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Litter stock, litterfall and nutrients in the Amazonia: defining patterns from last 40 years of scientific research

Estoque e fluxo de serapilheira e nutrientes na Amazônia: definindo padrões dos últimos 40 anos de pesquisa científica

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Nutrient cycling, guaranteed by the decomposition of litter, stands out as an essential process for maintaining Amazonian ecosystems. Studies on the litter layer on the soil surface are indispensable, primarily because they help provide information about functional and structural aspects of the ecosystem. Therefore, to define parameters related to the storage and production of litter and nutrients in Amazonia, we conducted a qualitative and quantitative analysis of articles in academic publications developed in Amazonia in the last 40 years (1980- 2019). We identified 83 articles, with the majority (85.39%) developed in Brazil. We found that 67% of these studies were related to the litterfall method and only 11.24% were related to both collection methods (litter stock and litterfall). The litter stock ranged from 4.94 ± 2.07 Mg ha^{-1} to 11.05 ± 4.67 Mg ha^{-1} for Agroforestry Systems (AFS) and Mixed Plantation (MIP), respectively. While litterfall ranged from 2.09 ± 1.14 Mg ha^{-1} year^{-1} to 9.01 ± 6.09 Mg ha^{-1} year^{-1} for pasture ecosystems (PAS) and AFS. The litter nutrients in Amazonia follow the following decreasing order: N>Ca>K>Mg>P. Our results indicate the need for more attention and investment in Amazonian forest research, so that more studies on the subject may be developed, especially those focusing on ecological restoration.

Keywords: bibliometric analysis, biogeochemical cycle, litter dynamics.

A ciclagem de nutrientes, garantida pela decomposição da serapilheira, destaca-se como um processo essencial para a manutenção dos ecossistemas amazônicos. Estudos sobre a camada de serapilheira na superfície do solo são indispensáveis, principalmente porque ajudam a fornecer informações sobre esses ecossistemas. Portanto, para definir parâmetros relacionados ao estoque e fluxo de serapilheira e nutrientes na Amazônia, realizamos uma análise qualitativa e quantitativa de artigos em publicações acadêmicas desenvolvidas na Amazônia nos últimos 40 anos (1980-2019). Identificamos 83 artigos, sendo a maioria (85,39%) desenvolvida no Brasil. Constatamos que 67% desses estudos estavam relacionados ao método de fluxo e apenas 11,24% deles estavam relacionados a ambos os métodos de coleta (estoque e fluxo de serapilheira). O estoque de serapilheira variou de 4,94 ± 2,07 Mg ha^{-1} a 11,05 ± 4,67 Mg ha^{-1} para Sistemas Agroflorestais (AFS) e Plantio Misto (MIP), respectivamente. Enquanto a serapilheira variou de 2,09 ± 1,14 Mg ha^{-1} ano^{-1} a 9,01 ± 6,09 Mg ha^{-1} ano^{-1} para ecossistemas de pastagem (PAS) e AFS. Os nutrientes da serapilheira na Amazônia seguem a seguinte ordem decrescente: N>Ca>K>Mg>P. Nossos resultados indicam a necessidade de maior atenção e investimento nas pesquisas florestais amazônicas, para que mais estudos sobre o assunto possam ser desenvolvidos, principalmente aqueles com foco na restauração ecológica.

Palavras-chave: análise bibliométrica, ciclo biogeoquímico, dinâmica de serapilheira.

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1. INTRODUCTION

Amazonia biome includes nine countries (Brazil, Bolivia, Colombia, Ecuador, Guyana, French Guiana, Peru, Suriname, and Venezuela). It is recognized for its extensive territory, especially because it includes a large part of the planet's biodiversity, besides having a significant socio-environmental and economic importance [1-3]. Among the economic activities developed in the region, mining and agriculture stand out. Gold, copper, and oil contribute over 50% of Peru's and Bolivia's exports. In Venezuela and Ecuador, the economy relies on oil exploration [4, 5]. In Brazil, agriculture started to play a more significant role in the economy of Amazonia from the 17th century onwards, when the Brazilian government created tax incentives for cocoa, sugar cane, and tobacco cultivation [6]. In Colombia, besides these activities, the economy is complemented by fishing [7]. In Suriname, agriculture played a crucial role in colonization, and today, the country possesses substantial energy potential through its mineral and hydrocarbon reserves [8].

