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Does the Process of Passive Forest Restoration Affect the Hydrophysical Attributes of the Soil Superficial Horizon?

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Abstract: There has been an increase in the area of secondary tropical forests in recent years due to forest restoration in degraded areas. Recent analyses suggest that the success of passive forest restoration is highly uncertain and needs to be better understood. This study aimed to investigate the behavior of saturated hydraulic conductivity (*Ks*) and some hydrophysical soil attributes between agricultural land uses, restored forests, and a degraded forest fragment. The areas evaluated are located in the municipality of Rio Claro, São Paulo, Brazil, under different types of land use: (i) two areas in the process of passive forest restoration: one of 18 and another of 42 years (NR18 and NR42); (ii) a degraded forest fragment (FFD); (iii) pasture (P), and (iv) sugarcane (SC). The hydraulic soil conductivity characterization was performed using the Beerkan method. Dry soil bulk density (*BD*), total porosity (*Pt*), macroporosity (*Mac*), microporosity (*Mic*), penetration resistance (*PR*), mean aggregate diameter (*MWD*), and soil organic carbon (*OC*) were also determined. The comparative analysis of the hydrophysical attributes of the soil superficial horizon in agricultural land uses (P and SC), restored forests (NR18 and NR42), and a degraded forest (DFF) confirms that the recovery of soil hydrological functioning in ongoing forest restoration processes can be a relatively slow process. In addition, the intensity of previous land use leaves footprints that can affect passive restoration areas for decades after agriculture abandonment, increasing the time for the recovery of *Ks* and soil hydrophysical attributes.

Keywords: soil hydraulic conductivity; aggregate stability; soil porosity; soil penetration resistance

1. Introduction

A substantial increase in the area of secondary tropical forests has been occurring in the last 20 years [1,2]. There is promising evidence that these areas have been increasing as a result of the ambitious goals implemented worldwide for the recovery of degraded and deforested land, such as the Bonn Challenge (2011) and the New York Declaration on Forest (2014). Many degraded areas, especially those that have not been subjected to many years of monoculture, are recovered using passive restoration techniques. One of these techniques is natural forest regeneration, which takes advantage of the resilience of degraded areas by stimulating the germination of local seed banks, seed dispersal processes, regrowth of trunks, or seedlings that resisted the disturbances. This restoration approach is economically advantageous because it reduces implementation costs, such as purchase of seedlings, inputs, application of silvicultural techniques, maintenance of plantations, and labor [3].

The potential of passive restoration to recover some groups of biodiversity in tropical regions (such as plants, birds, and invertebrates) and structural parameters of vegetation (density, biomass, and height) is well reported in the literature [4–6]. Furthermore, large-scale forest cover, either natural or restored, has impacts on climate, soil, and hydrology [7]. Soil is the substrate for forest restoration, and the knowledge of its functioning is essential for understanding and managing restoration processes. Thus, the success of forest restoration processes depends on the presence of a healthy soil environment in which seedlings and trees can develop successfully. The recovery of soil hydrophysical attributes is fundamental to maximize the success of restoration efforts [8]; however, it is still not fully understood in forest restoration because soil is still under-investigated in these environments. Monitoring soil hydrophysical attributes in forest restoration environments, such as soil bulk density, total porosity, macro and microporosity, and aggregate stability, can supply data on soil-related functions, such as root growth, water infiltration and drainage, gas exchange, biological activity, water retention, and carbon stock supply [9].

The hydraulic conductivity of saturated soil (*Ks*) is also a key parameter that describes the movement of water in the soil and exerts a dominating influence on the partitioning of rainfall into vertical and lateral flow paths. Therefore, estimates of *Ks* are essential for describing and modeling hydrological processes [10]. Moreover, *Ks* is dependent on the soil structure, an attribute deeply affected by soil management [11,12]. In forest ecosystems, it is expected that there will be greater input and decomposition of the litter, which is the main supply of organic matter to the soil and regulates the cycling of nutrients. Higher concentrations of organic matter in the soil also favor microbial and soil fauna activities and provide more suitable conditions for soil protection [13]. The formation and evolution of soil aggregates are driven by biological and microbial activities, and the supply of organic matter under forests helps to maintain the stability of soil aggregates [14]. The literature reports some studies that evaluated areas in different stages of passive restoration in tropical forests [4,7,15–19]. In some areas, improvements were observed in the contribution of soil biomass and biodiversity [4,17], lower soil bulk density, and greater total soil porosity [17,19], which probably influenced the formation of more stable aggregates in the soil and higher *Ks*. In general, the results reinforce the importance of expanding knowledge about the hydrophysical attributes in forest restoration areas, since the forest's age alone is not sufficient to restore soil functioning. Besides, different stages of forest restoration may show distinct signs of soil recovery.

Among Brazilian biomes, the Atlantic Forest suffered the most significant degradation, due to the conversion of primary forests to sugarcane and coffee plantations [20]. Currently, it has a high number of degraded fragments and only 12% of the original coverage [21]. In this biome, the current forest cover is a heterogeneous forest mosaic of different ages, located in different landscape conditions and, therefore, with varying levels of disturbance [22]. Understanding the degree of tropical forest disturbances and their recovery by restoration processes is challenging. In addition, the time that natural regeneration takes to recover the hydrophysical soil attributes disturbed by intense previous land use after deforestation is very variable [19]. These processes need to be better understood [18,23–26].

Considering that the soil structure and functioning are essential for the improvement of *Ks* [8,17,18] and that the impact of passive restoration on the soil hydrophysical functioning is still little known, this study aimed to answer the following question: Is passive restoration capable of improving soil *Ks*, as well as the physical attributes of the soil superficial horizon? To answer this question, we investigated the behavior of *Ks* and some soil physical attributes of the soil superficial horizon in forests of different ages undergoing passive restoration by natural regeneration, a degraded forest fragment, a pasture, and a sugarcane field.

2. Material and Methods

2.1. Study Area

The study was carried out in the county of Rio Claro (22°20′ S, 47°34′ W), São Paulo State, Southeast Brazil (Figure 1). The area is inserted in the Corumbataí River hydrographic basin, and has more than 1700 km^2 and more than 200 years of land-use change [22], with an altitude between 562 and 643 m a.s.l. The climate is classified as Cwa, according to Köppen classification, characterized by dry winters and rainy and hot summers [27]. The wettest period is from December to February, while the driest, from June to August. The average annual precipitation is 1344 mm, with an average annual temperature of 20.5 °C [27]. According to the geomorphological map of São Paulo state, the area is located in the Peripheral Depression of the São Paulo state [28]. The native forest cover is classified as semi-deciduous rainforest [29], belonging to the Atlantic Forest biome [30].

