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Hydrological Properties of Litter in Different Vegetation Types: Implications for Ecosystem Functioning

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Abstract: This study investigated the hydrological properties of litter in different vegetation cover types, including *Eucalyptus* sp. plantation, Agroforestry, and Restoration Forest. The research focused on evaluating litter accumulation, composition, water holding capacity, and effective water retention. The results revealed variations in litter accumulation among the stands, and especially *Eucalyptus* sp., which had a higher proportion of branches compared to leaves. The water holding capacity of the litter differed among the stands. Agroforest and Restoration Forest showed higher litter water capacities than *Eucalyptus* sp. The composition and decomposition stage of the litter fractions influenced their water retention capabilities, with leaves exhibiting superior water retention. In contrast, branches had lower water absorption due to their hydrophobic nature. Despite these differences, the effective water retention, which indicates the ability of litter to intercept precipitation, was similar among the stands. The findings highlight the importance of considering litter composition and species-specific characteristics in understanding the hydrological functions of litter. This knowledge contributes to effective conservation and management strategies for sustainable land use practices and water resource management. Further research is recommended to expand the study's scope to include a wider range of forest types and natural field conditions, providing a more comprehensive understanding of litter hydrological functions and their implications for ecosystem processes.

Keywords: forest hydrology; ecohydrology; litter water conservation; soil and water conservation; soil management; soil moisture

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1. Introduction

Litter plays a vital role in nutrient cycling and organic matter decomposition, with notable relevance for global biogeochemical cycles. It refers to the layer of organic or decomposing material present on the forest floor, consisting of a diverse range of components such as leaves, branches, flowers, fruit, seeds, and animal residue. The composition and characteristics of litter are influenced by various factors. For instance, in different types of ecosystems, such as tropical rainforests [1–5] or temperate forests [6–9], the dominant tree species and their specific leaf traits can significantly affect litter composition and decomposition rates [2,10]. Additionally, forest disturbances, such as logging or fire events, can alter litter dynamics and nutrient cycling processes [11–13]. As litter decomposes, it releases nutrients into the soil, which are then taken up by plants, contributing to their growth and overall ecosystem productivity [14–18]. Furthermore, litter provides habitat and food sources for a wide range of organisms [19,20], playing a crucial role in supporting biodiversity within the ecosystem.

From a hydrological perspective, the litter acts as sponge layer, separating precipitation from mineral soil, mediating rainfall splash impact, and reducing or often eliminating overland flow and soil erosion from the forest floor [21,22]. This has implications for infiltration during and after rainfall [2,23]. Understanding the interactions between rainfall, vegetation, and litter on the soil surface is of great importance to forest hydrologists and researchers interested in the partitioning and disposition of rainfall [6,24,25]. The water balance of an ecosystem involves many processes, including the interception of rainfall by vegetation, the portion of rainfall that passes through gaps in the canopy (throughfall), and the water that flows down the trunks or stems of trees (stemflow) [26–29]. The latter two represent the portion of rainfall that reaches the soil and interacts with a boundary layer between the soil surface and its interior [4,5], known as litter [2,23]. Additionally, the presence of a litter layer serves to minimize water evaporation from the soil, aiding the preservation of moisture within the topsoil [30]. However, it is important to note that water retention in the litter layer is an essential hydrological indicator in forest hydrology, and a significant portion of the precipitation may be retained by the litter layer, influencing both evaporation and soil–moisture dynamics [31–34].

Soil water conservation capacity involves various natural processes, land management practices, and the characteristics of the landscape that influence water infiltration, retention, and storage in the soil. This conservation capacity is crucial for sustaining ecological balance, agricultural productivity, and mitigating the negative impacts of water-related issues such as erosion, flooding, and drought. Conserving water and soil resources is essential for sustainable land management, agriculture, and overall environmental health. Implementing practices that enhance water and soil conservation capacity helps protect ecosystems, support biodiversity, and secure the availability of clean water for human and ecological needs. However, it is not possible to generalize the hydrological properties of litter independently of vegetation type (e.g., forest or agriculture crop) or structure. The dynamics of litter water interception vary depending on factors such as stand species composition, thickness, storage, water holding capacity, and degree of decomposition, which contribute to different levels of rainfall interception [4,6,35]. As litter has close contact with soil, the water and soil conservation capacity of a forest is also influenced by factors such as forest type, management practices, soil bulk density, and porosity [4,5,36]. Therefore, in the practice of forestry production on agricultural land, in addition to the state of litter coverage, we should also consider the differences in litter caused by the presence of different tree species. While numerous studies have investigated the impact of litter on hydrological processes, insufficient attention has been paid to the hydrological properties of litter under natural conditions, and especially different vegetation types or management.

In this study, our objective was to assess the water holding characteristics of litter and the physical properties of soil in three vegetation types: *Eucalyptus* sp. plantation, Agroforestry, and Restoration Forest. We aimed to investigate the impact of vegetation cover on litter water conservation. Our hypotheses were as follows: (1) litter hydrological properties exhibit variations among different vegetation types and (2) soil water content, bulk density, and resistance to penetration are influenced by litter hydrological properties. To the best of the authors' knowledge, this is the first study to compare different vegetation types, incorporating various management techniques. A comprehensive understanding of the role of litter in ecosystem water balance and nutrient cycling is crucial for evaluating ecosystem functioning, carbon sequestration, and sustainable land management practices. Further research in this field can offer valuable insights into the intricate relationships between precipitation, vegetation, and ecosystem processes, thereby contributing to the development of effective conservation and management strategies.

2. Materials and Methods

2.1. Study Sites

The experimental site is located at the Federal University of São Carlos—Sorocaba, Brazil (23°35′07″ S, 47°31′03″ W, Figure 1), representing three different soil coverings or vegetation types: EU: a stand of *Eucalyptus* sp. (6 years old); AF: a biodiverse successional agroforestry system including trees from the Atlantic Forest, *Musa* spp. (Banana), and some leguminous species such as *Cajanus cajan* (Feijão guandú), with exotic species (*Brachiaria* sp.) controlled through weeding (established 6 years ago); and RF: Restoration Forest including tree species from the Atlantic Forest and Cerrado (10 years old). Table 1 presents information on the stands. The plots were located 100 m from each other. The mean altitude is 580 m AMSL, and the climate is classified as Cwa or temperate, with dry and hot summers [37,38]. Mean annual temperature is 22 °C and mean annual rainfall is 1311 mm [39]. This site is in a transition region between the Atlantic Plateau and the Paulista Peripheral Depression. It comprises the following soil types: Red Yellow Dystrophic Argisol and Red Dystrophic Latosol [40]. Biotic and abiotic variables were collected simultaneously, allowing a reliable comparison between stands. Three 10 × 10 m plots were established in each stand, and data on throughfall, litter production, hydrological properties, soil bulk density, resistance penetration, and water content were monitored for 8 months, from December 2020 to July 2021.