Although these activities are essential for the economy, they cause significant, and in some cases, irreversible environmental damage to the Amazonian rainforest. The suppression of vegetation, which is a necessary process for the development of such economic practices, is responsible for chasing fauna away, causing soil loss, and above all, interrupting the hydrological and biogeochemical cycles [9]. The impact caused by forest loss in Amazonia is even more evident due to the nutritional limitations of its soils, which depend on the decomposition of forest residue layer found on the ground for nutrient cycling [10]. This layer, known as the litter layer, is made of leaves, branches, fruit, flowers, seeds, animal waste [11, 12] and it is responsible for the maintenance of the forest's ecosystems, acting as a biogeochemical matrix [13-15] returning essential elements to the soil, and consequently, to the vegetation.

The litter layer also functions as a mechanical barrier against weathering, making it a fundamental factor for the survival of Amazonia. That is because in addition to the nutritional limitation of the soil, the constant high rainfall levels cause intense soil loss due to erosion and leaching [16]. In addition, the litter layer enables water retention, providing ideal conditions for the reproduction of edaphic fauna, consequently improving physical and biological characteristics of soil [15, 17, 18]. Thus, due to all these attributes, the litter layer is considered an indicator of efficient forest restoration, facilitating periodical monitoring of ecosystems in the succession process, especially those where the exploration of natural resources increases constantly [17, 19, 20]. It is also considered a technique for preventing forest fires because its quantification makes it possible to estimate the dynamics of combustible materials in a given ecosystem [21].

Both the litterfall and the litter stock are influenced by biotic factors (i.e., the phenology of the species and the function of the edaphic fauna) [22] and abiotic (i.e., temperature and water availability) [23] factors. Therefore, to study the subject different methods for litterfall and litter stock qualification and quantification are necessary. For litterfall, it is customary to measure all organic material deposited in suspended collectors during a determined period [24-26]. In litter stock, only soil's organic material is quantified, with the support of a metallic collecting trap [17, 25]. After the collection process, it is necessary to estimate the dry mass of the whole material but for that, it is necessary to take the litter samples to an oven with air circulation and weight each sample individually in an analytical balance. Some studies also separate the litterfall and litter stock into fractions (i.e., leaves, branches, and reproductive material) to determine how much each fraction contributes to the litterfall and litter stock in general [21, 27, 28]. Others also analyze the quality based on the contents of its chemical elements to improve soil fertility [29, 30].

Litterfall and litter stock can be used to compare ecosystems [20, 25, 31]. However, one of the biggest obstacles of the existing studies on the subject is the absence of litter sampling and quantification patterns. Although megagram per hectare (Mg ha^{-1}) is the international litter measurement unit, many studies still use other units [27, 32], which makes it harder to match the results. Knowing the patterns of litterfall and litter stock, as well as its nutrients in different ecosystems in Amazonia, will help to strengthen the evaluations of these parameters for successful forest restoration of anthropized and degraded areas. That is because the litter layer is an efficient indicator, and the comparison between these reference values with the ones found during ecosystem monitoring undergoing ecological restoration is essential for a project to be successful.