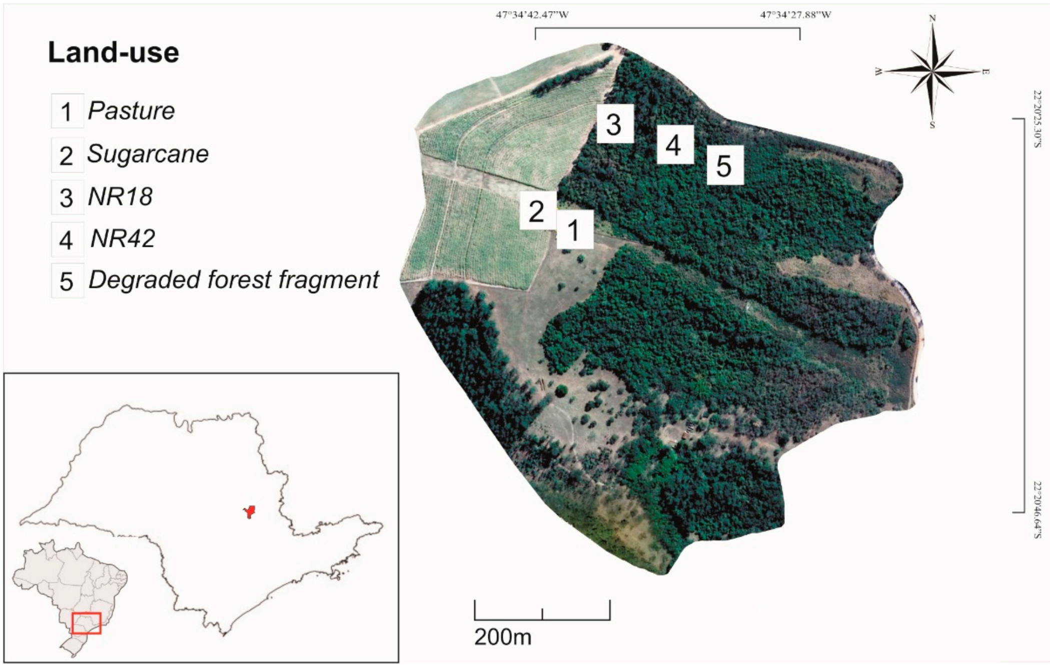

Figure 1. Location of the study areas in the state of São Paulo, Southeast Brazil. NR18: Natural regeneration 18 years; NR42: Natural regeneration 42 years.

The exploitation of the Brazilian Atlantic Forest was accentuated in the 20th century, resulting in severe changes to the ecosystems, primarily by reducing and increasing the pressure on biodiversity [31]. After almost 500 years of land-use changes, the Atlantic Forest, which covered about 150 million hectares in Brazil, currently has less than 12% of its original forest cover (1.2 million km^2) [21]. Nowadays, more than 80% of forest fragments are smaller than 50 ha [21], isolated, unprotected, and severely altered [32]. The few fragments larger than 100 ha are located on steep terrain, where human occupation is difficult [33].

The intense deforestation in the study area resulted from the exploitation and expansion of coffee, cotton, and pastures [32] during the first half of the twentieth century [31]. According to 1962 satellite images [22], the actual restored forest cover in the study area was previously occupied by pastures. Restoration by natural regeneration processes occurred due to two main reasons: (1) the abandonment of areas, which had low agricultural suitability, due to the predominance of steep slopes, and the presence of sandy and rocky soils [22]; and (2) environmental planning efforts to comply with the Brazilian Forest Code [22,30]. Currently, land use in this area is dominated by Urochloa decumbens

Stapf pastures (43.68%), sugar cane (25.57%), fragments of native forest (12.36%), and other types of land uses (14.5%) [34].

For the development of this study, we selected five different land uses: (a) pasture (P); (b) sugarcane (SC); (c) 18-year-old passive forest restoration by natural regeneration (NR18); (d) 42-year-old passive forest restoration by natural regeneration (NR42), and (e) degraded forest fragment (DFF) (Figures 1 and 2). The DFF area is currently isolated, but before this measure, there were intense cattle invasions associated with frequent burning in the contiguous sugar cane fields during the dry season that invaded the remnant fragment. Oxisols and Ultisols represent the soils of the study area, according to Soil Taxonomy, 2014 [35] with sandy loam and loamy, sandy textures (Table 1). The soil texture of the superficial horizon did not show important variations among the study sites being considered homogeneous.

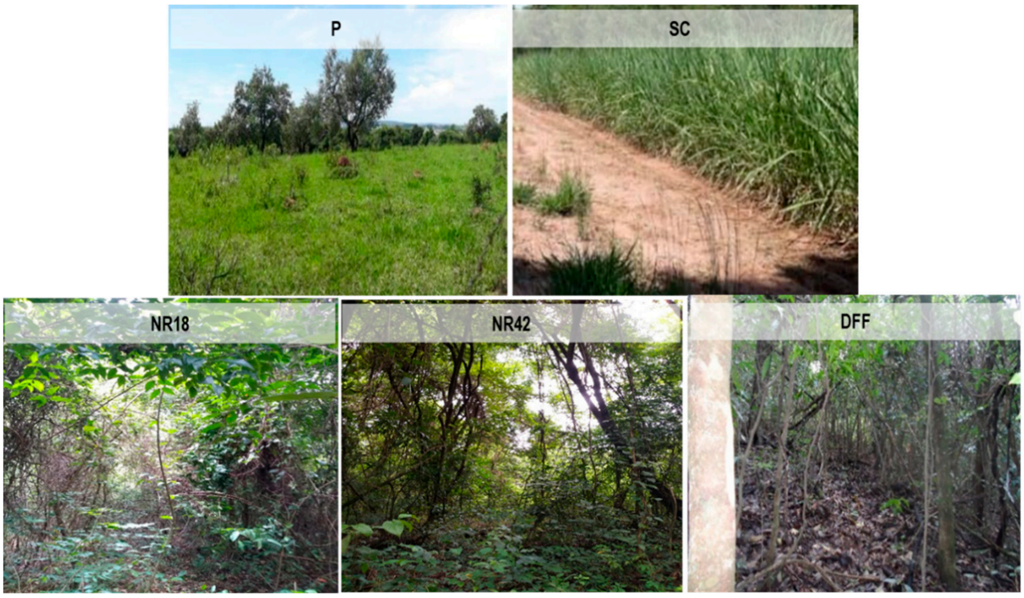

Figure 2. Image of the study areas. P: Pasture; SC: Sugarcane; NR18: Passive restoration by natural regeneration 18 years; NR42: Passive restoration by natural regeneration 42 years; DFF: Degraded forest fragment.

Table 1. Soil classification, soil particle density (ρs), particle size distribution, and textural classes for the soil superficial horizon (0.10 m) of the study areas.

Study Area	Clay (%)	Silt (%)	Sand (%)	ρs g cm^{-3}	Textural Classes	Soil Classification
P	18	4	78	2.63	Sandy loam	Oxisols
SC	19	5	76	2.66	Sandy loam	Oxisols
NR18	11	6	83	2.67	Loamy sand	Oxisols
NR42	14	15	71	2.64	Sandy loam	Ultisols
DFF	11	13	76	2.65	Sandy loam	Oxisols

P: Pasture; SC: Sugarcane; NR18: Natural regeneration 18 years; NR42: Natural regeneration 42 years; DFF: Degraded forest fragment.

2.2. Soil Sampling and Analytical Procedures

The field campaign and soil sampling were performed during July 2018. Within each study area, five sampling points were selected, distant 5.5 m from each other. The soil water infiltration was measured using the Beerkan method [36]. In each study area, ten water infiltration measurements were performed (two infiltration measurements at each sampling point), using a steel cylinder with an internal diameter of 0.16 m. The sampled infiltration surfaces were assumed to be large enough to allow the determination of representative *Ks* values that accounted for soil heterogeneity and the contribution of biopores [37]. The location of the insertion of the steel cylinder was previously prepared by removing the litter and other materials to expose the soil surface. Subsequently, the steel ring was inserted 0.01 m into the soil. For each measurement, a volume of 150 mL of water was added repeatedly into the steel cylinder. The time for complete infiltration of each poured volume was logged. This procedure was repeated until the difference between the infiltration times of two or three consecutive tests underwent minimal variation. In total, 50 infiltration runs (10 runs × 5 areas) of cumulative infiltration (I) as a function of time (t) were performed.

