. Água Branca	4/4	7.34 $\pm$ 16.23%	8.55 $\pm$ 31.18%	0.83	0.452
5. Quilombo	6/6	2.88 $\pm$ 40.36%	2.96 $\pm$ 49.76%	0.10	0.919
Global Pool	19/19	4.54 $\pm$ 51.42%	4.73 $\pm$ 44.61%	0.35	0.728

Note. TA = Trail-side slope (control); TR = Trail surface (impacted). For Global Pool (Comparison between (TA) and (TR) $n = 19$). Significance level at $p < 0.05$.

Regarding organic matter (OM) content, no statistically significant variations were observed between the TA and TR environments, mirroring the pH trend (Table 6). However, a marked variation was observed among the trails. The lowest average contents were observed at the Lama Mole site (2.44% in TA and 3.27% in TR), while the highest values were identified on the Água Branca trail, reaching 7.34% (TA) and 8.55% (TR). Unlike the behavior observed with pH, OM showed moderate to high internal dispersion at the local level.

This behavior is evidenced by the CV% values, which ranged from the Recanto da Paz TR (11.78%) to peaks of high spatial heterogeneity in the Sete Praias samples, where the CV% reached 44.30% (TA) and 50.67% (TR). This strong regional oscillation was directly

reflected in the analysis of the study's overall variation. When observing the total set of samples, organic matter registered a global average of 4.54 in (TA) and 4.73 in (TR), with a high global dispersion index in both locations, CV% of 51.42% (TA) and 44.61% (TR).

Table 6. Average pH.

Trails	<i>n</i> (TA/TR)	TA (Mean ± CV%)	TR (Mean ± CV%)	t-Value	<i>p</i> -Value
1. Recanto da Paz	3/3	4.51 ± 6.88%	4.73 ± 6.05%	−0.90	0.418
2. Sítio Lama Mole	2/2	4.38 ± 3.23%	4.48 ± 0.00%	−1.00	0.500
3. Sete Praias	4/4	4.37 ± 11.74%	4.30 ± 13.78%	0.18	0.864
4. Água Branca	4/4	3.71 ± 3.72%	3.69 ± 4.35%	0.19	0.856
5. Quilombo	6/6	4.75 ± 16.87%	4.74 ± 11.58%	0.03	0.980
Global Pool	19/19	4.37 ± 8.86%	4.38 ± 9.13%	−0.12	0.905

Note. TA = Trail-side slope (control); TR = Trail surface (impacted). For Global Pool (Comparison between (TA) and (TR) *n* = 19). Significance level at *p* < 0.05.

3.4. XRF

The determined oxide and chemical element contents revealed, for the most part, a pattern of strict stability and homogeneity between slope (TA) and trail surface (TR) (Table 7). At the local scale, most geochemical variables did not show statistically significant variations (*p* > 0.05), indicating that the underlying mineralogical composition of the soil tends to remain unchanged despite tourist use.

Table 7. XRF.

Parameter		SiO ₂ (Mean ± CV%)	Al ₂ O ₃ (Mean ± CV%)	Fe ₂ O ₃ (Mean ± CV%)	Ti (Mean ± CV%)	K ₂ O (Mean ± CV%)	MgO (Mean ± CV%)	P ₂ O ₅ (Mean ± CV%)
1. Recanto da Paz	TA	52.58 ± 1.3%	38.42 ± 3.6%	7.74 ± 12.2%	0.59 ± 30.6%	0.39 ± 24.6%	0.14 ± 3.5%	0.08 ± 22.2%
	TR	52.02 ± 4.8%	37.84 ± 6.4%	7.79 ± 17.6%	0.56 ± 23.8%	1.61 ± 75.8%	0.29 ± 19.8%	0.07 ± 14.3%
	t-value	0.38	0.35	−0.04	0.19	−1.72	−4.36	0.59
	<i>p</i> -value	0.736	0.746	0.966	0.858	0.225	0.047 *	0.590
2. Lama Mole	TA	50.28 ± 2.4%	36.86 ± 8.1%	8.83 ± 15.8%	1.36 ± 11.3%	0.88 ± 8.6%	0.18 ± 7.7%	0.01 ± 33.8%
	TR	54.32 ± 0.1%	35.88 ± 5.5%	7.92 ± 20.6%	0.47 ± 4.0%	1.42 ± 20.4%	0.47 ± 48.9%	0.09 ± 32.2%
	t-value	−4.76	0.37	0.59	8.14	−2.58	−1.80	−3.82
	<i>p</i> -value	0.130	0.747	0.612	0.073	0.210	0.320	0.156
3. Sete Praias	TA	48.21 ± 6.9%	36.22 ± 11.4%	11.84 ± 20.6%	1.84 ± 46.4%	0.63 ± 49.2%	0.30 ± 61.1%	0.03 ± 73.5%
	TR	51.42 ± 5.0%	36.02 ± 12.9%	10.77 ± 71.8%	0.72 ± 14.1%	0.18 ± 51.8%	0.46 ± 48.2%	0.02 ± 35.9%
	t-value	−1.52	0.06	0.26	2.60	−2.41	−1.07	1.12
	<i>p</i> -value	0.181	0.950	0.807	0.077	0.079	0.324	0.333
4. Água Branca	TA	50.15 ± 13.1%	36.18 ± 12.6%	9.30 ± 53.3%	2.67 ± 41.5%	0.92 ± 14.5%	0.25 ± 13.2%	0.02 ± 32.3%
	TR	51.17 ± 14.1%	38.17 ± 12.4%	8.23 ± 53.4	0.51 ± 56.7%	0.30 ± 41.1%	0.57 ± 74.5%	0.02 ± 50.5%
	t-value	−0.21	−0.64	0.32	3.78	−3.36	−1.53	0.24
	<i>p</i> -value	0.840	0.543	0.758	0.025 *	0.042 *	0.221	0.814
5. Quilombo	TA	47.81 ± 7.6%	39.72 ± 6.0%	11.03 ± 33.8%	1.15 ± 28.4%	0.75 ± 37.1%	0.26 ± 66.8%	0.02 ± 77.9%
	TR	49.07 ± 9.3%	38.03 ± 7.5%	10.08 ± 38.7%	1.01 ± 46.0%	1.09 ± 41.6%	0.35 ± 60.5%	0.03 ± 66.6%
	t-value	−0.45	1.11	0.42	0.60	−1.54	−0.79	−1.19
	<i>p</i> -value	0.670	0.293	0.676	0.557	0.158	0.447	0.262
Global Pool	TA	48.58 ± 9.4%	37.15 ± 10.5%	10.48 ± 37.9%	1.41 ± 53.2%	1.51 ± 68.4%	0.36 ± 64.1%	0.04 ± 65.8%
	TR	50.86 ± 8.5%	36.78 ± 9.2%	9.48 ± 38.4%	0.74 ± 50.8%	1.94 ± 79.5%	0.46 ± 58.5%	0.03 ± 68.4%
	t-value	−1.81	0.35	0.91	2.03	−1.01	−1.17	0.78
	<i>p</i> -value	0.086	0.725	0.370	0.056	0.321	0.256	0.444