An alternative to investigating this problem is to use bibliometrics, which is an effective method to quantify scientific research output on a specific subject. It enables us to identify trends and establish patterns within the chosen area [33]. This technique is used worldwide and frequently appears in the environmental field [33-36]. Therefore, this article intends to answer the following questions: Q1) Is there a pattern of the scientific production throughout the years?; Q2)

How does the distribution of the scientific production on litterfall and litter stock happen in Amazonian countries? And Q3) What is the variation in mean litterfall and stocks of litter and macronutrients in each Amazonian ecosystem already studied? Our hypotheses are the following ones: H1) Considering that national and foreign incentives and donations for scientific research have increased in Amazonia over the years, then scientific production tends to increase over time; H2) As more than 60% of Amazonia is in Brazilian territory, then we hope there is a higher amount of scientific publications in this country than in other countries; and H3) Higher floristic diversity and higher ecological processes balance, observed in the primary and secondary forest ecosystems, means higher patterns of litterfall, litter stock, and nutrients to be found in these ecosystems. In this scenario, our purpose is to qualify and quantify the scientific papers on litterfall and litter stock produced in Amazonia in the last 40 years (1980-2019).

2. MATERIAL AND METHODS

2.1. Data collection

We carried out a qualitative and quantitative review of the scientific articles published from January 1980 to December 2019. In this review, we used the following platforms: a) "Wiley Online Library (https://onlinelibrary.wiley.com/)"; b) "Google Scholar (https://scholar.google.com.br/?hl=pt)"; c) "ScienceDirect (https://www.sciencedirect.com/)"; d) "Springer Link (https://link.springer.com/)"; e) "SciElo (https://scielo.org/)" and f) "JSTOR (https://www.jstor.org/) (Figure 1). In these platforms, we searched for the following keywords: "litter or litterfall" and "Amazon or Amazonia" in Portuguese, English, and Spanish, choosing papers about litter storage and production that were developed in Amazonia.

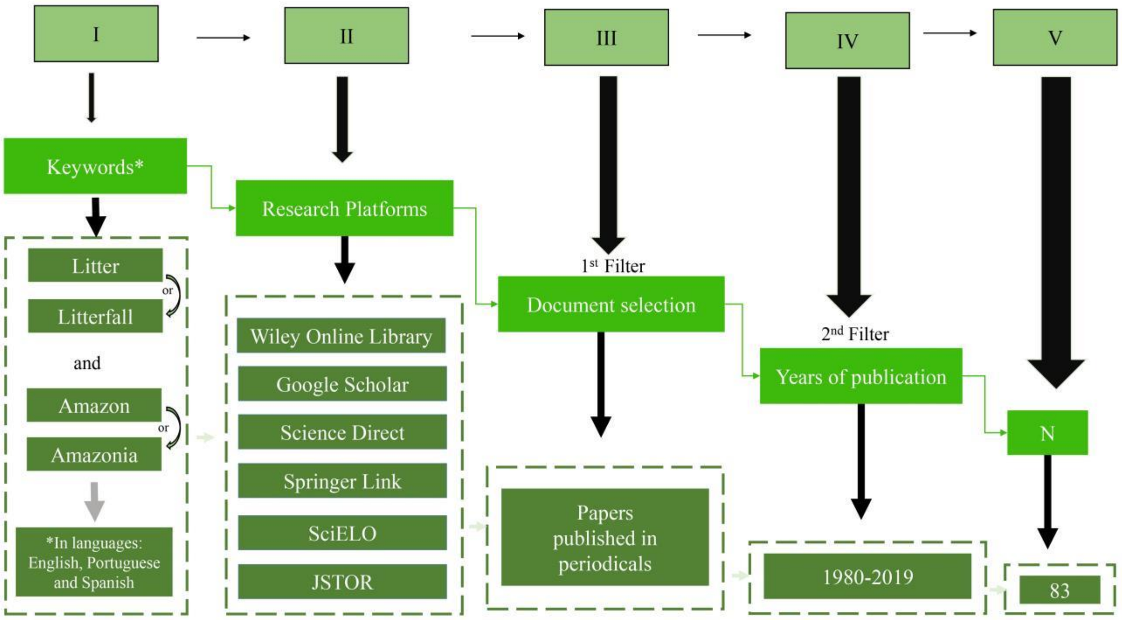

Figure 1: Proceedings established to run the bibliometric analysis of the scientific articles on litterfall and litter stock in the Amazonia biome, published between January 1980 and December 2019. N=total amount.