The values of *Ks* were estimated by the simplified Beerkan infiltration method (SSBI—Steady version of the Simplified method based on a Beerkan Infiltration run) [38]. The SSBI method estimates *Ks* as follows:

$$K_s = \frac{i_s}{\frac{\gamma\gamma_w}{r\alpha^*} + 1} \quad (1)$$

where i_s (L T^{-1}) is the slope of the linear regression fitted to the final portion of the cumulative infiltration time series, r (L) is the ring radius, γ_w is a dimensionless constant related to the shape of the wetting front often fixed at 1.818 [39], γ is an infiltration constant, often fixed at 0.75 [40,41], and α^* (L^{-1}) is the sorptive number, that expresses the relative importance of the capillary over gravity forces during water movement in unsaturated soil [42,43]. According to a previous investigation carried out on similar soils in the Atlantic forest [44], we assumed a value of $\alpha^* = 0.0012$ mm^{-1}, also taking into account that it represents the suggested first approximation value for most field soils [45].

At each sampling point, disturbed and undisturbed soil samples were collected at 0–0.10 m depth. The disturbed samples were collected to determine the gravimetric moisture content of the saturated soil (*Ug*, %), the organic carbon (*OC*, g kg^{-1}), and the soil particle density (ρs, g cm^{-3}). Undisturbed samples were collected using Kopeck metal rings with cutting edges measuring 0.05 × 0.05 m (diameter × height). These samples were used to determine: (a) the initial volumetric moisture content (θi, cm^3 cm^{-3}), (b) total porosity (*Tp*, cm^3 cm^{-3}), (c) macroporosity (*Mac*, cm^3 cm^{-3}), (d) microporosity (*Mic*, cm^3 cm^{-3}), (e) dry soil bulk density (*Pt*, g cm^{-3}) and (f) penetration resistance (*PR*, MPa). Bulk density (*BD*) was determined by the ratio of the dry soil mass and the cylinder volume [46]. The volumetric moisture content of the saturated soil (θs, cm^3 cm^{-3}) was obtained using the measure of *BD* ($\theta s = Ug \times BD$). We also computed the depths of wetting fronts for all infiltration experiments at the end of the experiment, Z_{wf} (L). For this purpose, we considered a piston flow width displacement of the volume of water in the soil porosity [47].

In the laboratory, each undisturbed soil sample was gradually saturated with water by capillary action and then weighed. The total porosity (*Tp*) was calculated by the ratio between *BD* and ρs [48]. The soil particle density (ρs) was determined by a helium gas pycnometer (ACCUPYC 1330, Micromeritics Instrument Corporation®, Norcross, GA, USA). *Mic* was estimated using the tension table with the soil matric potential of −6 kPa ($\Psi = -0.006$), and *Mac* was determined by the difference between *Tp* and *Mic*.

PR was determined using an electronic benchtop penetrometer (CT3 Texture Analyzer, Brookfield, Middlebore, MA, USA), equipped with a 25 kg load cell and a metal rod with a 30° semi-angle cone tip, a basal diameter of 3.81 mm, and penetration velocity of 10 mm min^{-1}. *PR* measurements were obtained through an automated data acquisition system. Such measures were collected at the center of each undisturbed soil sample with soil moisture equivalent to a water pressure of 10 kPa. For all samples, the measurements obtained from the upper (1 cm) and lower (1 cm) were discarded, following the procedures of Imhoff [49].

The determination of the aggregate means weight diameter (*MWD*) was performed using the dry methodology [50]. For this, 50 g of soil were collected from the 0–0.10 m depth. These samples were separated into size classes by sieving in a dry medium through a Solotest vibratory mechanical stirrer containing a set of mesh sieves: 4.0, 2.0, 1.0, 0.50, and 0.25 mm. The calculations of (*MWD*) were obtained using the equation of Kemper [51]:

$$MWD = \sum X_{is}.W_{is} \quad (2)$$

where *MWD* = mean weight diameter of the soil aggregates (mm); X_{is} = mean diameter of each class (mm); W_{is} = proportion of aggregates in each sieve class (i) (%).

2.3. Data Analysis

For each studied variable (*Ks*, *BD*, *Tp*, *Mac*, *Mic*, *PR*, *MWD*, and *OC*) analysis of variance (ANOVA) was performed, considering the type of land use as an explanatory variable (P, SC, NR18, NR42, and DFF), after having checked that the assumptions of normality of residues and homogeneity of variances were met, through the Shapiro–Wilk test and the Barllet test, respectively. In the case of significance at 10%, the Tukey test was applied, which compares the means two by two. For the variables *Ks* and *PR*, normality was determined using the natural logarithm of the value obtained initially, due to the high variability of the data [52]. For the *Mic*, the assumptions of ANOVA were not met, even after data transformation. A Kruskal–Wallis non-parametric test was then performed, also at a 10% significance level. To simultaneously compare the hydrophysical attributes of the soil between the different uses, a principal component analysis (PCA) was performed for standardized data. All analyses were performed in the R software (R Core Team, Vienna, Austria, 2018).

3. Results

Soil Hydrophysical Attributes of the Study Areas

The soils in the study area did not present soil particle distribution differences down to the depth of 0.30 m (Table 1). Among the different types of land use studied in this investigation, there were statistically significant differences for the variables *Ks*, *Mic*, *PR*, *MWD*, and *OC* (Table 2 and Figure 3). The *BD*, *Tp*, and *Mac* variables did not show statistically significant differences among the studied land uses (Table 2).

Table 2. Average values of the hydrophysical attributes of the soils in the study areas. *BD*: bulk density (g cm^{-3}); *Tp*: total porosity (cm^3 cm^{-3}); *Mac:* macroporosity (cm^3 cm^{-3}); *Mic*: microporosity (cm^3 cm^{-3}); *PR*: penetration resistance (Mpa); *MWD*: mean weight diameter of the soil aggregates (mm); *OC*: soil organic carbon content (g kg^{-1}), and *Ks*: saturated soil hydraulic conductivity (mm h^{-1}).

		Land Uses				
Attributes	**Statistic**	**P**	**SC**	**NR18**	**NR42**	**DFF**
BD	Mean	1.51 a	1.53 a	1.47 a	1.48 a	1.39 a
	CV	2.98	4.46	4.40	9.54	5.97
Tp	Mean	0.42 a	0.42 a	0.44 a	0.45 a	0.47 a
	CV	3.51	6.20	5.07	10.35	6.61
Mac	Mean	0.13 a	0.16 a	0.13 a	0.16 a	0.18 a
	CV	19.16	14.39	12.98	17.00	23.28
Mic	Mean	0.29 ab	0.25 b	0.30 a	0.28 ab	0.29 ab
	CV	6.30	6.21	5.26	17.55	5.37
PR	Mean	2.64 a	1.60 a	0.83 b	0.66 b	0.68 b
	CV	23.92	32.37	38.30	33.53	16.95
MWD	Mean	0.99 bc	0.76 c	0.75 c	1.34 ab	1.68 a
	CV	2.98	16.17	12.86	6.84	11.06
OC	Mean	14.00 a	7.33 c	8.66 bc	11.33 ab	9.33 bc
	CV	14.28	15.74	13.32	10.18	16.36
Ks	Mean	28.46 b	39.93 ab	70.30 a	124.22 a	36.28 ab
	CV	104.89	59.60	80.50	115.08	73.28

The letters refer to the comparison test of means two by two in the Tukey test at the 90% confidence level. Averages followed by the same letter do not differ statistically. CV: coefficient of variance (%). Reference values of CV: Low: <10%; medium: between 10 and 20%; high: between 20 and 30%, and very high: >30% [53]. Note: For *BD*, *Tp*, *Mac*, *Mic*, and *PR*, the number of soil samples = 5; for *Ks* = 10; for *MWD* and *OC* = 3.