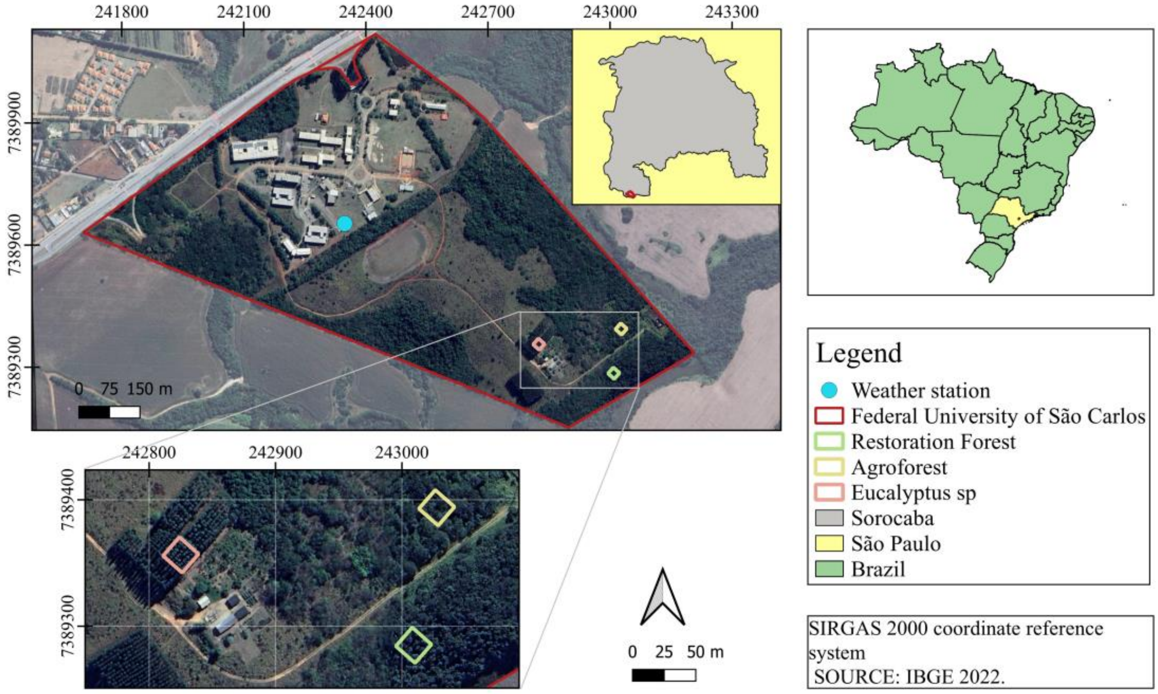

Figure 1. Studied site location at the Federal University of São Carlos—experimental site. Sorocaba, Brazil.

Table 1. Basic information on the sample sites.

Information	***Eucalyptus* sp. (EU)**	**Agroforest (AF)**	**Restoration Forest (RF)**
Density [trees ha^{-1}]	1667	1250	1667
Management	3 × 2 m planting system. Established in 2014.	Trees on 4 × 2 m, with *Musa* spp. (Banana) and leguminous species between rows. Exotic species controlled through weeding. Established in 2014.	3 × 2 m planting system. Established in 2010.
Diameter at breast height [m]	13.5 ± 0.1	14.6 ± 1.5	13.8 ± 2.6
Height [m]	21.5 ± 0.3	8.2 ± 0.2	10.3 ± 0.1
Litter thickness [cm]	1.3 ± 0.1	2.0 ± 0.1	1.5 ± 0.1
Slope aspect	N-NW	N-NW	N-NW
Slope (°)	10.0%	10.3%	10.2%

2.2. Rainfall and Throughfall

The total rainfall data [R, mm] during the experiment were collected from the weather station located at the experimental site. Throughfall data were obtained using 6 rain gauge collectors positioned 1.20 m above the forest floor in each plot. The collectors were placed under the trees, along the center of the planted row, with a 3 m distance between each other. Throughfall values were obtained following [4,27,41]. Each sampling consisted of one or more consecutive rainfall events. An event is defined as rainfall of at least 1 mm in depth preceded by a dry period of a minimum of 12 h. Sample collections were performed as soon as possible after the end of rainfall.

2.3. Determination of Litter Hydrological Properties

Litter samples were collected from a 100 × 100 cm litter square divided into 4 quadrants. The collection process followed a random sampling method [4,5], where one quadrant measuring 50 × 50 cm was randomly chosen for material collection on the forest floor. The collected samples were then immediately placed in plastic bags and transported to the laboratory. Each stand yielded a total of 240 litter bags (3 plots × 10 random quadrants × 8 months). In the laboratory, the litter samples were sieved to remove soil (mesh 6—3 mm, approximately) and then sorted into four fractions: branches, leaves, seeds, and unstructured material. The monthly and annual litter yield was estimated by summing the fractions. The fresh mass [FM, g] of each fraction was determined using an accurate scale [0.01 g] and rehydrated through immersion in water for 90 min. Subsequently, the litter fractions were placed on sieves and drained for 30 min to determine the humid litter mass [HM, g]. The dried mass [DM, g] of the litter was then determined by oven-drying the samples at 70 °C until a constant mass was achieved. Finally, the litter hydrological properties were calculated as shown in Table 2.

Table 2. Litter hydrological properties studied.

Indicator	Description	Equation
Water holding capacity [WHC, %]	is the amount of water that can be preserved in litter	$WHC = \left[\frac{HM-DM}{DM}\right] \times 100$
Effective water holding capacity [EWC, %]	is the water holding capacity of litter under ambient conditions [5,9]	$EWC = \left[\frac{FM-DM}{FM}\right] \times 100$
Effective water retention capacity [W_{eff}, t ha^{-1}]	is the maximum amount of rainwater that can be retained by the litter layer in the forest in the natural field environment. Is numerically smaller than water retention capacity [42]	$W_{eff} = \frac{(0.85\times WHC-EWC)\times M}{100}$ M = is the unit litter mass, t ha^{-1}
Maximum water retention capacity [W_{max}, t ha^{-1}]	is the maximum amount of water that can be retained after removing the amount of water contained in the litter under normal conditions [42]	$W_{max} = \frac{WHC\times M}{100}$ M = is the unit litter mass, t ha^{-1}

2.4. Soil Physical Properties

Soil bulk density and soil water content were determined by collecting three random samples from the 0 to 20 cm soil profiles in each plot (three plots per stand). Undisturbed samples were obtained using 100 cm^3 metallic volumetric rings. The weight of the samples was measured using a precision scale. The determination of these attributes was carried out using the thermogravimetric method, which involves weighing the freshly collected samples and then drying them in a forced circulation oven at 105 °C for 24 h. Soil bulk density (BD, g cm^{-3}) was calculated as the ratio of the dry soil mass (Ms, g) to the ring volume (V, m^3). Soil water content (SWC, %) was measured gravimetrically and expressed as a percentage of the weight of soil water to the weight of dry soil (g). Soil resistance to penetration (SRP, MPa) was assessed using Digital Falker PLG1020 Penetrograph, with three repetitions per plot, resulting in a total of nine measurements per stand. BD, SWC, and SRP were measured monthly, simultaneously with the collection of litter samples.

2.5. Statistical Analysis

To assess the homoscedasticity of variance in litter stocks and hydrological properties, the Bartlett test was employed. Additionally, the normality of the data was evaluated using the Lilliefors (Kolmogorov–Smirnov) test for statistical analysis. For normally distributed data, analysis of variance (ANOVA) with a significance level of 5% (Student's *t*-test) was conducted. The non-parametric Mann–Whitney test was used for data that did not meet the assumptions of ANOVA. The statistical analyses were performed using BioEstat 5.3 [43] and @Minitab 17.

3. Results

3.1. Weather Conditions

Accumulated rainfall throughout the research period was 667 mm; that is, approximately 55% of the annual precipitation. Mean temperature was 21.6 ± 3.5 °C, 5% higher than the normal recorded temperature (20.6 °C). The highest mean temperature was recorded in January (24.1 °C) and the lowest in July (15.1 °C) (Figure 2). The mean air humidity was 80.3 ± 1.4%. Throughfall (TF) in the *Eucalyptus* sp. (EU), Agroforestry (AF), and Restoration Forest (RF) areas was 395, 412, and 471 mm, respectively.