Note. TA = Trail-side slope (control); TR = Trail surface (impacted). For Global Pool (Comparison between (TA) and (TR) *n* = 19). * Significance level at *p* < 0.05.

As exceptions to this homogeneous behavior, only three occurrences of local statistical asymmetry were recorded (*p* < 0.05), in which the Recanto da Paz site showed a significant difference in MgO levels (*t* = −4.36 *p* = 0.047), driven by an increase in the average TR (0.29%) compared to TA (0.14%). Additionally, the Água Branca trail exhibited significant local variations for Ti (*t* = 3.78; *p* = 0.0259) and K₂O (*t* = −3.36; *p* = 0.042).

At the regional level, it was observed that the CV% of each trail remained predominantly low for stable oxides, such as SiO₂, which oscillated within narrow dispersion ranges, varying from 0.1% in the Lama Mole TR to peaks of 14.1% in the Água Branca TR. In contrast, the internal dispersion indices increased significantly in the elements with

lower percentage expression, highlighting the behavior of K_2O in the Recanto da Paz TR (CV = 75.8%) and P_2O_5 in the Quilombo TA (CV = 77.9%).

When the unified scenario was evaluated using Global Clustering ($n = 19$), the natural inter-trail variability manifested itself in the widening of the CV%, which reached significant levels for K_2O (CV = 68.4% in TA and 79.5% in TR). Still on the global scale, none of the analyzed parameters showed statistical significance ($p > 0.05$), with p -values fluctuating from borderline marks for Ti ($t = 2.03$; $p = 0.056$) to levels of almost absolute homogeneity, as verified for Al_2O_3 ($t = 0.35$; $p = 0.725$) (Table 7).

Therefore, the quantitative data analyzed demonstrate a divergence between the physical variables and other soil attributes in the trail surface (TR) compared to their respective trail-side slope (TA). The results indicate a statistically significant increase in bulk density ($p = 0.038$) and a concomitant reduction in total global porosity ($p = 0.016$) in the impacted environment (TR). In contrast, the granulometric parameters (Table 4), pH (Table 5), organic matter (Table 6), and elemental oxide contents via XRF (Table 7) showed no statistical significance ($p > 0.05$) under the unified Global Clustering test ($n = 19$). At the local level, isolated physical, textural, and geochemical deviations were recorded along the Água Branca trail, in addition to a punctual increase in MgO in TR of Recanto da Paz site, which were configured as restricted fluctuations compared to the regional CV%.

4. Discussion

The integrated analysis of the physical, chemical, and geochemical attributes of the soil among the different trails reveals clear differences in the scale of anthropogenic impacts. While trampling promotes intense localized degradation of soil physical structure, the underlying chemical and geochemical matrices remain largely stable. In this context, Figures 3 and 4 show both the visual diagnosis and the direct statistical validation of the correlations observed between these different attributes.

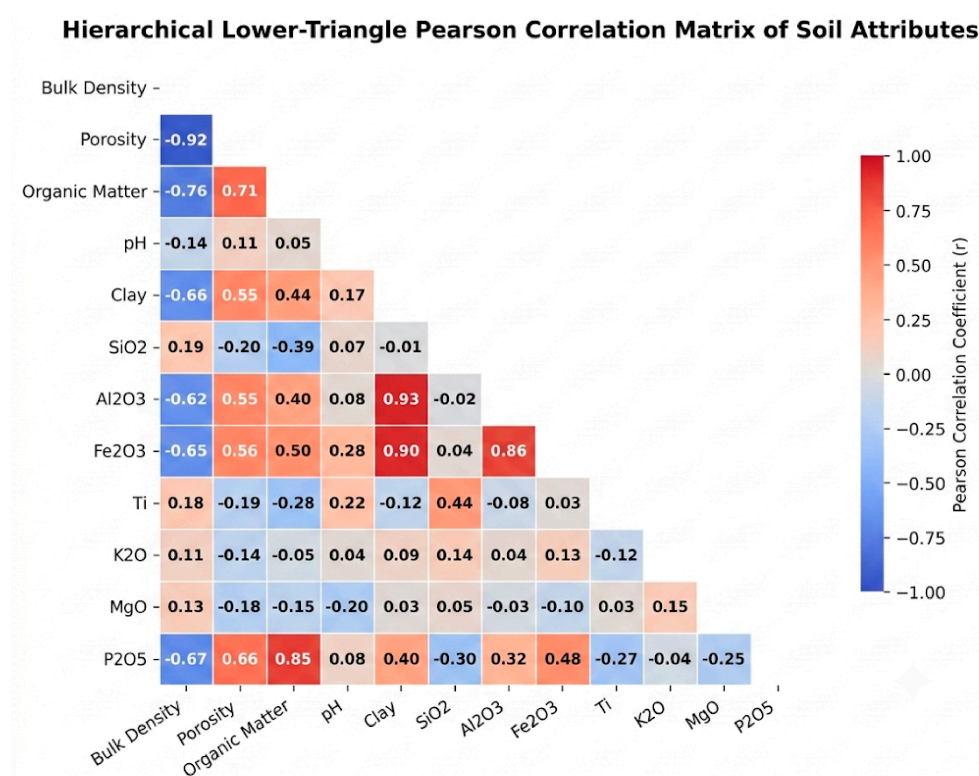


Figure 3. Pearson correlation matrix (r) integrating the physical, textural, and geochemical attributes of the soil. The values reflect the paired variation between –TR vs. TA–, isolating the impact from trampling from regional geological characteristics.