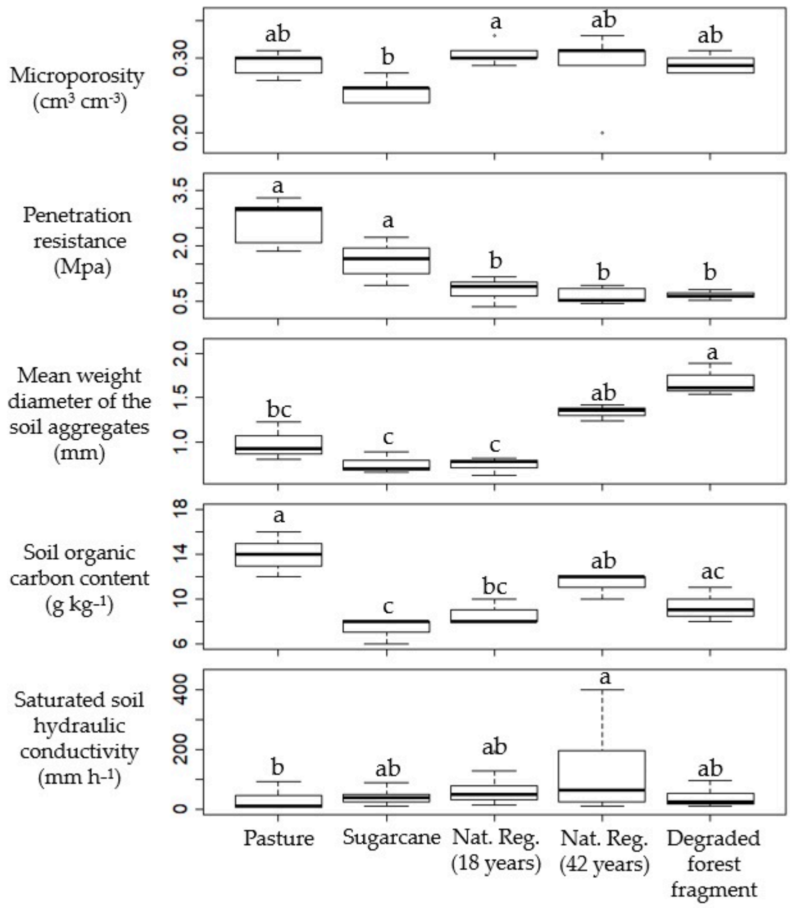

Figure 3. Boxplot of hydrophysical attributes for the different land uses. Line within the box is the median. The bars represent standard error. Note: For this figure, we only considered the soil physical attributes that presented significant differences, according to Table 2. Nat.Reg = natural regeneration.

Considering soil *Mic*, SC only differed from NR18. For this attribute, NR42 presented a medium value of the coefficient of variance (CV) and the rest a low CV. Significant differences were observed for *PR* between the agricultural (P and SC) and the passive restoration areas (NR18 and NR42). *PR* values for P and SC were higher than NR18, NR42, and DFF (Figure 3). NR18 and DFF had *PR* values three times lower than P, and NR42 had *PR* values four times lower than P. When compared to SC, the passive restoration areas and DFF also presented lower *PR* values. High CV values for *PR* were found for SC, NR18, and NR42.

The land use with the highest passive restoration age—NR42—presented similar *MWD* values to DFF and P and differed from all the other land uses. We noted that the youngest passive restoration area—NR18–presented *MWD* values similar to both agricultural land uses (P and SC). For this attribute, CV values were low for P and NR42 and medium for SC, NR18, and DFF (Table 2; Figure 3).

Considering the soil *OC* content, P had the highest values and was similar to NR42, while SC, NR18, and DFF presented lower values. All land uses had medium CV's (Table 2).

The mean values of the wetting front depths ranged from 219 to 319 mm, depending on the site. Therefore, *Ks* data may be considered representative of the studied upper layers (Table 1). In addition, we did not detect any restrictive layer that may have affected *Ks* predictions [54].

Ks was moderately high for P and presented significant differences with both passive restoration areas. NR18 and NR42 had high *Ks* values, approximately double and four times the *Ks* value of P, respectively. SC and DFF had similar values of *Ks*. All land uses presented high CV values for *Ks*, especially NR42, followed by P (Table 2).

Although no significant differences among land uses were observed for *BD*, a tendency of decrease in this attribute could be observed in the forest land uses when compared to the agricultural land uses (Table 2). The same was valid for *Tp*, where the restoration age showed a tendency to improve, presenting similar values to DFF. The behavior of *Ks* also showed a tendency to increase according to restoration age, considering the mean and absolute values of this attribute (Figure 3).

A PCA was performed to investigate and relate the soil hydrophysical attributes between the different land uses (Table 3 and Figure 4).

Table 3. Principal component analysis (PCA) loadings for the first and second components of the principal component analysis.

Variables	Component 1	Component 2
Ks		0.49
BD	0.556	0.109
Tp	−0.578	
Mac	−0.353	0.512
Mic	−0.262	−0.618
PR	0.391	−0.316

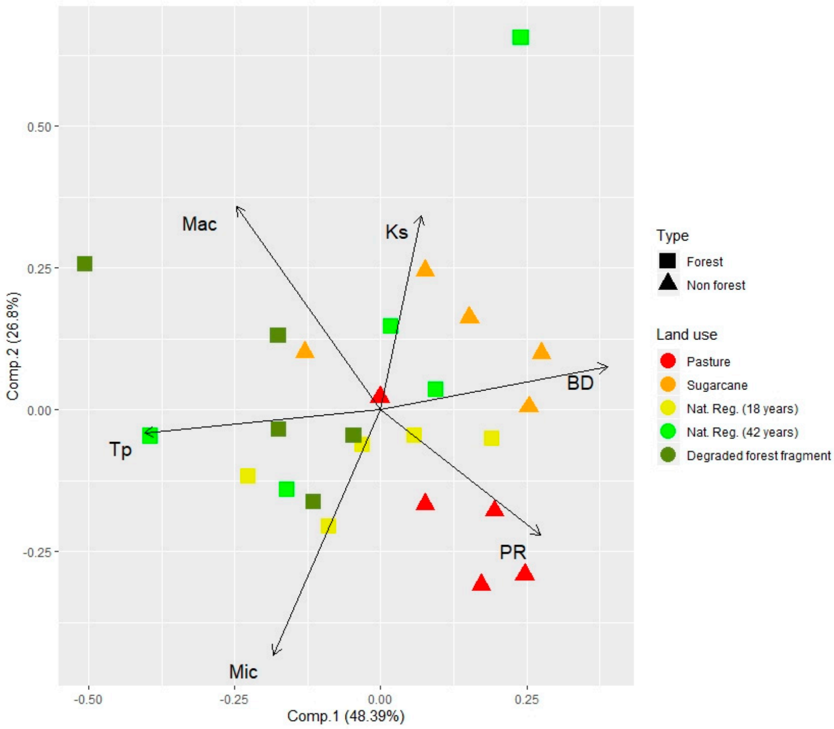

Figure 4. Principal Component Analysis (PCA) biplot based on soil attributes: Log *Ks* (mm h^{-1}), *BD* (g cm^{-3}), *Tp* (cm^3 cm^{-3}), *Mic* (cm^3 cm^{-3}), *Mac* (cm^3 cm^{-3}), *PR* (Mpa). Symbols represent plot sites for each land-cover type: Nat.Reg = natural regeneration.