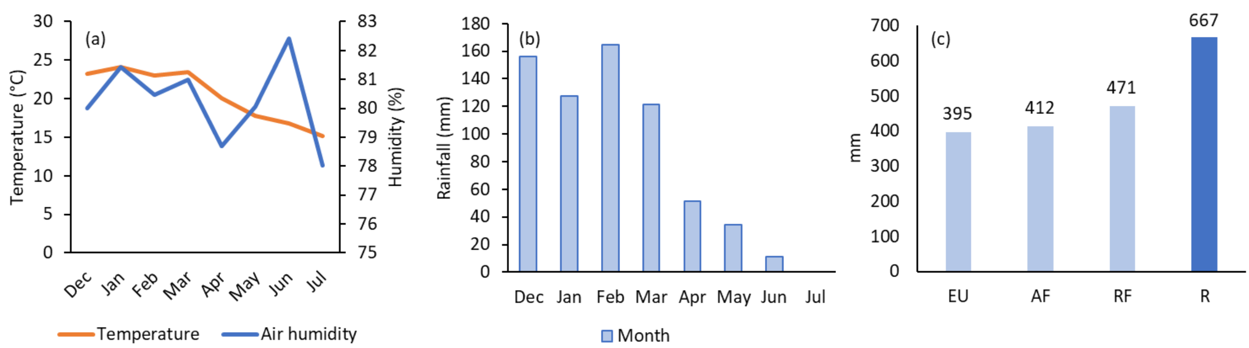

Figure 2. Mean air temperature and humidity (**a**), rainfall (**b**), throughfall in *Eucalyptus* sp. (EU), Agroforest (AF), Restoration Forest (RF), and total rainfall (R) during period of study (**c**).

3.2. Litter Accumulation and Composition

The mean litter accumulation ranged from 5.4 to 8.3 t ha^{-1} in the EU, 4.2 to 11 t ha^{-1} in the Agroforestry (AF) area, and 3.5 to 8.0 t ha^{-1} in the Restoration Forest (RF) area. Among the different components, branches accounted for 39% of the total litter in the EU, while leaves were the predominant fraction in the AF area (44%) and the RF area (47%). Seeds represented the lowest fraction in all stands, with percentages of 3.4% in the EU, 9.3% in the AF, and 3.2% in the RF. Although the litter accumulation was similar among the stands, there were significant differences in the mass of leaf and branch fractions (Figure 3).

3.3. Hydrological Properties of Litter

The total litter water holding capacity (WHC) differed between the Eucalyptus (EU) area and the Agroforestry (AF) and Restoration Forest (RF) areas (Table 3). The order of WHC was EU < RF < AF, with AF and RF having 1.33 and 1.30 times the water holding capacity of EU, respectively. The WHC for the unstructured fraction was similar among the stands, and it increased in the following order: RF < AF < EU. EU had the lowest values for leaves, branches, and seeds. The water holding capacity of leaves and seeds was similar between AF and RF, while branches showed significant variation among the three stands ($p < 0.05$). Although the mean effective water holding capacity (EWC, %) was similar among the stands ($p > 0.05$), the EWC was consistently higher for RF, followed by AF > EU, for total litter as well as for the unstructured fraction, leaves, branches, and seeds.

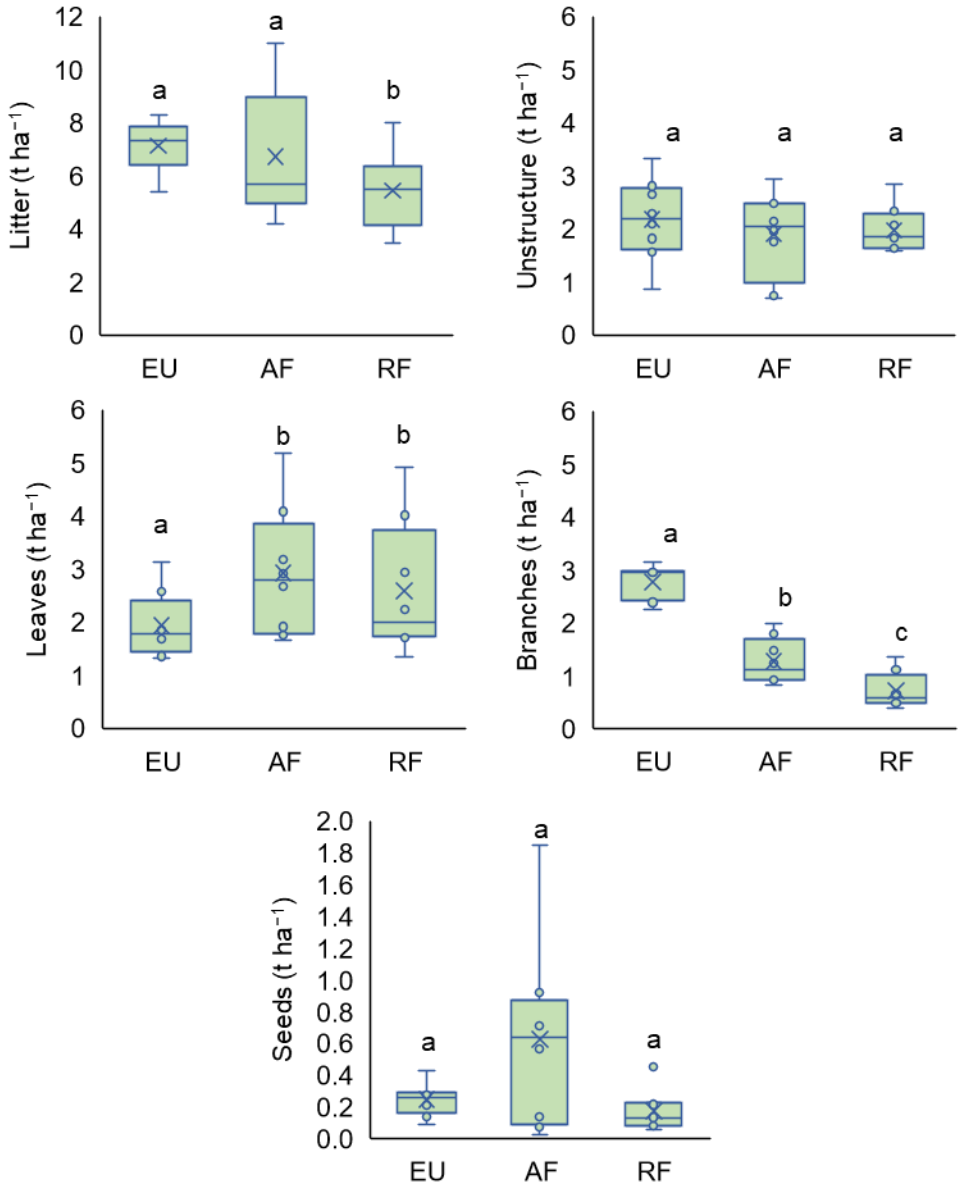

Figure 3. Mean litter accumulation, unstructured, leaves, branches, and seeds in *Eucalyptus* sp. (EU), Agroforest (AF), and Restoration Forest (RF). Different lowercase letters mean significant differences ($p < 0.05$).

Table 3. Water holding capacity [WHC, %], effective water holding capacity [EWC, %], effective water retention [W_{eff}, t ha^{-1}], and maximum retention capacity [W_{max}, t ha^{-1}].