To facilitate the comparison between ecosystems, after reading the articles we extracted and grouped different nomenclatures which had the same meaning, such as: Primary forest – PRF (including: "primary forest", "native forest", "primary woods", "native woods"); Secondary forest – SCF (including: "secondary forest", "capoeira", "post regeneration forest", "natural fallow”); Alluvial forest – ALF (including: “Igapo”, “Floodplain”, “Mangrove”, “Flooded forest”); Pasture – PAS (including: “Pasture”, including variations such as: “Degraded pasture” and “Pasture dominated by other plant species”) and Agroforestry System – AFS (including: “Agroforestry system”, “Consortium between agricultural and arboreal species”; “Silvicultural system”, “Silvopastoral system” and “Agrosilvopastoral system”); as for the consortium systems which were not classified as AFS’s, these were classified as Mixed plantation – MIP (including: “Mixed cultures”, “Planting of natives species seedlings”, “Mixed Planting”, “Planting of arboreal species”) and Monospecific planting – MOP (including: “Monoculture”, “Monospecific planting”, “Single-species planting”).

2.2. Data analysis

We performed the qualitative and quantitative analysis using the following variables: a) number of published articles per year; b) number of articles per country; c) collection methods of litterfall and litter stock; d) shape of the traps used to collect the material; e) number of fractions into which the litterfall was divided; f) average quantity of litter storage and litter production in Amazonian ecosystems; and h) average quantity of macronutrient storage and production in Amazonian ecosystems. To answer the first question, the total amount of articles was grouped in an interval of 5 years (1980-1984, 1985-1989, 1990-1994, 1995-1999, 2000-2004, 2010-2014, 2015-2019). The number of articles per country will answer the second question, about the publication distribution. For the third question, we extracted the average of litter and nutrients observed in each article, when the authors evaluated them. To create a pattern for the data, the quantities of litterfall dry mass and the nutrient contents, when necessary, were converted to Mg ha^{-1} and kg ha^{-1}, respectively. We plotted a box plot with these values, where it was possible to observe the interquartile ranges for the variables in each ecosystem.

An analysis of the Hierarchical Cluster was carried out to group the ecosystems, based on their litterfall, litter stock, and nutrient reference values. To accomplish that, we created data patterns to minimize the dimensional differences between the studied variables. Furthermore, we calculated the cophenetic coefficient to evaluate the dendrogram distortion and the reliability of the Euclidian distance applied. To analyze and plot, we used the tools of the statistical software R version 4.0.5 [37] and the packages *ggplot2*, *FactoMineR* and *actoextra*.

3. RESULTS

3.1. Features of the academic papers on litterfall and litter stock

We counted 83 articles published in academic journals. We noticed an irregular distribution along the 40-year analyzed period due to the reduced number of articles published in 1990-1994 and 2010-2014 (Figure 2). We observed a smaller number of published articles in 1980-1984 and 1990-1994, which increased in the interval from 2015-2019. We verified a drop of 66.67% in the number of articles published in 2005-2009 compared with 2010-2014. We also noticed that in 2015-2019 the number of publications was 3.6 times higher than the previous period. From the total amount of articles, most of them were published in Brazil (85.39%), and there were no articles on the subject from Bolivia and French Guiana (Figure 3).