Component 1 represents 48.39% of the data variation, and the variables most related to this Axis were *BD* (positively) and *Tp* (negatively) (Table 3 and Figure 4). In addition, *BD* was positively correlated to *PR*, while *Tp* was mainly correlated to *Mac* and, to a lesser extent, to *Mic*. *Ks* remained almost perpendicular to component 1; this demonstrated that there was no correlation between this attribute with *BD*, considering all land uses.

The higher values of component 1 indicate higher levels of soil degradation, while the lower values indicate the opposite. On this Axis, the forest areas are positioned to the left, while the non-forest areas are on the right. In this case, the highest values of *BD* and lower values of *Tp* were associated with agricultural land uses (P and SC), while the lower *BD* values were associated with DFF. Therefore, the sequence of the most degraded to the least degraded areas was P, SC, NR18, NR42, and DFF, with a remarkable tendency for less degradation of the two areas in the process of restoration and DFF.

Component 2 explained 26.8% of the data variation. The variables most correlated to this Axis were *Mac* (positively) and *Mic* (negatively), and *Ks* had a low relationship with *Mac*, *Tp,* and *BD*. Considering the land use, it is possible to notice that the forest areas were distributed along the entire Axis, while P was below, and SC was above. Besides that, the highest values of *Mac* were more associated with SC, while *Mic* and *PR* were related to P. As for the restoration areas (NR18 and NR42), we noticed a tendency to decrease *Mic* and increase *Ks*, according to the ages of passive restoration.

4. Discussion

According to the *Ks* classification of the Soil Survey Staff [55], the *Ks* values obtained in the studied areas varied between high (36 < 360 mm h^{-1}) and moderately high (3.6 < 36 mm h^{-1}). At the P site, *Ks* was moderately high due to soil compaction, evidenced by the high *PR* value, high *Mic* (Figures 3 and 4), and low *MWD* (Table 2). *PR* integrates the effects of soil bulk density and moisture, affecting the soil physical conditions for root growth [56]. The *PR* value for P was above 2 Mpa, which is considered a critical limit for root growth in the literature [57,58]. This result reports the degradation of the area, as demonstrated in the PCA (Figure 4). The high content of *OC* is explained by the accumulation of biomass in pastures, promoted by the root system of grasses that are abundant during the year and by the organic matter added by the animals [57,59], but its effect on soil aggregation was not observed due to the high level of compaction in this area. The decrease in *Ks* has been similarly reported in several studies after the establishment of pastures in tropical soils and occurred due to changes in the soil pore distribution caused by animal trampling. A study at the watershed scale in the Atlantic Forest biome showed moderately high values of *Ks* (22 mm h^{-1}) in the surface 0.15 m soil layer in pasture when compared to eucalyptus (40 mm h^{-1}) and a 44-year-old secondary forest (61 mmh^{-1}) [60]. Another study, carried out in the Amazon, also reported a decrease in soil water infiltration after conversion from forest to pasture, from 1258 to 100 mm [61]. The reduction in soil water infiltration and, consequently, lower *Ks*, promote lateral water fluxes [10,62–64], higher runoff and, consequently, higher soil erosion [65].

The absence of soil cover combined with agricultural machinery used in the SC area promoted the lowest values of *MWD* and *OC*, which probably influenced the lower value of *Ks* when compared to NR18 and NR42. Even though *Ks* in SC did not differ statistically from NR18 and NR42, the latter have higher absolute values. This land use was highly associated with soil *Mac* (Figure 4), which was probably associated with soil tillage operations carried out during sugarcane replanting and in the period between ratoon-crop harvests. These soil management practices can have positive effects, in the short term, on the physical quality of the soil, due to the modifications provided to the soil porosity, mainly in the superficial soil horizons [66,67].

The values obtained for *Ks* in the NR18 and NR42 areas were classified as high, according to Soil Survey Staff [55]. Indeed, these *Ks* values indicated a good ability of the soil to infiltrate and percolate plant-available water to the root zone and to drain excess water out of the root zone [64]. These areas showed a tendency to improve the *MWD* and *OC* variables, where the latter is one of the primary agents of formation and stabilization of soil aggregates in the soil superficial horizons, with a direct influence on porosity [68,69]. The *MWD* indicates the largest stable aggregates in the soil in terms of structural organization. Aggregates with *MWD* greater than 0.25 mm are considered stable [68]. The addition of *OC* (root activity, growth, and functioning; death of plant tissues; among others) provides substrate for microbial growth and the production of secondary organic compounds that act as cementing agents. These agents help aggregate formation [70] and stabilization that increase their resistance when submitted to external forces [71]. A tendency for higher soil aggregation was evident in the NR18 and NR42 areas, improving soil structure and, consequently, *Ks* (Figure 3). Indeed, soils with a high degree of aggregate stability usually also have good soil physical quality, with good soil porosity, aeration, water retention and infiltration [72]. In this sense, soils with greater aggregate stability are considered structurally superior to similar soils with weaker aggregation [73].

The high variability of *Ks* obtained in NR42 (Figures 3 and 4) suggested the occurrence of preferential flows in this area, which can occur due to several factors, among them, the presence of continuous biopores created by large roots of decomposed trees or channels created by macrofauna [25,43,74]. This hypothesis corroborates studies developed in forests under tropical climates [18,64,75,76]. However, although preferential flows are considered a common phenomenon in forested soils, future studies are needed to understand better how they work in areas of passive restoration and their effects in space and time, considering that they are the main cause of groundwater pollution and contamination [77].

The set of soil attributes of the soil superficial horizon analyzed in this study demonstrated that the DFF land use was the least degraded (Figure 4). The lower value of *BD* and higher values of *Tp*, *Mac,* and *MWD (*Table 2*)* show that, although the forest fragment has suffered some degradation in the past, it still maintains its functionality, even though *Ks* presented lower values when compared to NR18 and NR42. The fact that DFF presented lower *Ks* values when compared to the restored areas can be possibly due to other factors that affect this attribute in natural environments, such as plant density and diversity, canopy cover [3,19], geological and topographic variations [78], soil water repellency [44,77], among others.

The joint analysis of the hydrophysical attributes evaluated here, through the PCA, showed that areas in the process of passive restoration had a lower degree of degradation when compared to areas of agricultural use (Figure 4). This lower degree of degradation in restored areas can be interpreted as a general tendency of improvement in the hydrophysical attributes after restoration initiation. High values of *Ks*, aggregate stability, and the improvement tendencies in the other evaluated attributes evidence the soil hydrophysical recovery in the restored forests (Table 2; Figures 3 and 4) [79].

The time scale for the recovery of the hydrophysical attributes in restoration areas in our study was longer than other studies that observed positive changes in these attributes in shorter periods after restoration implementation. In a study in Mexico, areas with passive restoration times of 0, 4, 10, and 20 years after pasture abandonment showed a significant *BD* improvement associated with an increase in water infiltration rates with restoration age [23]. On the other hand, *OC* contents were lower in the 10- and 20-year-old restored forests (3.94 and 3.71%, respectively) when compared to the actual pasturelands (4.79%). Higher water infiltration rates and OC contents were observed with increasing age of forest restoration (15 and 20 years) with values varying between 493 and 2.462 mm h^{-1} when compared to pastures in Costa Rica [75]. Other studies also showed improvements in hydrophysical attributes in shorter periods (8 to 12 years) after restoration initiation [76,80]. The longer time needed to recover the hydrophysical attributes in our study could be explained by the longer period this area was previously occupied by pastures and also by the legacy effect of intense degradation processes that occurred before restoration. This legacy effect phenomenon was observed by Piché and Kelting [14] in soils under 55- to 60-year-old secondary forests. These previous land-use effects could explain the slow recovery of *Mac*, *TP,* and *BD* (Table 2) in NR18 and NR42.