Stand	Total	Unstructured	Leaves	Branches	Seeds
			Water holding capacity [WHC, %]		
Eucalyptus sp.	164 ± 6.8 a	228 ±16 a	193 ± 28 a	94 ± 3.8 a	141 ± 8 a
Agroforest	218 ± 12 b	222 ± 20 a	272 ± 32 b	200 ± 19 b	179 ± 15 b
Restoration	212 ±14 b	220 ± 18 a	265 ± 15 b	160 ± 24 c	204 ± 39 b
			Effective water holding capacity [EWC, %]		
Eucalyptus sp.	23 ± 3 a	25 ± 4 a	26 ± 2 a	17 ± 2 a	24 ± 2 a
Agroforest	25 ± 3 ab	25 ± 3 a	28 ± 3 a	28 ± 2 b	27 ± 2 a
Restoration	34 ± 4 b	34 ± 5 a	33 ± 3 a	35 ± 3 b	36 ± 3 a

Different lowercase letters in the same column mean significant differences ($p < 0.05$).

The maximum water holding capacity (W_{max}) was significantly different only between EU and AF, ranging from 10.3 t ha^{-1} (AF) to 31.7 t ha^{-1} (RF) (Figure 4). In EU and RF, the W_{max} was 1.6 and 1.4 times that of AF, respectively. The W_{max} of the unstructured layer varied among the stand types, with AF (4.3 ± 0.7 t ha^{-1}) < RF (12.1 ± 1.5 t ha^{-1}) < EU (16.3 ± 1.2 t ha^{-1}). There was a significant difference in the W_{max} of leaves between EU and AF ($p < 0.05$), with the order being EU (4.1 ± 0.36 t ha^{-1}) < RF (5.5 ± 1.0 t ha^{-1}) < AF (8.2 ± 1.3 t ha^{-1}). RF had the highest W_{max} for branches, followed by AF and EU. Seeds showed the order of W_{max} as AF < RF < EU, with significant differences between AF and RF for branches and seeds.

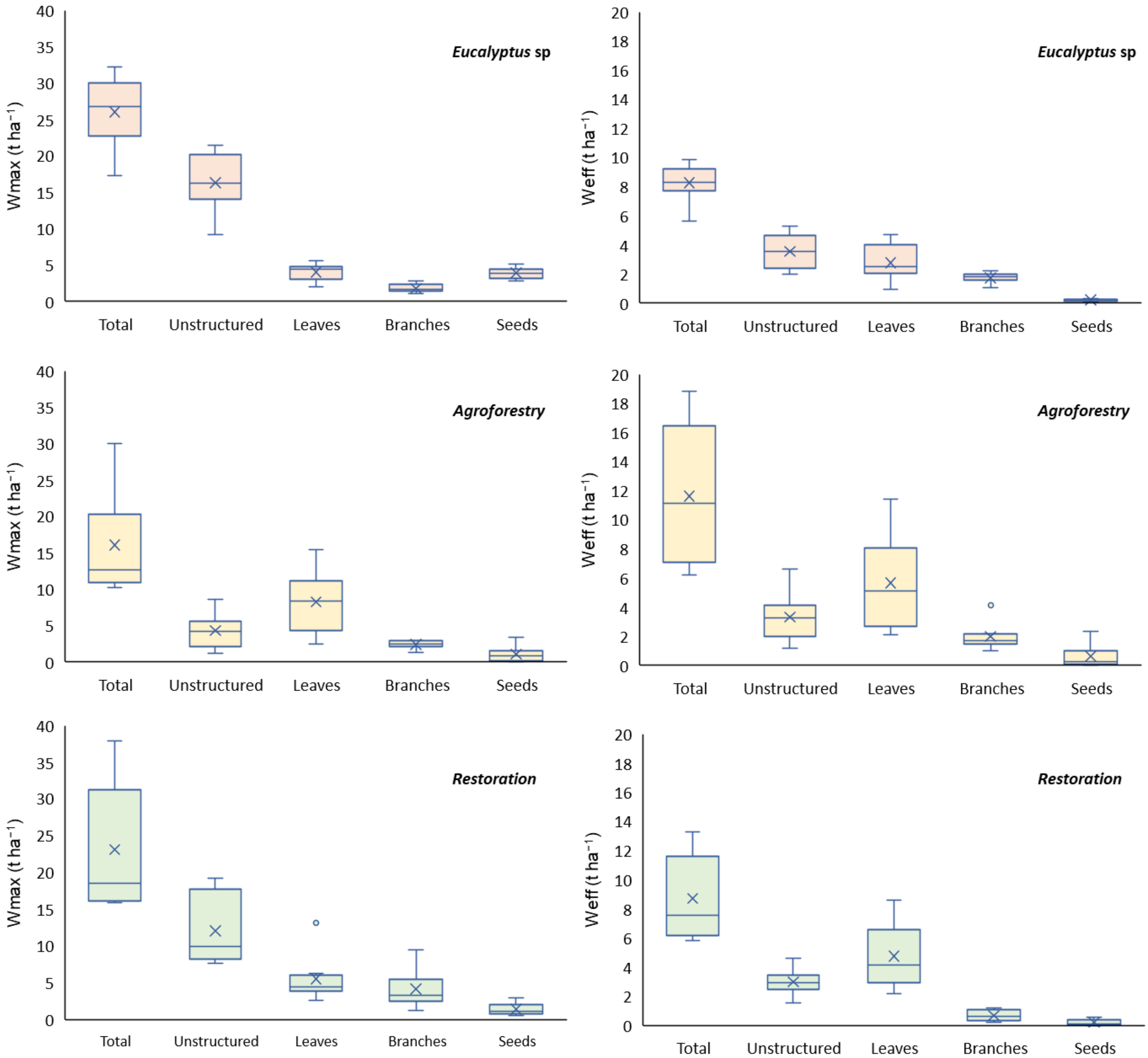

Figure 4. Litter maximum water retention capacity [W_{max}, t ha^{-1}] and effective water retention [W_{eff}, t ha^{-1}].

The effective water retention capacity (W_{eff}) of litter did not differ among stands and ranged from 5.6 t ha^{-1} for EU to 18.3 t ha^{-1} for AF (Figure 3). The mean W_{eff} followed the order: EU (8.3 ± 0.5 t ha^{-1}) < RF (8.7 ± 1.0 t ha^{-1}) < AF (11.6 ± 1.7 t ha^{-1}). For all stands, leaves had the highest W_{eff}, followed by the unstructured fraction, branches, and seeds. The W_{eff} for litter was similar among stands. The W_{eff} for the unstructured fraction ranged from 2.0 t ha^{-1} to 5.3 t ha^{-1} for EU, from 1.7 t ha^{-1} to 6.6 t ha^{-1} for AF, and from 1.6 t ha^{-1}

to 4.6 t ha^{-1} for RF. The mean W_{eff} for the unstructured fraction was similar among stands, following the order: RF < AF < EU. Significant differences were observed between leaves for EU × AF and RF. The mean W_{eff} for leaves followed the order: EU (2.8 ± 0.4 t ha^{-1}) < RF (4.8 ± 0.8 t ha^{-1}) < AF (5.7 ± 1.2 t ha^{-1}). For branches, W_{eff} was similar between EU and AF, and followed the order: RF (0.7 ± 0.1 t ha^{-1}) < EU (1.7 ± 0.1 t ha^{-1}) < AF (2.0 ± 0.3 t ha^{-1}). W_{eff} for seeds was similar among stands, increasing in the order of: EU (0.2 ± 0.02 t ha^{-1}) < RF (0.3 ± 0.07 t ha^{-1}) < AF (0.6 ± 0.3 t ha^{-1}).