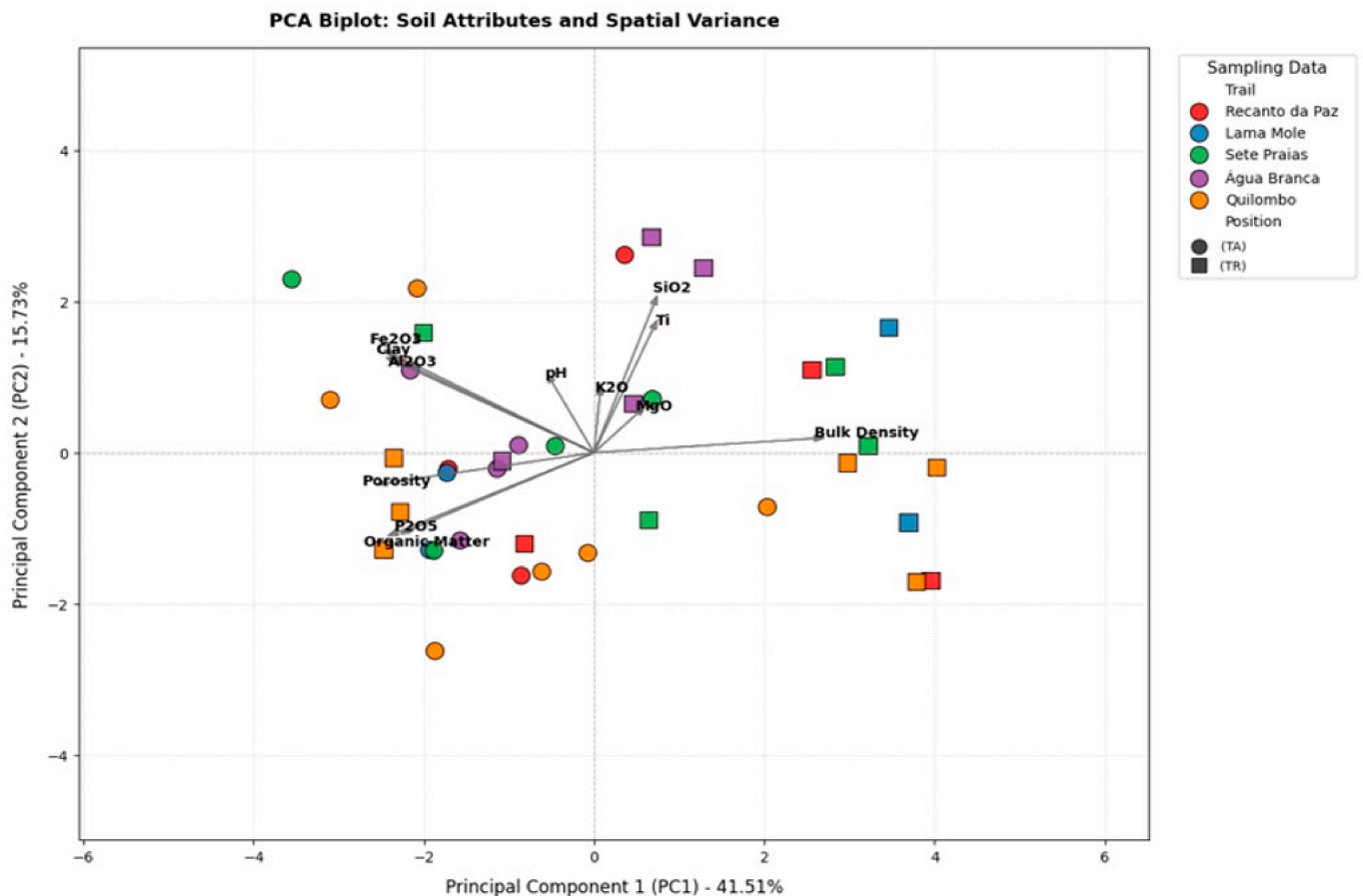


Figure 4. Principal Component Analysis (PCA) biplot of soil attributes along the studied trails in Ubatuba, SP. The points represent soil samples differentiated by trail (colors) and position (TA and TR), and the vectors indicate the direction and strength of the physicochemical variables.

The integration between the processes of physical soil degradation and geochemical stability in the trails is confirmed by Pearson's coefficients. The impact of public use is manifested in the strong negative correlation between apparent density and total porosity ($r = -0.92$), which mathematically proves the collapse of the soil's porous space due to trampling. On the other hand, the geochemical and mineral attributes show stability, because although visitor traffic disrupts the surface physics, the essential chemical signature remains preserved by the lithological matrix. When observing the Correlation Matrix, the blue cells highlight the negative associations (such as the reduction in porosity and organic matter in response to increased density), while the red cells reveal significant positive connections, such as the biochemical link between organic matter and phosphorus ($r = 0.85$). Complementarily, the multivariate analysis (Figure 4) spatializes these data, clearly separating the physical variables (indicators of local anthropogenic impact) from the geochemical attributes (indicators of lithological control) on distinct axes.

4.1. Soil Compaction and Textural and Geochemical Resilience

The significant increase in bulk density ($p = 0.038$) (Table 2), coupled with the systematic reduction in total porosity ($p = 0.016$) (Table 3), confirms that pedestrian traffic acts as a mechanical disturbance in the trail surface (TR). This process tends to restrict root penetration, compromise water infiltration, and accelerate surface runoff, as widely documented in analogous tropical environments [8,10,42–44,65,66]. According to the thresholds established by [67], the critical physical degradation observed at the Lama Mole and Sete Praias

Sites, where the bulk density systematically exceeded the limit of 1.5 g/cm^3 , constitutes a state of structural compaction capable of inducing severe hydrological alterations.

This pattern of physical degradation is validated when observing the correlation matrix of the lower triangle (Figure 3), which highlights a robust negative correlation between bulk density and porosity ($r = -0.92$). This behavior reflects the direct impact of trampling on the trail surface (TR), where mechanical compaction consistently results in maximum soil density values and critical reductions in porosity levels.

However, this physical restructuring at the microscale is not replicated at the geochemical level (XRF). The refractory oxides SiO_2 , Al_2O_3 , Fe_2O_3 and the stable element Ti showed non-statistical significance ($p > 0.05$) in the Global Cluster ($n = 19$), indicating that the elemental composition of these soils is largely unaffected. The absolute dominance of silica, aluminum, and iron reflects an advanced stage of tropical weathering, directly inheriting its signature from the regional geology of porphyritic granites and migmatitic gneisses [68,69]. Therefore, although trampling reduces the volume of voids (porosity), it leaves intact the permanent mineral identity of the soil matrix.