5. Conclusions

The comparative analysis of the soil superficial horizon's hydrophysical attributes in agricultural land uses (P and SC), forests of different ages undergoing passive restoration by natural regeneration (NR18 and NR42), and a degraded forest fragment (DFF) confirms that the evolution of different soil hydrological functions in the ongoing restoration of natural ecosystems can be a relatively slow process.

The observed trend of increasing *Ks* and recovery of soil physical attributes in passive forest restoration of different ages leads us to conclude that the time that the secondary succession takes to recover the soil hydrological properties, disturbed by the previous deforestation and the use of pastures, are not governed just by the restoration time.

The intensity of previous land use leaves footprints that can affect areas submitted to natural regeneration processes for decades after agriculture abandonment and is one of the main critical factors that affect soil physical attributes and *Ks* over time. This is alarming because it is well known that the soil hydrophysical attributes affect fluid flow and transport, and can, consequently, influence runoff generation and water table recharge.

Important ecosystem services, such as water regulation and provision, depend on the recovery of soil hydrological functions in degraded environments. Knowledge of how forest restoration processes, either active or passive, affect soil function, is essential. The data presented and discussed in this study adds to this knowledge and shows that the recovery of soil hydrophysical functioning is a slow process and varies according to the type of soil attribute and the previous land use and its degradation legacy.

Author Contributions: N.A.P. carried out the data collection and wrote the initial draft; M.C. participated in the design of the study and helped to draft and edit the manuscript; L.F.S.d.S. and R.C.B. provided important advice on the concept of the structuring of the manuscript; S.D.P., R.C.B., L.F.S.d.S., G.d.G. and R.P.N. analyzed the data and made great contributions to writing the manuscript. All authors reviewed and approved the final manuscript.

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References

1. Chazdon, R. Beyond Deforestation: Restoring Forests and Ecosystem Services on Degraded Lands. *Science* **2008**, *320*, 1458–1460. [CrossRef] [PubMed]
2. Filoso, S.; Bezerra, M.O.; Weiss, K.C.B.; Palmer, M.A. Impacts of forest restoration on water yield: A systematic review. *PLoS ONE* **2017**, *12*, e0183210. [CrossRef] [PubMed]
3. Chazdon, R.L. Regeneração de florestas tropicais. *Boletim Museu Paraense Emílio Goeldi Ciencias Naturais* **2012**, *7*, 195–218.
4. Crouzeilles, R.; Ferreira, M.S.; Chazdon, R.; Lindenmayer, D.B.; Sansevero, J.B.B.; Monteiro, L.; Iribarrem, A.; Latawiec, A.E.; Strassburg, B.B.N. Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Sci. Adv.* **2017**, *3*, e1701345. [CrossRef]
5. Meli, P.; Holl, K.D.; Benayas, J.M.R.; Jones, H.P.; Jones, P.C.; Montoya, D.; Mateos, D.M. A global review of past land use, climate, and active vs. passive restoration effects on forest recovery. *PLoS ONE* **2017**, *12*, e0171368. [CrossRef]
6. Rozendaal, D.M.A.; Bongers, F.; Aide, T.M.; Dávila, E.Á.; Ascarrunz, N.; Balvanera, P.; Becknell, J.M.; Bentos, T.V.; Brancalion, P.H.S.; Cabral, G.A.L.; et al. Biodiversity recovery of Neotropical secondary forests. *Sci. Adv.* **2019**, *5*, eaau3114. [CrossRef]
7. Godsey, S.; Elsenbeer, H. The soil hydrologic response to forest regrowth: A case study from southwestern Amazonia. *Hydrol. Process.* **2002**, *16*, 1519–1522. [CrossRef]
8. Giannini, V.; Bertacchi, A.; Bonari, E.; Silvestri, N. Rewetting in Mediterranean reclaimed peaty soils and its potential for phyto-treatment use. *J. Environ. Manag.* **2018**, *208*, 92–101. [CrossRef]
9. Burger, J.A.; Kelting, D.L. Using soil quality indicators to assess forest stand management. *For. Ecol. Manag.* **1999**, *122*, 155–166. [CrossRef]
10. Zimmermann, A.; Schinn, D.S.; Francke, T.; Elsenbeer, H.; Zimmermann, B. Uncovering patterns of near-surface saturated hydraulic conductivity in an overland flow-controlled landscape. *Geoderma* **2013**, *195*, 1–11. [CrossRef]
11. Mesquita, M.G.B.; Moraes, S.O. The dependence of the saturated hydraulic conductivity on physical soil properties. *Ciência Rural* **2004**, *34*, 963–969. [CrossRef]
12. Ahuja, L.R.; Naney, J.W.; Green, R.E.; Nielsen, D.R. Macroporosity to Characterize Spatial Variability of Hydraulic Conductivity and Effects of Land Management. *Soil Sci. Soc. Am. J.* **1984**, *48*, 699–702. [CrossRef]