3.4. Soil Physical Properties

There were no significant differences in the mean values of soil bulk density (BD), soil retention potential (SRP), and soil water content (SWC) among the stands (Figure 5). The BD was 1.0 ± 0.05 g cm^{-3} for all three stands. EU had the highest SRP (5.1 ± 1.5 MPa), followed by RF (4.9 ± 1.3 MPa) and AF (4.6 ± 1.2 MPa). The mean SWC was highest in RF (19.0 ± 3.7%), followed by AF (16.9 ± 3.5%) and EU (15.1 ± 3.1%). Soil water content ranged from 2.4% to 34.0% in EU, from 1.6% to 36.6% in AF, and from 2.5% to 40.3% in RF.

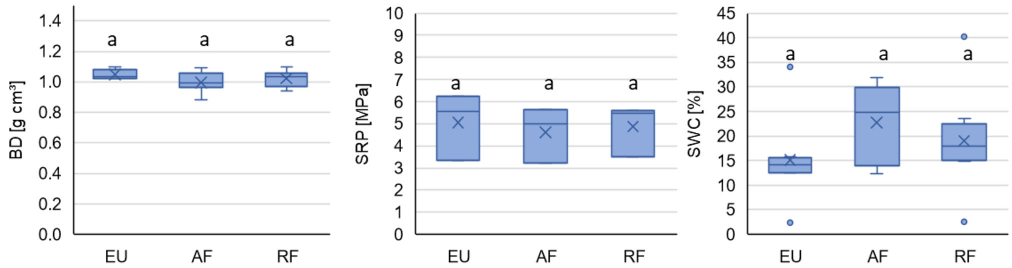

Figure 5. Soil bulk density [BD, g cm^3], soil resistance of penetration [SRP, MPa], and soil water content [SWC, %] in *Eucalyptus* sp. (EU), Agroforest (AF), and Restoration Forest (RF). Different lowercase letters in the same column mean significant differences ($p < 0.05$).

4. Discussion

4.1. Hydrological Properties and Water Retention Capacity of Litter

Litter serves as a crucial component in the hydrological cycle within ecosystems [8,44,45] and it also plays a significant role in various soil management practices and vegetation covers [45]. In our study, the litter mass of *Eucalyptus* sp. was above the average of other studies, although it varied within the range reported in the literature. For example, it exceeded the average deposition of 6.33 Mg ha^{-1} at 14 years of age [46] but was lower than the 16.6 t ha^{-1} at 7 years of age [47]. Compared with other forest types, the average litter mass of *Eucalyptus* sp. and Agroforest was higher than that of approximately 46-year-old Cerrado (5.5 t ha^{-1}) [4], while the latter was similar to the litter mass of Restoration Forest. It is worth noting that the composition and dynamics of litter formation can vary depending on the species present in the study area. In this case, the *Eucalyptus* sp. planting consisted of trees of the same species, while the Agroforest and Restoration Forest were composed of a diversity of plants species. This difference in species composition likely contributed to the higher proportion of branches in the litter of *Eucalyptus* sp. compared with other studies where the leaf fraction was more dominant [10,48].

The results demonstrate variations in litter hydrological properties among the different vegetation types. Understanding the hydrological properties of litter fractions is essential, as it influences the overall water holding capacity of the litter layer. The water holding capacity of litter depends not only on the quantity of organic material deposited but also on the composition and degree of decomposition of its fractions. Litter layers with higher decomposition levels have a larger specific surface area, enhancing their water retention potential [5,49,50]. It is important to note that water holding capacity reflects the ideal water holding condition and may not fully represent litter interception under field conditions [4,5,7]. The water holding capacity of the litter was found to differ significantly between the stands, with Agroforestry and Restoration Forest showing higher capacity compared with *Eucalyptus* sp. This variation can be attributed to differences in litter composition, particularly the proportion of leaves and branches. The water holding capacity of the unstructured fraction of *Eucalyptus* sp. was relatively high due to its lower surface adhesion [51,52], resulting in greater water retention rates. In contrast, in Agroforest and Restoration Forest, the leaf fraction exhibited the highest water holding capacity due to its higher surface adhesion. The composition and decomposition stage of the litter fractions, particularly the higher proportion of branches in *Eucalyptus* sp., influenced the water holding capacity. The hydrophobic nature of branches limited their water absorption capacity, while leaves showed higher surface adhesion and superior water retention. Stems or branches, mainly composed of xylem with thick fibers and a relatively stable structure between cells, have limited water absorption capacity despite the presence of an internal tubular structure [24]. Additionally, the hydrophobic nature of branches is a well-known characteristic that can also be attributed to the presence of lignin in their composition [53,54]. Lignin, being a complex aromatic polymer, contributes to the structural integrity of plant cell walls and imparts rigidity to woody tissues. As a hydrophobic substance, lignin naturally repels water [53–57]. It is important to note that the lignin content can vary not only between different tree species [53] but also between different parts of the same tree, such as leaves, stems, and branches. Moreover, the proportion of branches in the litter layer can vary depending on the tree species composition and forest management practices. This variability can influence the overall water holding capacity of the litter and its hydrological functions in different ecosystems. Overall, for all stands, the water holding capacity was lower than that observed for Amazon Forest [5] and Cerrado under various stages of regeneration [4]. Notably, the water retention rates of *Eucalyptus* sp. in this study were lower than those reported in other *Eucalyptus* sites [48].

Despite differences in water holding capacity, the effective water retention capacity (W_{eff}) of the litter was found to be similar among the stands. The similarity in W_{eff} indicates that *Eucalyptus* sp., Agroforest, and Restoration Forest have the ability to effectively retain water, contributing to enhanced rainwater storage within the ecosystem. This fact may explain the similarity in soil bulk density, soil resistance to penetration, and soil water content among the studied sites, although the water retention capacity was higher for Agroforest. This suggests that the hydrological properties of litter did not have a direct impact on soil physical properties in the studied stands. However, it is important to note that in this study, the soil physical properties were investigated at the topsoil level (0–20 cm for soil bulk and water content and 0–60 cm for resistance of penetration), and these properties can vary according to the soil profile [58–60]. Nevertheless, as reported by [36,61], W_{eff} defines the effective interception of precipitation by litter, which is an important hydrological property that can be used to consistently evaluate the potential to absorb rainfall and reduce surface runoff [9,42,61]. Effective water retention is influenced by factors such as litter water content, storage capacity, and rainfall characteristics [5]. Our study shows that the mean annual capacity of litter for both stands to retain water was higher for both sites than that observed for acacia–grass forest, eucalyptus–grass forest, and bamboo–grass forest [61]. However, *Eucalyptus* sp., Agroforest, and Restoration Forest were lower than *Acacia mangium* and higher than *Hevea brasiliensis* [9]. Moreover, Agroforest was W_{eff} slightly higher than Amazon Forest [5]. However, the W_{max}, which measures the rainfall absorption capacity, was higher in *Eucalyptus* sp., Agroforest, and Restoration Forest compared with previous studies on acacia–grass forest, eucalyptus–grass forest, and bamboo–grass forest [61]. It was also higher than *Eucalyptus robusta* [9] but lower than *Acacia mangium* [9]. Moreover, W_{max} for *Eucalyptus* sp. and Restoration Forest was higher than Amazon Forest [5]. Considering that 1 mm of rainfall is equivalent to 1 t ha^{-1} [9,61], the litter in *Eucalyptus* sp., Agroforest, and Restoration Forest could intercept an average of 26 mm, 16 mm, and 23 mm of rainfall, respectively, during the studied period. Considering the effective water retention for the studied period, *Eucalyptus* sp., Agroforest, and Restoration Forest intercepted a mean of 8.3, 11.6, and 8.7 mm of rainfall, respectively.