The absence of statistically significant changes in overall texture between (TA) and (TR) ($p > 0.05$) corroborates the conceptual models of erodibility in humid tropical soils. The degradation model assumes that trampling acts primarily by destroying the physical structure (bulk density and short-term porosity) long before sheet erosion processes can reconfigure the granulometric matrix of deeper horizons. Therefore, although trampling reduces the volume of voids, it leaves intact the permanent mineral identity and the underlying textural signature of the soil profile.

4.2. Selective Erosion and Soil Texture

Despite the overall stability of soil texture ($p > 0.05$), trends in the CV% reveal an active process of selective erosion triggered by trampling (Table 4). Texture plays a critical role in erodibility; fine sand and silt fractions are highly prone to transport, while clay aggregates resist initial breakage, unless mechanically disturbed by pedestrian traffic [44,70–73]. This dynamic behavior and the localized variation in clay content between environments can be tracked in the multivariate profile of Figure 3 (Clay axis).

Additionally, the slope of the terrain also acts as a controlling factor in selective erodibility and the speed of surface water flow. All trails (Quilombo, Sete Praias, Lama Mole, Recanto da Paz and Água Branca) occupy slopes with medium to steep gradients (estimated range of 15% to 35% inclination), which increases the kinetic energy of rainwater and justifies the preferential mechanical dragging of fine clay and silt fractions from the exposed trail surface.

On the Quilombo trail, which presents the finest textural class (clay-loam), the combination of low organic matter, structural compaction and a mineralogy dominated by kaolinite leads to plastic deformation [27,74]. As kaolinite exhibits a lamellar structure that naturally reduces drainage capacity, mechanical sealing of the surface creates mudflats that persist long after rainfall events [11,66] (Figure 5).

On the other hand, Sítio Recanto da Paz trail and Água Branca trail (Figure 6), which have sections with sloping terrain prone to surface runoff, have their high vulnerability, associated with high levels of silt and fine sand, significantly mitigated by the high organic matter content and the protection of the vegetation cover. In these two trails, organic matter acts as a mechanical buffer. Even with the slope, it promotes the aggregation of particles, maintaining higher porosities and lower bulk densities, which reduces the erodibility of these trails, despite their naturally susceptible textural fractions [4,15,75].



Figure 5. Sampling points on the TR—Quilombo Trail (white arrows) showing moist and clayey soil; in both cases, the trail is quite slippery. Photos: Maria Jorge.



Figure 6. Presence of litter on a part of Agua Branca trail surface. Photos: Maria Jorge.

Highlighting that although organic matter mitigates these effects in vegetated areas, exposed sectors with steeper slopes become highly vulnerable to torrential dynamics. This scenario is evidenced in Figure 7, which illustrates the advancement of erosive processes and the morphological instability generated by the kinetic force of rainwater in unprotected trail surfaces.

The multivariate validation of this biological protection mechanism is clearly shown in Figure 4. In the PCA biplot, it can be observed that the vectors of Organic Matter and Phosphorus point in the opposite direction to the vector of bulk density, strongly clustering in the lower triangle of the Pearson matrix (Figure 3; $r = 0.72$). This strong statistical association shows that the conservation of organic matter content and the maintenance of

vegetation cover act as factors of ecological resilience in the trails, shielding the soil against the severe advance of mechanical compaction.



Figure 7. Visual indicators of erosive processes and physical soil degradation on the trails. (a) Quilombo Trail section with chronic root exposure and surface gulying in an area with the presence of *Pinus* sp.; (b) Sete Praias Trail section with deep gulying resulting from channeling and increased kinetic energy of surface runoff in a section with a pronounced slope. The red arrows indicate the preferred direction of the degradative hydrological flow. Photos by Maria Jorge.

4.3. Chemical Stability and Nutrient Dynamics

The soil chemical matrix demonstrated stability between sampling environments and between trails, as evidenced by the statistically insignificant differences in pH between TA and TR ($t = 0.35$; $p = 0.72$) (Table 5). The low CV% (8.86%) confirms a high base homogeneity, typical of ultra-acidic tropical soils ($\text{pH} < 5.0$) exposed to intense weathering, high temperatures and rainfall regimes exceeding 2000 mm/year [76,77].

Unlike the profiles observed by [78], which exhibited sharp vertical chemical gradients, the acid–base profile at the trail points remains stable. This indicates that, even where sheet erosion has removed the surface layers in the trail surfaces, the newly exposed subsurface horizons mirror the chemical properties of the undisturbed control areas, not exhibiting significant chemical degradation. Thus, this pH stability shows that trampling along the trails does not have the power to alter the deep soil chemistry. In ancient and highly weathered tropical soils, acidity is controlled by a very stable natural barrier, dominated by aluminum, hydrogen, and iron oxides [76]. As this basic mineral structure is highly resistant (buffered), mechanical impact on the surface and loss of vegetation cannot break this equilibrium, keeping the regional chemical signature intact [76,77].

On the other hand, highly mobile and less concentrated nutrients (K_2O , MgO , and P_2O_5) represent a scenario of activity and environmental instability. The significant local changes observed for K_2O and MgO in Água Branca and Recanto da Paz ($p < 0.05$), respectively, where the maximum values paradoxically concentrated in the trail surfaces (TRs), reflect the behavior of the trails characterized by greater preservation of surrounding vegetation cover and lower intensity of morphological degradation.

This can be explained by two interdependent mechanisms. The first results from continuous trampling, which promotes the densification of the surface layer and the sealing of soil pores; this process establishes a physical barrier that restricts vertical leaching, retaining cations in the upper portion of the profile. The second is associated with the fact that, because they are densely forested trails protected against severe erosion processes, pedestrian traffic acts by mechanically fragmenting the leaf litter deposited on the roadbed. This fragmentation accelerates the release and subsequent fixation of nutrients by local organic matter, preventing the loss of these elements through surface runoff [20,36].