13. De Andrade, A.G.; Tavares, S.D.L.; Coutinho, H.D.C. Contribuição da serrapilheira para recuperação de áreas degradadas e para manutenção da sustentabilidade de sistemas agroecológicos. *Embrapa Solos* **2003**, *24*, 55–63.
14. Piché, N.; Kelting, D.L. Recovery of soil productivity with forest succession on abandoned agricultural land. *Restor. Ecol.* **2015**, *23*, 645–654. [CrossRef]
15. Ziegler, A.D.; Giambelluca, T.; Tran, L.T.; Vana, T.T.; Nullet, M.A.; Fox, J.; Vien, T.D.; Pinthong, J.; Maxwell, J.; Evett, S. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Evidence of accelerated overland flow generation. *J. Hydrol.* **2004**, *287*, 124–146. [CrossRef]
16. Paul, M.; Catterall, C.P.; Pollard, P.; Kanowski, J. Recovery of soil properties and functions in different rainforest restoration pathways. *For. Ecol. Manag.* **2010**, *259*, 2083–2092. [CrossRef]
17. Nyberg, G.; Bargués-Tobella, A.; Kinyangi, J.; Ilstedt, U. Soil property changes over a 120-yr chronosequence from forest to agriculture in western Kenya. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 2085–2094. [CrossRef]
18. Gageler, R.; Bonner, M.; Kirchhof, G.; Amos, M.; Robinson, N.; Schmidt, S.; Shoo, L.P. Early Response of Soil Properties and Function to Riparian Rainforest Restoration. *PLoS ONE* **2014**, *9*, e104198. [CrossRef]
19. Lozano, S.; Cooper, M.; Meli, P.; Ferraz, S.F.; Rodrigues, R.R.; Sauer, T.J. Land restoration by tree planting in the tropics and subtropics improves soil infiltration, but some critical gaps still hinder conclusive results. *For. Ecol. Manag.* **2019**, *444*, 89–95. [CrossRef]
20. Sparovek, G.; Barretto, A.; Berndes, G.; Martins, S.; Maule, R. Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996–2006. *Mitig. Adapt. Strat. Glob. Chang.* **2008**, *14*, 285–298. [CrossRef]
21. Ribeiro, M.C.; Metzger, J.P.; Martensen, A.C.; Ponzoni, F.J.; Hirota, M.M. The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. *Biol. Conserv.* **2009**, *142*, 1141–1153. [CrossRef]
22. Ferraz, S.F.; Ferraz, K.M.; Cassiano, C.C.; Brancalion, P.H.S.; da Luz, D.T.; Azevedo, T.N.; Metzger, J.P. How good are tropical forest patches for ecosystem services provisioning? *Landsc. Ecol.* **2014**, *29*, 187–200. [CrossRef]
23. Peñuela, M.C.; Drew, A.P. A Model to Assess Restoration of Abandoned Pasture in Costa Rica Based on Soil Hydrologic Features and Forest Structure. *Restor. Ecol.* **2004**, *12*, 516–524. [CrossRef]
24. Bruijnzeel, L.A. Hydrological functions of tropical forests: Not seeing the soil for the trees? *Agric. Ecosyst. Environ.* **2004**, *104*, 185–228. [CrossRef]
25. Zwartendijk, B.; Meerveld, H.J.; Ghimire, C.; Bruijnzeel, L.; Ravelona, M.; Jones, J. Rebuilding soil hydrological functioning after swidden agriculture in eastern Madagascar. *Agric. Ecosyst. Environ.* **2017**, *239*, 101–111. [CrossRef]
26. Mendes, M.S.; Latawiec, A.E.; Sansevero, J.B.B.; Crouzeilles, R.; Moraes, L.F.D.; Castro, A.; Alves-Pinto, H.N.; Brancalion, P.H.S.; Rodrigues, R.R.; Chazdon, R.L.; et al. Look down-there is a gap-the need to include soil data in Atlantic Forest restoration. *Restor. Ecol.* **2018**, *27*, 361–370. [CrossRef]
27. Alvares, C.A.; Stape, J.L.; Sentelhas, P.C.; Gonçalves, J.L.M.; Sparovek, G. Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift* **2013**, *22*, 711–728. [CrossRef]
28. De Oliveira, J.B.; Menk, J.R.F.; Barbieri, J.L.; Rotta, C.L.; Tremocoldi, W. *Levantamento Pedologico Semidetalhado de Estado de São Paulo: Quadricula de Araras*; Instituto Agronômico de Campinas: Campinas/São Paulo, Brasil, 1982.
29. Koffler, N.F. Uso das terras da bacia do rio Corumbataí em 1990. *Geografia* **1993**, *18*, 135–150.
30. Rodrigues, R.R. A vegetação de Piracicaba e municípios do entorno. *Circular Técnica IPEF* **1999**, *189*, 1–17.
31. Pinto, L.P.; Bedê, L.; Paese, A.; Fonseca, M.; Paglia, A.; Lamas, I. Mata Atlântica Brasileira: Os desafios para conservação da biodiversidade de um hotspot mundial. In *Biologia da Conservação: Essências*; Rocha, C.F.D., Bergallo, H.G., Sluys, M.V., Alves, M.A.S., Eds.; RiMa Editora: Rio de Janeiro, Brazil, 2006; pp. 91–118.
32. Da Fonseca, G.A. The vanishing Brazilian Atlantic forest. *Biol. Conserv.* **1985**, *34*, 17–34. [CrossRef]
33. Silva, W.G.S.; Metzger, J.P.; Simões, S.; Simonetti, C. Relief influence on the spatial distribution of the Atlantic Forest cover on the Ibiúna Plateau, SP. *Braz. J. Biol.* **2007**, *67*, 403–411. [CrossRef] [PubMed]
34. Valente, R.; Vettorazzi, C. Forest structure assessment in the Corumbataí river basin, SP. *Sci. For.* **2005**, *68*, 45–57.
35. Soil Survey Staff. *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*; Natural Resources Conservation Service: Whashington, DC, USA, 1999.

36. Lassabatere, L.; Angulo-Jaramillo, R.; Ugalde, J.M.S.; Cuenca, R.; Braud, I.; Haverkamp, R. Beerkan Estimation of Soil Transfer Parameters through Infiltration Experiments-BEST. *Soil Sci. Soc. Am. J.* **2006**, *70*, 521–532. [CrossRef]
37. Angulo-Jaramillo, R.; Bagarello, V.; Lovino, M.; Lassabatère, L. *Infiltration Measurements for Soil Hydraulic Characterization*; Springer International Publishing: Berlim, Germany, 2016. [CrossRef]
38. Bagarello, V.; Di Prima, S.; Iovino, M. Estimating saturated soil hydraulic conductivity by the near steady-state phase of a Beerkan infiltration test. *Geoderma* **2017**, *303*, 70–77. [CrossRef]
39. White, I.; Sully, M.J. Macroscopic and microscopic capillary length and time scales from field infiltration. *Water Resour. Res.* **1987**, *23*, 1514–1522. [CrossRef]
40. Reynolds, W.D.; Elrick, D.E. Pressure infiltrometer. In *Methods of Soil Analysis*; Dane, J.H., Topp, G.C., Eds.; Part 4, Physical Methods, SSSA Book Series, No. 5; Soil Science Society of America: Madison, WI, USA, 2002; Volume 4, pp. 826–836.
41. Haverkamp, R.; Ross, P.J.; Smettem, K.; Parlange, J.Y. Three-Dimensional analysis of infiltration from the disc infiltrometer: 2. Physically based infiltration equation. *Water Resour. Res.* **1994**, *30*, 2931–2935. [CrossRef]
42. Raats, P.A.C. Analytical Solutions of a Simplified Flow Equation. *Trans. ASAE* **1976**, *19*, 683–689. [CrossRef]
43. Di Prima, S.; Stewart, R.D.; Castellini, M.; Bagarello, V.; Abou Najm, M.R.; Pirastru, M.; Giadrossich, F.; Iovino, M.; Angulo-Jaramillo, R.; Lassabatere, L. Estimating the macroscopic capillary length from Beerkan infiltration experiments and its impact on saturated soil hydraulic conductivity predictions. *J. Hydrol.* **2020**. [CrossRef]
44. Lozano, S.; Cooper, M.; Ferraz, S.F.; Rodrigues, R.R.; Lassabatere, L.; Castellini, M.; Di Prima, S. Assessing Water Infiltration and Soil Water Repellency in Brazilian Atlantic Forest Soils. *Appl. Sci.* **2020**, *10*, 1950. [CrossRef]
45. Elrick, D.E.; Reynolds, W.D. Methods for Analyzing Constant-Head Well Permeameter Data. *Soil Sci. Soc. Am. J.* **1992**, *56*, 320–323. [CrossRef]
46. Grossman, R.B.; Reinsch, T. 2.1 Bulk Density and Linear Extensibility. In *Methods of Soil Analysis: Part 4 Physical Methods*; Dane, J.H., Topp, G.C., Eds.; Soil Science Society of America: Madison, WI, USA, 2002; Volume 5, pp. 201–228. [CrossRef]
47. Lassabatere, L.; Di Prima, S.; Angulo-Jaramillo, R.; Keesstra, S.; Salesa, D. Beerkan multi-runs for characterizing water infiltration and spatial variability of soil hydraulic properties across scales. *Hydrol. Sci. J.* **2019**, *64*, 165–178. [CrossRef]
48. Vomocil, J.A. Porosity. In *Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling*; Black, C.A., Ed.; Soil Science Society of America: Madison, WI, USA, 1965; Volume 9, pp. 299–314.
49. Imhoff, S.; Da Silva, A.P.; Junior, M.D.S.D.; Tormena, C.A. Quantificação de pressões críticas para o crescimento das plantas. *Revista Brasileira Ciência Solo* **2001**, *25*, 11–18. [CrossRef]
50. Salton, J.C.; Silva, W.M.; Tomazi, M.; Hernani, L.C. *Determinação da Agregação do Solo—Metodologia em Uso na Embrapa Agropecuária Oeste*; Embrapa Agropecuária Oeste. Comunicado Técnico, 184; Embrapa Agropecuária Oeste: Dourados, Brazil, 2012; 8p.
51. Kemper, W.D.; Rosenau, R.C. Aggregate Stability and Size Distribution. In *Methods of Soil Analysis*; Klute, A., Ed.; Soil Science Society of America: Madison, WI, USA, 1986; pp. 425–442.
52. Reynolds, W.; Drury, C.F.; Yang, X.; Tan, C. Optimal soil physical quality inferred through structural regression and parameter interactions. *Geoderma* **2008**, *146*, 466–474. [CrossRef]
53. Gomes, F.P. *Curso de Estatística Experimental*, 12th ed.; Nobel: São Paulo, Brazil, 1990; 467p.
54. Di Prima, S.; Winiarski, T.; Angulo-Jaramillo, R.; Stewart, R.D.; Castellini, M.; Najm, M.R.A.; Ventrella, D.; Pirastru, M.; Giadrossich, F.; Capello, G.; et al. Detecting infiltrated water and preferential flow pathways through time-lapse ground-penetrating radar surveys. *Sci. Total Environ.* **2020**, *726*, 138511. [CrossRef] [PubMed]
55. Soil Science Division Staff. Soil Survey Manual. In *USDA Handbook 18*; Ditzler, C., Scheffe, K., Monger, H.C., Eds.; Government Printing Office: Washington, DC, USA, 2017.
56. Tormena, C.A.; Barbosa, M.C.; Da Costa, A.C.S.; Gonçalves, A.C.A. Densidade, porosidade e resistência à penetração em Latossolo cultivado sob diferentes sistemas de preparo do solo. *Sci. Agric.* **2002**, *59*, 795–801. [CrossRef]