4.2. Implications for Ecosystem Functioning

It is important to highlight that a previous study conducted on *Pinus tabulaeformis* plantations revealed that around half of the throughfall was retained in the soil without any litter mass. In the litter-covered treatments, this proportion ranged from 77.0% to 87.9% [44], indicating that the presence of litter significantly enhanced rainwater storage [62]. These findings highlight the importance of considering litter composition and species-specific characteristics when assessing the hydrological functions of litter. The variations in litter hydrological properties observed in this study have important ecological implications for ecosystem functioning and water resource management. The higher water holding capacity of Agroforestry and Restoration Forest litter implies that these stands can retain more water, which has implications for water availability within the ecosystem. Increased water retention can lead to enhanced soil moisture, providing a vital water resource for plants and microorganisms, especially during dry periods. Restoration Forest, which exhibited higher effective water retention capacity, can serve as a valuable model for ecosystem restoration efforts. Restoring degraded areas with diverse native tree species can improve litter hydrological properties, leading to enhanced ecosystem services and ecological functionality. Agroforestry systems, with their capacity for higher water retention, can be integrated into water-sensitive agricultural practices to improve water availability for crops and reduce water-related risks, such as soil erosion and flooding. This improved water availability can contribute to the overall productivity and resilience of the ecosystem. Furthermore, litter acts as a natural barrier against soil erosion by reducing the impact of rainfall and slowing down or preventing surface runoff. The ability of Agroforestry and Restoration Forest to retain more water in their litter layers can be particularly beneficial in mitigating soil erosion and preserving soil health. Regarding biodiversity support, litter provides a habitat and food source for various organisms, supporting biodiversity within the ecosystem. The differences in litter composition and hydrological properties among the stands can influence the diversity and abundance of soil-dwelling organisms, contributing to overall ecosystem biodiversity.

Finally, the results obtained in this study provide valuable insights into the hydrological properties of litter in the specific stands investigated. However, further research is needed to expand the scope of the study and examine a wider range of forest types and species to obtain a more comprehensive understanding of litter hydrological functions. Additionally, field conditions and natural variability should be considered to better assess the actual litter interception and water retention capacities of different ecosystems. Such knowledge can contribute to improved water resource management and the development of sustainable land use practices that consider the hydrological role of litter in ecosystem functioning.

5. Conclusions

This study provides valuable insights into the hydrological properties of litter in different vegetation cover types, highlighting variations in water holding capacity and effective water retention among *Eucalyptus* sp., Agroforestry, and Restoration Forest. The results revealed variations in litter accumulation, composition, water holding capacity, and effective water retention among the stands. The litter accumulation in *Eucalyptus* sp. had a higher proportion of branches compared to leaves. The water holding capacity of the litter varied among the stands, with Agroforest and Restoration Forest exhibiting higher capacities than *Eucalyptus* sp. Leaves showed higher surface adhesion and superior water retention, while branches exhibited lower water absorption due to their hydrophobic nature. Despite differences in water holding capacity, the effective water retention, which defines the effective interception of precipitation by litter, was similar among the stands. Moreover, litter hydrological properties did not affect soil bulk density, soil retention potential, and soil water content. These findings emphasize the importance of considering litter composition and species-specific characteristics when assessing the hydrological functions of litter. The results contribute to our understanding of the intricate relationship between vegetation cover, litter properties, and water balance in ecosystems. This knowledge can aid in the development of effective conservation and management strategies for sustainable land use practices, carbon sequestration, and water resource management. Further research is recommended to broaden the scope of the study, encompassing a wider range of forest types and species, as well as considering field conditions and natural variability. This would provide a more comprehensive understanding of litter hydrological functions and their implications for ecosystem processes.

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References

1. Vasconcelos, S.S.; Zarin, D.J.; Araújo, M.M.; Rangel-Vasconcelos, L.G.T.; Carvalho, C.J.R.; Staudhammer, C.L.; Oliveira, F. de A. Effects of Seasonality, Litter Removal and Dry-Season Irrigation on Litterfall Quantity and Quality in Eastern Amazonian Forest Regrowth, Brazil. *J. Trop. Ecol.* **2008**, *24*, 27–38. [CrossRef]
2. Giácomo, R.G.; Alves, M.C.; Camara, R.; Pereira, M.G.; de Arruda, O.G.; Souto, S.N.; de Moraes, M.L.T. Litterfall and Nutrient Input in a Degraded Area. *Floresta E Ambiente* **2017**, *24*, e20160028. [CrossRef]
3. Martius, C.; Höfer, H.; Garcia, M.V.B.; Römbke, J.; Hanagarth, W. Litter Fall, Litter Stocks and Decomposition Rates in Rainforest and Agroforestry Sites in Central Amazonia. *Nutr. Cycl. Agroecosyst.* **2004**, *68*, 137–154. [CrossRef]
4. Pereira, L.C.; Balbinot, L.; Lima, M.T.; Bramorski, J.; Tonello, K.C. Aspects of Forest Restoration and Hydrology: The Hydrological Function of Litter. *J. For. Res.* **2021**, *33*, 543–552. [CrossRef]
5. Lima, J.A.; Tonello, K.C. Rainfall Partitioning in Amazon Forest: Implications of Reduced Impact Logging on Litter Water Conservation. *Hydrology* **2023**, *10*, 97. [CrossRef]
6. Su, S.; Liu, X. The Water Storage Function of Litters and Soil in Five Typical Plantations in the Northern and Southern Mountains of Lanzhou, Northwest China. *Sustainability* **2022**, *14*, 8231. [CrossRef]
7. Li, W.; Li, Y.; Long, M.; Li, X. Study on Water-Holding Properties of Litters in Different Types of Forests of Yuntaishan Mountain Area in Shibing County, Guizhou Province. In *IOP Conference Series: Materials Science and Engineering*; Institute of Physics Publishing: Bristol, UK, 2018; Volume 394.
8. Xia, L.; Song, X.; Fu, N.; Cui, S.; Li, L.; Li, H.; Li, Y. Effects of Forest Litter Cover on Hydrological Response of Hillslopes in the Loess Plateau of China. *Catena* **2019**, *181*, 104076. [CrossRef]
9. Tu, Z.; Chen, S.; Ruan, D.; Chen, Z.; Huang, Y.; Chen, J. Differential Hydrological Properties of Forest Litter Layers in Artificial Afforestation of Eroded Areas of Latosol in China. *Sustainability* **2022**, *14*, 14869. [CrossRef]
10. Santos, A.F.A.; Carneiro, A.C.P.; Martinez, D.T.; Caldeira, S.F. Capacidade de Retenção Hídrica Do Estoque de Serapilheira de Eucalipto. *Floresta E Ambiente* **2017**, *24*, e20150303. [CrossRef]
11. Throop, H.L.; Abu Salem, M.; Whitford, W.G. Fire Enhances Litter Decomposition and Reduces Vegetation Cover Influences on Decomposition in a Dry Woodland. *Plant Ecol.* **2017**, *218*, 799–811. [CrossRef]
12. Bryanin, S.; Kondratova, A.; Abramova, E. Litter Decomposition and Nutrient Dynamics in Fire-Affected Larch Forests in the Russian Far East. *Forests* **2020**, *11*, 882. [CrossRef]
13. Bomfim, B.; Silva, L.C.R.; Pereira, R.S.; Gatto, A.; Emmert, F.; Higuchi, N. Litter and Soil Biogeochemical Parameters as Indicators of Sustainable Logging in Central Amazonia. *Sci. Total Environ.* **2020**, *714*, 136780. [CrossRef] [PubMed]
14. Watanabe, T.; Fukuzawa, K.; Shibata, H. Temporal Changes in Litterfall, Litter Decomposition and Their Chemical Composition in Sasa Dwarf Bamboo in a Natural Forest Ecosystem of Northern Japan. *J. For. Res.* **2013**, *18*, 129–138. [CrossRef]
15. Zhu, X.; Liu, W.; Chen, H.; Deng, Y.; Chen, C.; Zeng, H. Effects of Forest Transition on Litterfall, Standing Litter and Related Nutrient Returns: Implications for Forest Management in Tropical China. *Geoderma* **2019**, *333*, 123–134. [CrossRef]
16. Horodecki, P.; Nowiński, M.; Jagodziński, A.M. Advantages of Mixed Tree Stands in Restoration of Upper Soil Layers on Postmining Sites: A Five-Year Leaf Litter Decomposition Experiment. *Land Degrad. Dev.* **2019**, *30*, 3–13. [CrossRef]
17. Ge, X.; Zeng, L.; Xiao, W.; Huang, Z.; Geng, X.; Tan, B. Effect of Litter Substrate Quality and Soil Nutrients on Forest Litter Decomposition: A Review. *Acta Ecol. Sin.* **2013**, *33*, 102–108. [CrossRef]
18. Tonello, K.C.; Pereira, L.C.; Balbinot, L.; Nnadi, E.O.; Mosleh, M.H.; Bramorski, J. Patterns of Litter and Nutrient Return to the Soil during Passive Restoration in Cerrado, Brazil. *Biologia* **2023**, *78*, 399–414. [CrossRef]