Regarding phosphorus (P_2O_5), the results indicated statistical homogeneity between the TA and TR environments in all trails ($p > 0.05$), consolidating the characteristic of a structurally scarce and immobile nutrient in these highly weathered tropical environments [79,80]. Despite the stability of the average levels, the element exhibited severe spatial instability, reaching a CV of 77.9% in the Quilombo trail. This strong local oscillation is directly linked to the irregular distribution of biomass remnants in the riverbed, which is mathematically illustrated in the correlation matrix (Figure 3), revealing a robust positive correlation between P_2O_5 and Organic Matter ($r = 0.85$), as well as a strong negative correlation with bulk density ($r = -0.67$).

This strong chemical dependence is consistent with previous studies, which point to organic matter as the main factor in phosphorus retention in forest soils under trampling [74]. Furthermore, the overall stability observed in the average levels ($p > 0.05$) reflects the conceptual model, indicating that in trails with preserved vegetation, geochemical responses tend to reach a plateau of stability. Thus, unlike other mobile nutrients, phosphorus dynamics are not governed by isolated physical compaction of the trail surface, but rather by the strict dependence on the presence of residual organic horizons. The nutrient remains chemically protected against loss by surface runoff only in sectors where vegetation cover and litter have been effectively preserved [75].

4.4. Methodological Implications of Global Clustering Versus Local Scale

The comparison between the local dynamics of the trails and the unified Global Clustering provides a critical methodological insight for trail degradation studies. The local analysis revealed isolated statistical significance; however, when evaluated through Global Clustering, these localized changes are diluted by the large regional natural and lithological variation (with the CV% increasing to up to 79.5%).

Finally, it is necessary to acknowledge a conceptual limitation of the present sampling design: the absence of direct empirical data regarding the absolute flow of visitors, such as daily frequency, type of foot traffic, and the seasonality of events on the five trails. Although a direct count of the number of visitors was not conducted, the large differences in the length and accessibility of the trails serve as indirect indicators of the intensity of tourist use. For example, a distinct recreational pressure is expected between a short and easily accessible trail, such as Recanto da Paz (907 m), and a long and remote route, such as the Quilombo trail (9500 m), which is indeed the case.

In short routes like the Recanto da Paz trail, mechanical stress tends to be frequent and uniformly distributed along the terrain, as observed in fieldwork. In contrast, in extensive linear systems like the Quilombo trail, the flow of people walking behaves in a spatially asymmetrical way, fragmenting the stress intermittently along the topographic profile.

Regarding scale, this can be evidenced by multivariate analysis. In the PCA Biplot (Figure 4), the data variation is divided into two main forces: the physical disturbance of hiking separates the sampling positions (distinguishing the point shapes), while the regional geological context groups the areas (gathering the colors of the trails). This differentiation statistically proves that recreational hiking acts as a local physical impact, being unable to

alter the regional geochemical signature of the soil. Consequently, structural assessments of trail degradation should prioritize physical indicators of soil compaction and selective erodibility over macroelemental mineral balances, which remain intrinsically linked to the baseline of regional geodiversity.

5. Conclusions

This study demonstrates that the physical properties of the soils on trails in southern Ubatuba (SP) are strongly influenced by interactions between organic matter content, texture and anthropogenic disturbance. Trails such as Água Branca and Sítio Recanto da Paz, characterized by higher organic matter content, exhibit lower bulk density and higher porosity. This highlights the stabilizing role of organic matter in maintaining soil structure under compaction. In contrast, soils with a higher clay fraction and lower organic matter content show greater vulnerability to physical degradation under trampling.

The statistical results indicate that recreational use primarily alters the surface structure. These modifications are consistent with compaction and disruption of pore continuity, which reduces infiltration and alters surface hydrological processes. In contrast to physical attributes, the absence of significant variations in pH and geochemical constituents indicates that the mineralogical matrix remains preserved. This contrast indicates that current degradation processes are predominantly structural, affecting organic horizons without altering the underlying pedogenic matrix.

Multivariate models and statistical patterns indicate a clear differentiation of scales, whereby recreational use produces primarily physical and structural impacts on the trail sites and does not alter the regional soil chemistry and mineral composition, which remain linked to the parent material ($p > 0.05$).

The results also show that trampling promotes spatial heterogeneity in the distribution of organic matter and fine particle size fractions. These patterns indicate surface redistribution processes, with localized zones of removal and accumulation, rather than uniform degradation. Clay-rich soils respond less uniformly to mechanical disturbance, reinforcing their sensitivity to deformation under repeated use.

These findings have important implications for risk management and mitigation in steep coastal environments. Soil compaction and loss of structural integrity contribute to surface instability and runoff concentration, increasing the risk of mass movements during intense rainfall events. Given the history of landslides in the region, the conservation of the organic horizon and the control of compaction should be prioritized in civil defense and environmental conservation strategies.

Future studies incorporating X-ray diffraction (XRD) will be important for refining the understanding of clay mineralogy (e.g., kaolinite and gibbsite). Such information will improve assessments of soil stability under extreme conditions, contributing to more effective environmental management and hazard mitigation.