57. Taylor, H.M.; Roberson, G.M.; Parker, J.J. Soil strength-root penetration relations for medium-to coarse-textured soil materials. *Soil Sci.* **1966**, *102*, 18–22. [CrossRef]
58. Taylor, H.M. Effects of soil strength on seedling emergence, root growth and crop yields. In *Compaction of Agricultural Soils*; Barnes, K.K., Ed.; ASAE: St. Joseph, MI, USA, 1971; pp. 292–304.
59. Júnior, M.M.; Melo, W.J. Carbono, carbono da biomassa microbiana e atividade enzimática em um solo sob mata natural, pastagem e cultura do algodoeiro. *Revista Brasileira Ciência Solo* **1999**, *23*, 257–263. [CrossRef]
60. Salemi, L.F.; Groppo, J.D.; Trevisan, R.; De Moraes, J.M.; Ferraz, S.F.; Villani, J.P.; Duarte-Neto, P.J.; Martinelli, L. Land-use change in the Atlantic rainforest region: Consequences for the hydrology of small catchments. *J. Hydrol.* **2013**, *499*, 100–109. [CrossRef]
61. Scheffler, R.; Neill, C.; Krusche, A.; Elsenbeer, H. Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier. *Agric. Ecosyst. Environ.* **2011**, *144*, 281–289. [CrossRef]
62. Biggs, T.; Dunne, T.; Muraoka, T. Transport of water, solutes and nutrients from a pasture hillslope, southwestern Brazilian Amazon. *Hydrol. Process.* **2006**, *20*, 2527–2547. [CrossRef]
63. Chaves, J.; Neill, C.; Germer, S.; Neto, S.G.; Krusche, A.; Elsenbeer, H. Land management impacts on runoff sources in small Amazon watersheds. *Hydrol. Process.* **2008**, *22*, 1766–1775. [CrossRef]
64. Zimmermann, B.; Elsenbeer, H.; De Moraes, J.M. The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *For. Ecol. Manag.* **2006**, *222*, 29–38. [CrossRef]
65. Germer, S.; Neill, C.; Krusche, A.; Elsenbeer, H. Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *J. Hydrol.* **2010**, *380*, 473–480. [CrossRef]
66. Satiro, L.S.; Cherubin, M.R.; Safanelli, J.L.; Lisboa, I.P.; Da Rocha Junior, P.R.; Cerri, C.E.P.; Cerri, C.C. Sugarcane straw removal effects on Ultisols and Oxisols in south-central Brazil. *Geoderma Reg.* **2017**, *11*, 86–95. [CrossRef]
67. Topp, G.C.; Reynolds, W.D.; Cook, F.J.; Kirby, J.M.; Carter, M.R. Physical attributes of soil quality. Soil quality for crop production and ecosystem health. In *Development in Soil Science*; Gregorich, E.G., Carter, M.R., Eds.; Elsevier: New York, NY, USA, 1997; Volume 25, pp. 21–58. [CrossRef]
68. Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant Soil* **2002**, *241*, 155–176. [CrossRef]
69. Filho, C.C.; Muzilli, O.; Podanoschi, A.L. Estabilidade dos agregados e sua relação com o teor de carbono orgânico num Latossolo Roxo distrófico, em função de sistemas de plantio, rotações de culturas e métodos de preparo das amostras. *Revista Brasileira Ciência Solo* **1998**, *22*, 527–538. [CrossRef]
70. Bronick, C.; Lal, R. Soil structure and management: A review. *Geoderma* **2005**, *124*, 3–22. [CrossRef]
71. Salton, J.C.; Mielniczuk, J.; Bayer, C.; Boeni, M.; Conceição, P.C.; Fabrício, A.C.; Macedo, M.C.M.; Broch, D.L. Agregação e estabilidade de agregados do solo em sistemas agropecuários em Mato Grosso do Sul. *Revista Brasileira Ciência Solo* **2008**, *32*, 11–21. [CrossRef]
72. An, S.; Mentler, A.; Mayer, H.; Blum, W.E. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest and shrub vegetation on the Loess Plateau, China. *Catena* **2010**, *81*, 226–233. [CrossRef]
73. Vezzani, F.M. *Qualidade do Sistema Solo na Produção Agrícola. 184 f. 2001. Tese de Doutorado. Tese (Doutorado em Ciência do Solo)*; Universidade Federal do Rio Grande do Sul: Porto Alegre, Brazil, 2001.
74. Allaire, S.E.; Roulier, S.; Cessna, A.J. Quantifying preferential flow in soils: A review of different techniques. *J. Hydrol.* **2009**, *378*, 179–204. [CrossRef]
75. Deuchars, S.; Townend, J.; Aitkenhead, M.J.; Fitzpatrick, E. Changes in soil structure and hydraulic properties in regenerating rain forest. *Soil Use Manag.* **2006**, *15*, 183–187. [CrossRef]
76. Hassler, S.K.; Zimmermann, B.; Van Breugel, M.; Hall, J.S.; Elsenbeer, H. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. *For. Ecol. Manag.* **2011**, *261*, 1634–1642. [CrossRef]
77. Doerr, S.H.; Ritsema, C.J.; Dekker, L.W.; Scott, D.F.; Carter, D. Water repellence of soils: New insights and emerging research needs. *Hydrol. Process.* **2007**, *21*, 2223–2228. [CrossRef]
78. Cooper, M.; Medeiros, J.C.; Rosa, J.D.; Soria, J.E.; Toma, R.S. Soil functioning in a toposequence under rainforest in São Paulo, Brazil. *Revista Brasileira Ciência Solo* **2013**, *37*, 392–399. [CrossRef]

79. Hillel, D. Soil structure and aggregation. In *Introduction to Soil Physics*; Academic Press: London, UK, 1980; pp. 40–52, 200–204.
80. Muñoz-Villers, L.E.; Holwerda, F.; Alvarado-Barrientos, M.S.; Geissert, D.; Marín-Castro, B.; Gómez-Tagle, A.; McDonnell, J.J.; Asbjornsen, H.; Dawson, T.; Bruijnzeel, L.A. Efectos hidrológicos de la conversión del bosque de niebla en el centro de Veracruz, México. *Bosque* **2015**, *36*, 395–407. [CrossRef]