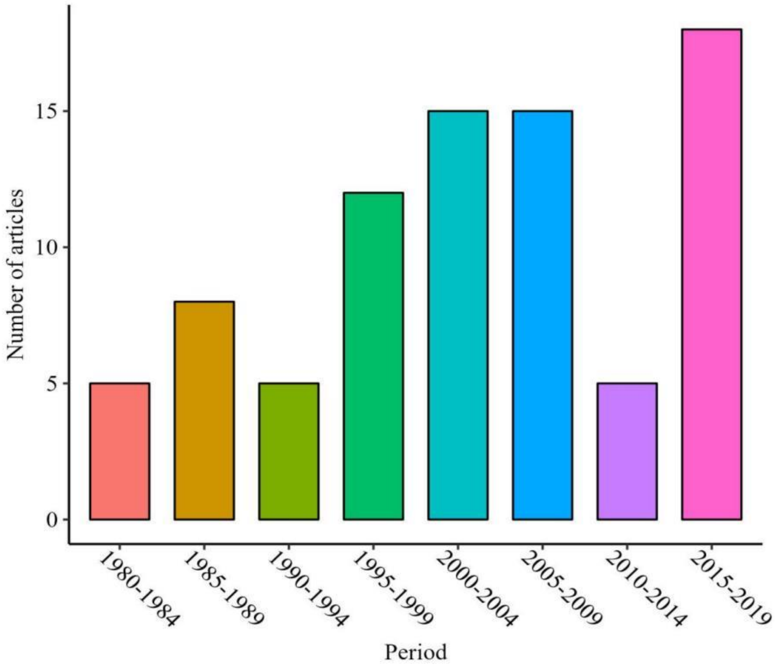

Figure 2: Timeline of published articles on litterfall and litter stock in Amazonia in the last 40 years (1980-2019).

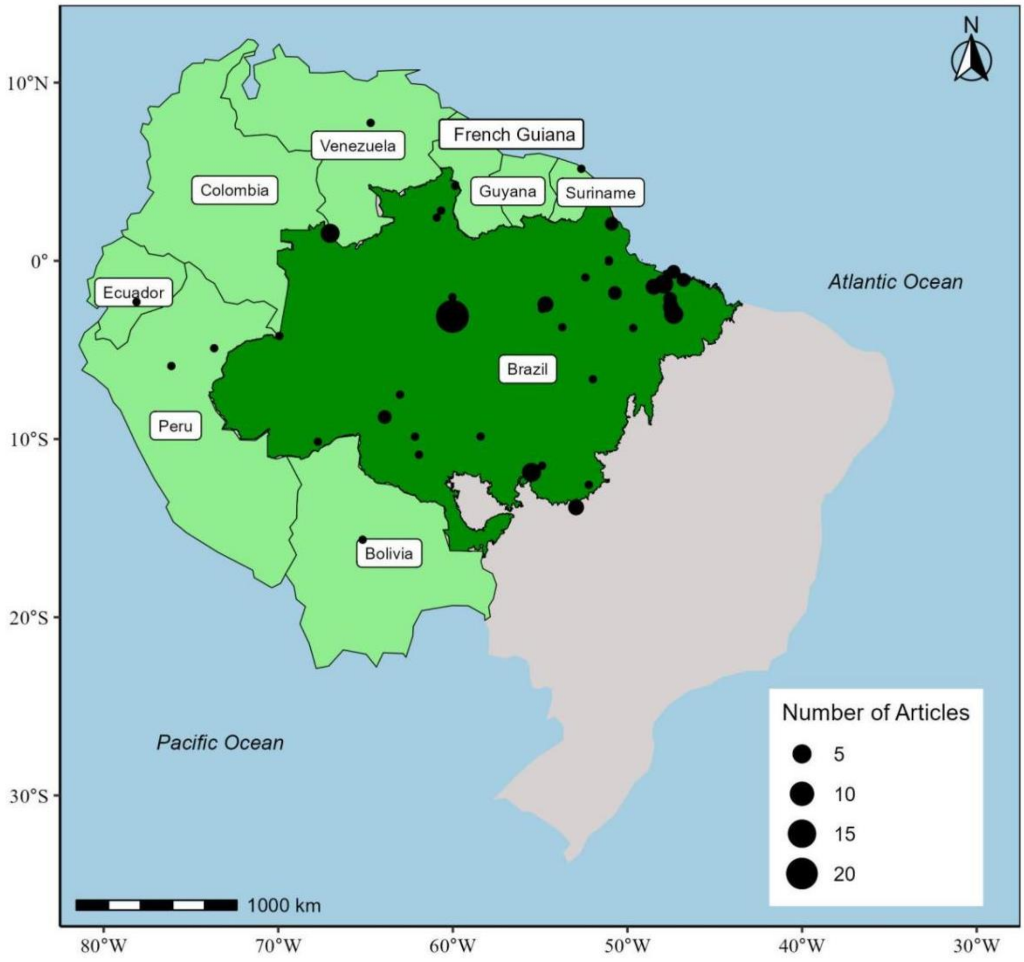

Figure 3: Distribution of published articles on "litterfall and litter stock" in the countries that are part of Amazonia in the last 40 years (1980-2019).