19. Peng, Y.; Vesterdal, L.; Peñuelas, J.; Peguero, G.; Wu, Q.; Heděnec, P.; Yue, K.; Wu, F. Soil Fauna Effects on Litter Decomposition Are Better Predicted by Fauna Communities within Litterbags than by Ambient Soil Fauna Communities. *Plant Soil* **2023**, *487*, 49–59. [CrossRef]
20. Yue, K.; De Frenne, P.; Van Meerbeek, K.; Ferreira, V.; Fornara, D.A.; Wu, Q.; Ni, X.; Peng, Y.; Wang, D.; Heděnec, P.; et al. Litter Quality and Stream Physicochemical Properties Drive Global Invertebrate Effects on Instream Litter Decomposition. *Biol. Rev.* **2022**, *97*, 2023–2038. [CrossRef]
21. Neris, J.; Tejedor, M.; Rodríguez, M.; Fuentes, J.; Jiménez, C. Effect of Forest Floor Characteristics on Water Repellency, Infiltration, Runoff and Soil Loss in Andisols of Tenerife (Canary Islands, Spain). *Catena* **2013**, *108*, 50–57. [CrossRef]
22. Chen, S.; Cao, T.; Tanaka, N.; Gao, T.; Zhu, L.; Zou, C.B. Hydrological Properties of Litter Layers in Mixed Forests in Mt. Qinling, China. *IForest* **2018**, *11*, 243–250. [CrossRef]
23. Cheng, J.D.; Lin, J.P.; Lu, S.Y.; Huang, L.S.; Wu, H.L. Hydrological Characteristics of Betel Nut Plantations on Slopelands in Central Taiwan. *Hydrol. Sci. J.* **2008**, *53*, 1208–1220. [CrossRef]
24. Xie, J.; Su, D. Water-Holding Characteristics of Litter in Meadow Steppes with Different Years of Fencing in Inner Mongolia, China. *Water* **2020**, *12*, 2374. [CrossRef]
25. Bai, Y.; Zhou, Y.; Du, J.; Zhang, X.; Di, N. Effects of a Broadleaf-Oriented Transformation of Coniferous Plantations on the Hydrological Characteristics of Litter Layers in Subtropical China. *Glob. Ecol. Conserv.* **2021**, *25*, e01400. [CrossRef]
26. Tonello, K.C.; Van Stan, J.T.; Rosa, A.G.; Balbinot, L.; Pereira, L.C.; Bramorski, J. Stemflow Variability across Tree Stem and Canopy Traits in the Brazilian Cerrado. *Agric. For. Meteorol.* **2021**, *308–309*, 108551. [CrossRef]
27. Tonello, K.C.; Rosa, A.G.; Pereira, L.C.; Matus, G.N.; Guandique, M.E.G.; Navarrete, A.A. Rainfall Partitioning in the Cerrado and Its Influence on Net Rainfall Nutrient Fluxes. *Agric. For. Meteorol.* **2021**, *303*, 108372. [CrossRef]
28. Van Stan, J.T.; Gutmann, E.; Friesen, J. *Precipitation Partitioning by Vegetation: A Global Synthesis*; Springer International Publishing: Berlin/Heidelberg, Germany, 2020; ISBN 9783030297022.
29. Lima, J.; Tonello, K.C. Rainfall Partitioning in Amazon Forest: Implications of Reduced Impact Logging for Hydrological Processes. *Agric. For. Meteorol.* **2023**, *327*, 109505. [CrossRef]
30. Van Stan, J.T.; Coenders-Gerrits, M.; Dibble, M.; Bogeholz, P.; Norman, Z. Effects of Phenology and Meteorological Disturbance on Litter Rainfall Interception for a Pinus Elliottii Stand in the Southeastern United States. *Hydrol. Process.* **2017**, *31*, 3719–3728. [CrossRef]
31. Acharya, B.S.; Stebler, E.; Zou, C.B. Monitoring Litter Interception of Rainfall Using Leaf Wetness Sensor under Controlled and Field Conditions. *Hydrol. Process.* **2017**, *31*, 240–249. [CrossRef]
32. Melissa, K.; Dickow, C.; Marques, R.; Pinto, C.B.; Höfer, H. Produção de Serapilheira Em Diferentes Fases Sucessionais de Uma Floresta Subtropical Secundária, Em Antonina, PR. *Cerne* **2011**, *18*, 75–86.
33. Winkler, J.P.; Negreiros, A.B. A Serrapilheira Como Bioindicador de Qualidade Ambiental Em Fragmentos de Eucalyptus. *Rev. Cont. (UFRRJ)* **2018**, *7*, 175–202. [CrossRef]
34. Floriancic, M.G.; Allen, S.T.; Meier, R.; Truniger, L.; Kirchner, J.W.; Molnar, P. Potential for Significant Precipitation Cycling by Forest-Floor Litter and Deadwood. *Ecohydrology* **2022**, *16*, e2493. [CrossRef]
35. Zagyvai-Kiss, K.A.; Kalicz, P.; Szilágyi, J.; Gribovszki, Z. On the Specific Water Holding Capacity of Litter for Three Forest Ecosystems in the Eastern Foothills of the Alps. *Agric. For. Meteorol.* **2019**, *278*, 107656. [CrossRef]
36. Li, Y.; Li, B.; Zhang, X.; Chen, J.J.; Zhan, F.D.; Guo, X.H.; Zu, Y.Q. Differential Water and Soil Conservation Capacity and Associated Processes in Four Forest Ecosystems in Dianchi Watershed, Yunnan Province, China. *J. Soil Water Conserv.* **2015**, *70*, 198–206. [CrossRef]
37. Dubreuil, V.; Fante, K.P.; Planchon, O.; Sant'Anna Neto, J.L. Climate Change Evidence in Brazil from Köppen's Climate Annual Types Frequency. *Int. J. Climatol.* **2019**, *39*, 1446–1456. [CrossRef]
38. Pinheiro, R.C.; Tonello, K.C.; Valente, R.O.A.; Mingoti, R.; Santos, I.P. Occupation and Hydrologic Characterization of Ipaneminha Watershed, Sorocaba-SP. *IRRIGA* **2011**, *16*, 234. [CrossRef]
39. Lima, M.T.; Urso-Guimarães, M.V.; Van Stan, J.T.; Tonello, K.C. Stemflow Metazoan Transport from Common Urban Tree Species (São Paulo, Brazil). *Ecohydrology* **2023**, *16*, e2517. [CrossRef]
40. Oliveira, J.B.; Camargo, M.N.; Rossi, M.; Calderano Filho, B. *Solos Do Estado de São: Descrição Das Classes Registradas No Mapa Pedológico*; Embrapa Solos: Rio de Janeiro, Brazil; Instituto Agronômico: Campinas, Brazil, 1999.
41. Lloyd, C.R.; Marques, A.O. Spatial Variability of Throughfall and Stemflow Measurements in Amazonian Rainforest. *Agric. For. Meteorol.* **1988**, *42*, 73. [CrossRef]
42. Zhou, Q.; Keith, D.M.; Zhou, X.; Cai, M.; Cui, X.; Wei, X.; Luo, Y. Comparing the Water-Holding Characteristics of Broadleaved, Coniferous, and Mixed Forest Litter Layers in a Karst Region. *Mt. Res. Dev.* **2018**, *38*, 220–229. [CrossRef]
43. Ayres, M.; Ayres, M., Jr.; Ayres, D.L.; Santos, A.A. *Bioestat 5.0 Aplicações Estatísticas Nas Áreas Das Ciências Biológicas e Médicas*; IDSM: Belém, Brazil, 2007.
44. Cui, Y.; Pan, C.; Zhang, G.; Sun, Z.; Wang, F. Effects of Litter Mass on Throughfall Partitioning in a Pinus Tabulaeformis Plantation on the Loess Plateau, China. *Agric. For. Meteorol.* **2022**, *318*, 108908. [CrossRef]
45. Zhu, H.; Wang, G.; Yinglan, A.; Liu, T. Ecohydrological Effects of Litter Cover on the Hillslope-Scale Infiltration-Runoff Patterns for Layered Soil in Forest Ecosystem. *Ecol. Eng.* **2020**, *155*, 105930. [CrossRef]