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References

1. Cole, D.N. Minimizing conflict between recreation and nature. In *Ecology of Greenways: Design and Function of Linear Conservation Areas*, 1st ed.; Smith, D.S., Hellmund, P.C., Eds.; University Minnesota Press: Minneapolis, MN, USA, 1993; pp. 105–122.
2. Hammitt, W.E.; Cole, D.N. *Wildland Recreation: Ecology and Management*; John Wiley & Sons: New York, NY, USA, 1998; 361p.
3. Takahashi, L. Caracterização dos Visitantes, Suas Preferências e Percepções e Avaliação dos Impactos da Visitação Pública em Duas Unidades de Conservação do Estado do Paraná. Ph.D. Thesis, Universidade Federal do Paraná, Curitiba, Brazil, 1998.
4. Leung, Y.; Marion, J.L. The influence of sampling interval on the accuracy of trail impact assessment. *Landsc. Urban Plan.* **1999**, *43*, 167–179. [\[CrossRef\]](#)
5. Magro, T.C. Impactos do Uso Público em Uma Trilha no Planalto do Parque Nacional do Itatiaia. Ph.D. Thesis, Universidade de São Paulo, São Carlos, Brazil, 1999.
6. Lynn, N.A.; Brown, R.D. Effects of recreational use impacts on hiking experiences in natural areas. *Landsc. Urban Plan.* **2003**, *64*, 77–87. [\[CrossRef\]](#)
7. Moreira, J.C.; Bigarella, J.J. Interpretação ambiental e Geoturismo em Fernando de Noronha. In *Turismo e Práticas Socioespaciais: Múltiplas Abordagens e Interdisciplinaridades*; Castilho, C.J.M., Viegas, J.M., Eds.; Universitária da UFPE: Recife, Brazil, 2008; pp. 171–192.
8. Figueiredo, M.d.A.; Assis Brito, I.; Takeuchi, R.C.; Almeida-Andrade, M.; Vieira Rocha, C.T. Compactação do solo como indicador pedogeomorfológico para erosão em trilhas de unidades de conservação: Estudo de caso no Parque Nacional da Serra do Cipó, MG. *Rev. Geogr.* **2010**, *3*, 236–247.
9. Rangel, L.A. O Impacto da Utilização de Trilhas na Área de Proteção Ambiental de Cairuçu-Paraty-Rio de Janeiro. Master's Dissertation, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil, 2014.
10. Jorge, M.C.O.; Guerra, A.J.T.; Fullen, M.A. Geotourism, Geodiversity and Geoconservation in Ubatuba Municipality, São Paulo State, Brazil. *Geogr. Rev.* **2016**, *29*, 23–29.
11. Rangel, L.A.; Jorge, M.C.O.; Guerra, A.J.T.; Fullen, M.A. Geotourism and Soil Quality on Trails Within Conservation Units in South-East Brazil. *Geoheritage* **2019**, *11*, 1151–1161. [\[CrossRef\]](#)
12. Stolz, J.; Megerle, H.E. Geotrails as a medium for education and geotourism: Recommendations for quality improvement based on the results of a research project in the Swabian Alb UNESCO global geopark. *Land* **2022**, *11*, 1422. [\[CrossRef\]](#)
13. Williams, M.A.; Rolls, S.; McHenry, M.T. Optimising geotrail planning by leveraging least-cost path for sustainable geotourism development: A case study on a Tasmanian west coast post-mining landscape. *Inf. Technol. Tour.* **2025**, *27*, 477–512. [\[CrossRef\]](#)
14. Leung, Y.; Marion, J.L. Trail degradation as influenced by environmental factors: A state-of-knowledge review. *J. Soil Water Conserv.* **1996**, *51*, 130–136. [\[CrossRef\]](#)
15. Lal, R. Degradation and resilience of soils. *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **1997**, *352*, 997–1010. [\[CrossRef\]](#)
16. Guerra, A.J.T.; Jorge, M.C.O.; Rangel, L.A.; Bezerra, J.F.R.; Loureiro, H.A.S.; Garritano, F.N. Erosão dos solos, diferentes abordagens e técnicas aplicadas em voçorocas e erosão em trilhas. *William Morris Davis-Rev. Geomorfol.* **2020**, *1*, 75–117.
17. Cole, D.N.; Schreiner, G.S. *Impacts Backcountry Recreation: Site Management and Rehabilitation—An Annotated Bibliography*; General Technical Report INT-121; U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: Fort Collins, CO, USA, 1981.
18. Brigh, J.A. Hiker impact on herbaceous vegetation along trails in an evergreen woodland of Central Texas. *Biol. Conserv.* **1986**, *36*, 53–69. [\[CrossRef\]](#)
19. Cole, D.N.; Landres, P.B. Threats to wilderness ecosystems: Impacts and research needs. *Ecol. Appl.* **1996**, *6*, 168–184. [\[CrossRef\]](#)
20. Marion, J.L.; Cole, D.N. Spatial and temporal variation in soil and vegetation impacts on campsites. *Ecol. Appl.* **1996**, *6*, 520–530. [\[CrossRef\]](#)
21. Kutiel, P.; Zhevelev, H.; Harrison, R. The effect of recreational impacts on soil and vegetation of stabilized coastal dunes in Sharon Park, Israel. *Ocean Coast. Manag.* **1999**, *42*, 1041–1060. [\[CrossRef\]](#)
22. Nepal, S. Trail impacts in Sagarmatha National Park. *Environ. Manag.* **2003**, *32*, 312–321. [\[CrossRef\]](#)
23. Nepal, S.K.; Amor-Nepal, S.A. Visitor Impacts on Trails in the agarmatha (Mt. Everest) National Park, Nepal. *AMBIO J. Hum. Environ.* **2004**, *33*, 334–340. [\[CrossRef\]](#)
24. Barros, A.; Gonnet, J.; Pickering, C. Impacts of informal trails on vegetation and soils in the highest protected area in the Southern Hemisphere. *J. Environ. Manag.* **2013**, *127*, 50–60. [\[CrossRef\]](#)

25. Wolf, I.D.; Croft, D.B. Impacts of tourism hotspots on vegetation communities show a higher potential for self-propagation along roads than hiking trails. *J. Environ. Manag.* **2014**, *143*, 173–185. [\[CrossRef\]](#)
26. Salesa, D.; Cerdà, A. Soil erosion on mountain trails as a consequence of recreational activities. A comprehensive review of the scientific literature. *J. Environ. Manag.* **2020**, *271*, 110990. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Pereira, L.S.; Rodrigues, A.M.; Jorge, M.C.O.; Guerra, A.J.T.; Booth, C.A.; Fullen, M.A. Detrimental effects of tourist trails on soil system dynamics in Ubatuba municipality, São Paulo State Brazil. *CATENA* **2022**, *216*, 106431. [\[CrossRef\]](#)
28. Pickering, C.M.; Norman, P. Comparing impacts between formal and informal recreational trails. *J. Environ. Manag.* **2017**, *193*, 270–279. [\[CrossRef\]](#)
29. Tabarelli, M.; Peres, M.C.A.; Melo, F.P.L. The “few winners and many losers” paradigm revisited: Emerging prospects for tropical forest diversity. *Biol. Conserv.* **2012**, *155*, 136–140. [\[CrossRef\]](#)
30. Baret, S.; Strasberg, D. The effects of opening trails on exotic plant invasion in protected areas on La Réunion Island (Mascarene Archipelago, Indian Ocean). *Rev. Ecol. Terre Vie* **2005**, *60*, 325–332. [\[CrossRef\]](#)
31. Rodolfo, M.; Temponi, L.G.; Candido, J.R. Levantamento de plantas exóticas na trilha do Poço Preto, Parque Nacional do Iguaçu, Paraná, Brasil. *Rev. Bras. Biociências* **2008**, *6*, 22–24.
32. Siles, M.F.R. Efeitos do Pisoteio Humano Experimental Sobre a Vegetação em Fragmentos de Floresta Pluvial Tropical Atlântica, São Paulo, Brasil. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 2009.
33. Cole, D.N. *Disturbance and Recovery of Trampled Montane Grassland and Forests in Montana*; USDA Forest Service Research Paper INT-389; Intermountain Research Station: Ogden, UT, USA, 1988; p. 37.
34. Torn, A.; Tolvanen, A.; Norokorpi, Y.; Tervo, R.; Siikamaki, P. Comparing the impacts of hiking, skiing and horse riding on trail and vegetation in different types of forest. *J. Environ. Manag.* **2009**, *90*, 1427–1434. [\[CrossRef\]](#)
35. Wimpey, J.F.; Marion, J.L. The influence of use, environmental and managerial factors on the width of recreation trails. *J. Environ. Manag.* **2010**, *91*, 2028–2037. [\[CrossRef\]](#)
36. Marion, J.L. Trail sustainability: A state-of-knowledge review of trail impacts, influential factors, sustainability ratings, and planning and management guidance. *J. Environ. Manag.* **2023**, *340*, 117868. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Eisenlohr, P.V.; Melo, M.M.R.F.; Silva, M.R.; Schmal, P.; Ferreira-Junior, W.G.; Dias, A.S.; Silva, A.F. Floristic variations in a woody plant community along a trail in a Semideciduous Seasonal Forest, Viçosa, Minas Gerais State, Brazil. *Hoehnea* **2011**, *38*, 61–71. [\[CrossRef\]](#)
38. Wilson, J.P.; Seney, J.P. Erosional impact of hikers, horses, motorcycles, and off-road bicycles on mountain trails in Montana. *Mt. Res. Dev.* **1994**, *14*, 77–88. [\[CrossRef\]](#)
39. Pickering, C.M.; Hill, W.; Newsome, D.; Leung, Y.F. Comparing hiking, mountain biking and horse riding impacts on vegetation and soils in Australia and the United States of America. *J. Environ. Manag.* **2010**, *91*, 551–562. [\[CrossRef\]](#)
40. Hawkins, J.; Weintraub, M.N. The Effect of Trails on Soil in the Oak Openings of Northwest Ohio. *Nat. Areas J.* **2011**, *31*, 391–399. [\[CrossRef\]](#)
41. Figueiredo, M.d.A.; Fonseca Filho, R.E.; Varajão, A.F.D.C. Qualidade do Solo como Geoindicador para o Manejo de uma Trilha no Parque Nacional da Serra do Cipó, MG, Brasil. *Anu. Inst. Geociênc.* **2012**, *35*, 199–208. [\[CrossRef\]](#)
42. Saraiva, A.C.R. Impactos aos atributos físicos do solo em trilhas ocasionados pelo ecoturismo em Ubatuba-SP. *Rev. Univap* **2011**, *17*, 32–40. [\[CrossRef\]](#)
43. Rangel, L.A.; Guerra, A.J.T. Degradação de trilhas na Reserva Ecológica da Juatinga em Paraty–Rio de Janeiro. *Rev. Ambiente Água* **2014**, *9*, 752–766. [\[CrossRef\]](#)
44. Rangel, L.A.; Jorge, M.C.O.; Guerra, A.J.T.; Fullen, M.A. Soil Erosion and Land Degradation on Trail Systems in Mountainous Areas: Two Case Studies from Southeast Brazil. *Soil Syst.* **2019**, *3*, 56. [\[CrossRef\]](#)
45. Feola, E.; Nucci, J.C.; Santos, L.J.C. Avaliação de impactos do uso público em uma trilha no Parque Estadual do Pico do Marumbi–PR. *Geogr. Rio Claro* **2008**, *33*, 157–175.
46. Conway, J.S. A Soil Trail? A Case Study from Anglesey, Wales, UK. *Geoheritage* **2010**, *2*, 15–24. [\[CrossRef\]](#)
47. Chadwick, O.A.; Brimhall, G.H.; Hendricks, D.M. From a black to a gray box—a mass balance interpretation of pedogenesis. *Geomorphology* **1990**, *3*, 369–390. [\[CrossRef\]](#)
48. Nascimento Filho, V.F. *Técnicas Analíticas Nucleares de Fluorescência de Raios X por Dispersão de Energia (EDXRF) e por Reflexão Total (TXRF)*; Centro de Energia Nuclear na Agricultura/CENA-USP: Piracicaba, Brazil, 1999; p. 32.
49. Simabuco, S.M. Emprego da Fluorescência de Raios X por Dispersão de Energia no Estudo da Dinâmica da Vinhaça no Solo. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 1993.
50. Anjos, M.J.; Lopes, R.T.; de Jesus, E.F.O.; Assis, J.T.; Cesareo, R.; Barradas, C.A.A. Quantitative analysis of metals in soil using X-ray fluorescence. *Spectrochim. Acta Part B At. Spectrosc.* **2000**, *55*, 1189–1194. [\[CrossRef\]](#)
51. Revenko, A.G. X-ray fluorescence analysis of rocks, soils and sediments. *X-Ray Spectrom.* **2002**, *31*, 264–273. [\[CrossRef\]](#)
52. Du, P.; Xie, Y.F.; Wang, S.J.; Zhao, H.H.; Zhang, Z.; Wu, B.; Li, F.S. Potential Sources of and Ecological Risks from Heavy Metals in Agricultural Soils, Daye City, China. *Environ. Sci. Pollut. Res.* **2015**, *22*, 3498–3507. [\[CrossRef\]](#)