46. Souza, J.A.; Davide, A.C. Decomposição de Serapilheira e Nutrientes Em Uma Mata Não Minerada e Em Plantações de Bracatinga (Mimosa Scabrella) e de Eucalipto (Eucalyptus Saligna) Em Áreas de Mineração de Bauxita. *Cerne* **2001**, *7*, 101–113.
47. Balieiro, F.D.C.; Franco, A.A.; Pereira, M.G.; Campello, E.F.C.; Dias, L.E.; de Faria, S.M.; Alves, B.J.R. Dinâmica Da Serapilheira e Transferência de Nitrogênio Ao Solo, Em Plantios de Pseudosamanea Guachapele e Eucalyptus Grandis. *Pesqui. Agropecuária Bras.* **2004**, *39*, 597–601. [CrossRef]
48. Melos, A.R.; Sato, A.M.; Coelho Netto, A.L. Produção, Estoque e Retenção Hídrica Da Serrapilheira Em Encosta Sob Plantio de Híbridos de Eucalyptus Urophylla e Eucalyptus Grandis: Médio Vale Do Rio Paraíba Do Sul. *Anuário Do Inst. De Geociências* **2010**, *33*, 66–73. [CrossRef]
49. Pereira, M.G.; Menezes, L.F.T.; Schultz, N. Aporte e Decomposição Da Serapilheira Na Floresta Atlântica, Ilha Da Marambaia, Mangaratiba, RJ. *Ciência Florest.* **2008**, *18*, 443–454. [CrossRef]
50. Pires, L.A.; Miranda De Britez, R.; Martel, G.; Pagano, S.N. Produção, Acúmulo e Decomposição Da Serapilheira Em Uma Restinga Da Ilha Do Mel, Paranaguá, PR, Brasil. *Acta Bot. Bras.* **2006**, *20*, 173–184. [CrossRef]
51. Santos, F.M.; Chaer, G.M.; Diniz, A.R.; Balieiro, F.C. Nutrient Cycling over Five Years of Mixed-Species Plantations of Eucalyptus and Acacia on a Sandy Tropical Soil. *For. Ecol. Manag.* **2017**, *384*, 110–121. [CrossRef]
52. Mateus, F.A.; Couto Miranda, C.; Valcarcel, R.; Figueiredo, P.H.A. Estoque e Capacidade de Retenção Hídrica Da Serrapilheira Acumulada Na Restauração Florestal de Áreas Perturbadas Na Mata Atlântica. *Floresta E Ambiente* **2013**, *20*, 336–343. [CrossRef]
53. Rahman, M.M.; Tsukamoto, J.; Rahman, M.M.; Yoneyama, A.; Mostafa, K.M. Lignin and Its Effects on Litter Decomposition in Forest Ecosystems. *Chem. Ecol.* **2013**, *29*, 540–553. [CrossRef]
54. Vogelmann, E.S.; Prevedello, J.; Reichert, J.M. Origem Dos Compostos Hidrofóbicos e Seus Efeitos Em Florestas de Pinus e Eucalyptus. *Ciência Florest.* **2015**, *25*, 1067–1079. [CrossRef]
55. Tonello, K.C.; Campos, S.D.; de Menezes, A.J.; Bramorski, J.; Mathias, S.L.; Lima, M.T. How Is Bark Absorbability and Wettability Related to Stemflow Yield? Observations From Isolated Trees in the Brazilian Cerrado. *Front. For. Glob. Chang.* **2021**, *4*, 650665. [CrossRef]
56. Cunha, G.M.; Costa, G.S.; Gama-Rodrigues, A.C. Litter Stock and Quality in Eucalyptus Grandis in Northern Rio de Janeiro State, Brazil. *Floresta E Ambiente* **2020**, *27*, e20180129. [CrossRef]
57. Ma, X.; Chen, J.; Zhu, J.; Yan, N. Lignin-Based Polyurethane: Recent Advances and Future Perspectives. *Macromol. Rapid Commun.* **2021**, *42*, 2000492. [CrossRef] [PubMed]
58. Meena, R.S.; Lal, R.; Yadav, G.S. Long-Term Impacts of Topsoil Depth and Amendments on Soil Physical and Hydrological Properties of an Alfisol in Central Ohio, USA. *Geoderma* **2020**, *363*, 114164. [CrossRef]
59. Haruna, S.I.; Anderson, S.H.; Udawatta, R.P.; Gantzer, C.J.; Phillips, N.C.; Cui, S.; Gao, Y. Improving Soil Physical Properties through the Use of Cover Crops: A Review. *Agrosystems Geosci. Environ.* **2020**, *3*, e20105. [CrossRef]
60. Wei, Y.; Wu, X.; Xia, J.; Miller, G.A.; Cai, C.; Guo, Z.; Arash, H. The Effect of Water Content on the Shear Strength Characteristics of Granitic Soils in South China. *Soil Tillage Res.* **2019**, *187*, 50–59. [CrossRef]
61. Tu, Z.; Chen, S.; Chen, Z.; Ruan, D.; Zhang, W.; Han, Y.; Han, L.; Wang, K.; Huang, Y.; Chen, J. Hydrological Properties of Soil and Litter Layers of Four Forest Types Restored in the Gully Erosion Area of Latosol in South China. *Forests* **2023**, *14*, 360. [CrossRef]
62. Biao, Z.; Wenhua, L.; Gaodi, X.; Yu, X. Water Conservation of Forest Ecosystem in Beijing and Its Value. *Ecol. Econ.* **2010**, *69*, 1416–1426. [CrossRef]