53. Coringa, E.d.A.O.; Couto, E.G.; Torrado, P.V. Geoquímica de solos do pantanal norte, Mato Grosso. *Rev. Bras. Ciência Solo* **2014**, *38*, 1784–1793. [CrossRef]
54. Stockmann, U.; Cattle, S.R.; Minasny, B.; McBratney, A.B. Utilizing portable X-ray fluorescence spectrometry for in-field investigation of pedogenesis. *CATENA* **2016**, *139*, 220–231. [CrossRef]
55. Giuseppe, D.D.; Melchiorre, M.; Tessari, U.; Faccini, B. Relationship between particle density and soil bulk chemical composition. *J. Soils Sediments* **2016**, *16*, 909–915.
56. Melquíades, F.L.; Appoloni, C.R. Application of XRF and field portable XRF for environmental analysis. *J. Radio Anal. Nucl. Chem.* **2004**, *262*, 533–541. [CrossRef]
57. Wastowski, A.D.; da Rosa, G.M.; Cherubin, M.R.; Rigon, J.P.G. Caracterização dos níveis de elementos químicos em solo, submetido a diferentes sistemas de uso e manejo, utilizando espectrometria de fluorescência de raios-x por energia dispersiva (EDXRF). *Quim. Nova* **2010**, *33*, 1449–1452. [CrossRef]
58. IBGE—Instituto Brasileiro de Geografia e Estatística. Malha Municipal Digital do Brasil–2022. Available online: <https://www.ibge.gov.br/cidades-e-estados/sp/ubatuba.html> (accessed on 22 February 2025).
59. Cruz, O. A Serra do Mar e o Litoral na Área de Caraguatatuba-SP: Contribuição a Geomorfologia Litorânea Tropical. Ph.D. Thesis, Universidade de São Paulo, São Paulo, Brazil, 1974.
60. Hasui, Y.; Haralyi, N.L.E.; Costa, J.B.S. Megaestruturação pré-cambriana do território brasileiro baseada em dados geofísicos e geológicos. *Geociências* **1993**, *12*, 7–31.
61. Secretaria do Meio Ambiente do Estado de São Paulo. *Plano de Manejo do Parque Estadual da Serra do Mar*; Secretaria do Meio Ambiente, Instituto Florestal: São Paulo, Brazil, 2006.
62. Monteiro, C.A.d.F. *A Dinâmica Climática e as Chuvas no Estado de São Paulo*; USP/IGEOG: São Paulo, Brazil, 1973.
63. Jorge, M.C.O.; Mendes, I.A.; Sato, S.E. Caracterização Pluviométrica do Município de Ubatuba: Período de 1978 a 1999. In Proceedings of the X Simpósio Brasileiro de Geografia Física Aplicada, Rio de Janeiro, Brasil, 21–23 September 2003.
64. Teixeira, P.C.; Donagemma, G.K.; Fontana, A.; Teixeira, W.G. *Manual de Métodos de Análises de Solos*; EMBRAPA: Brasília, Brazil, 2017; p. 574.
65. Maganhotto, R.F.; Santos, L.J.C.; Souza, L.C.P.; Miara, M.A. Variação dos atributos físicos do solo devido ao trânsito de pessoas em trilha localizada na Região de Paranaguá-PR. *Rev. Geogr.* **2010**, *5*, 94–114. [CrossRef]
66. Fullen, M.A.; Catt, J.A. *Soil Management: Problems and Solutions*; Arnold: London, UK, 2004; p. 269.
67. Naghdi, R.; Solgi, A.; Ilstedt, U. Soil chemical and physical properties after skidding by rubber-tired skidder in Hyrcanian forest, Iran. *Geoderma* **2016**, *265*, 12–18. [CrossRef]
68. Moraes, S.M.; Rodrigues, J.B.; Sachs, L.L.B.; Dehler, N.M. *Integração Geológica da Folha Santos 1:250.000 (SF-23-Y-D)*; CPRM—Serviço Geológico do Brasil: Brasília, Brazil, 1999.
69. Queta, F.M.; Duarte, I.M.R.; Bonito, F.A.B. Caracterização geológica e geotécnica de solos residuais tropicais da Região Central de Angola. In *Engenharia Como Motor Para a Inovação e o Desenvolvimento*; Silva Gomes, J.F., António, C., Afonso, C.F., Matos, A.S., Eds.; LusoImpress, S.A.: Inhambane, Mozambique, 2014; p. 209.
70. Lal, R.; Elliot, W. Erodibility and erosivity. In *Soil Erosion Research Methods*; Lal, R., Ed.; Soil and Water Conservation Society: Washington, DC, USA, 1998; pp. 141–160.
71. Neyshabouri, M.R.; Ahmadi, A.; Rouhipour, H.; Asadi, H.; Irannajad, M. Soil texture fractions and fractal dimension of particle size distribution as predictors of interrill erodibility. *Turk. J. Agric. For.* **2011**, *35*, 95–102. [CrossRef]
72. Bonilla, C.A.; Johnson, O.I. Soil erodibility mapping and its correlation with soil properties in Central Chile. *Geoderma* **2012**, *189–190*, 116–123. [CrossRef]
73. Vaezi, A.R.; Hasanzadeh, H.; Cerdà, A. Developing an erodibility triangle for soil textures in semi-arid regions, NW Iran. *CATENA* **2016**, *142*, 221–232. [CrossRef]
74. Godefroid, S.; Koedam, N. The impact of forest paths upon adjacent vegetation: Effects of the path surfacing material on the species composition and soil compaction. *Biol. Conserv.* **2004**, *119*, 405–419. [CrossRef]
75. Monz, C.A.; Pickering, C.M.; Hadwen, W.L. Recent advances in recreation ecology and the implications of different relationships between recreation use and ecological impacts. *Front. Ecol. Environ.* **2013**, *11*, 441–446. [CrossRef]
76. Volkweiss, S.J. Química da acidez dos solos. In *Seminário Sobre Corretivos da Acidez do Solo*; Kaminski, J., Volkweiss, J., Becker, F.C., Eds.; Universidade Federal de Santa Maria: Santa Maria, Brazil, 1989.
77. Meurer, E.J. *Fundamentos da Química do Solo*; Editora Evangraf: Porto Alegre, Brazil, 2012; p. 266.
78. Sato, C.A. Caracterização da Fertilidade do Solo e da Composição Mineral de Espécies Arbóreas de Restinga do Litoral Paulista. Master's Dissertation, Universidade Estadual Paulista Júlio de Mesquita Filho, Rio Claro, Brazil, 2007.

79. Sanchez, P.A.; Logan, T.J. Myths and science about the chemistry and fertility of soils in the tropics. In *Myths and Science of Soil of the Tropics*; Lal, R., Sanchez, P.A., Eds.; Special Publication 29; SSSA / ASA: Madison, WI, USA, 1992; pp. 35–46.
80. Berek, A.K.; Hue, N.V. Improving nutrient retention of highly weathered tropical soils with biochars. In *The Second International Conference on Green Agro-Industry (ICGAI): Resource Management for Sustainable Future*; Universitas Pembangunan Nasional (UPN) “Veteran”: Yogyakarta, Indonesia, 2015; pp. 183–195.

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