3.2. Litter production and litter stock in Amazonia

Most of the articles (n = 60) had litterfall as parameter of research, whereas 23 of them evaluated litter stock. Only 11 articles evaluated both litter stock and litterfall. When related to the litter collectors, different shapes were used in the development of the articles we found in our search, with the square-shaped collector (Figure 4a and d) being the most prevalent one to quantify litter stock and litterfall. The rectangular (Figure 4b) and circular (Figure 4c) collectors were uncommon and limited to the quantification of litterfall. We observed that in 2017 the “Marimon-Hay” equipment (Figure 4e) was used to collect litter stock; however, it was found in only one of the articles we analyzed (Table 1).

Table 1: Shape of the collectors used to quantify litterfall and litter stock in Amazonia in the last 40 years (1980-2019).

Shape	**Number of studies**	
	Litterfall	**Litter stock**
Square	50	22
Rectangular	3	---
Circular	3	---
Conical	4	
Marimon-Hay Equipament	---	1

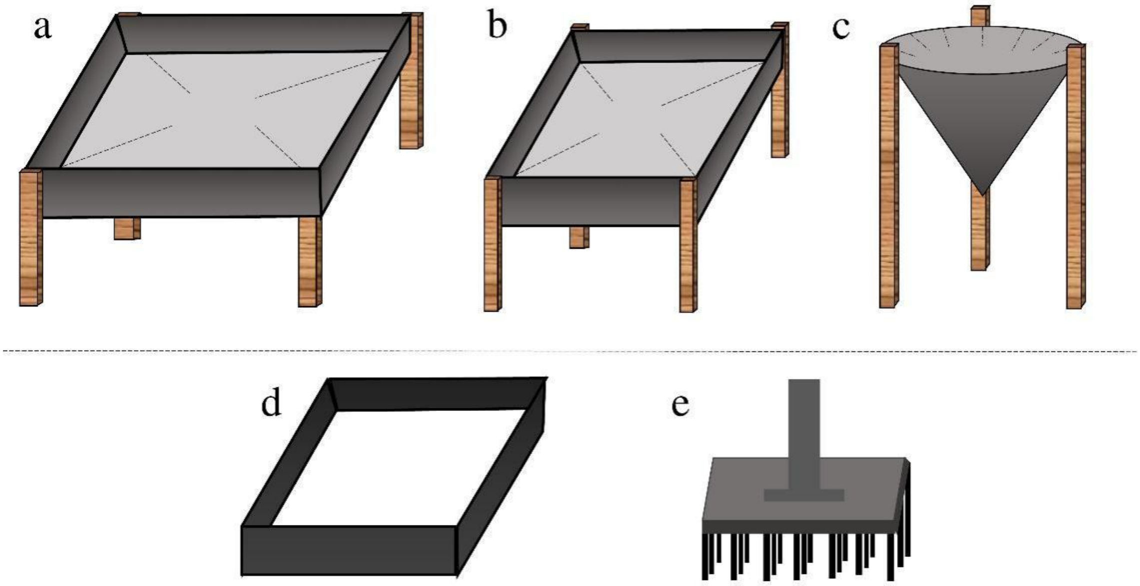

Figure 4: Shape of collectors used to litterfall and litter stock collection in Amazonia in the last 40 years (1980-2019). a = rectangular collector; b and d = square collector; c = conical collector; e = Marimon-Hay equipment.

We realized that most articles did not sort the litter sample into fractions (30.11%). In cases where the litter was sorted, it was usually divided into four fractions (24.73%). The separation into five or more fractions was a minor occurrence (Figure 5).

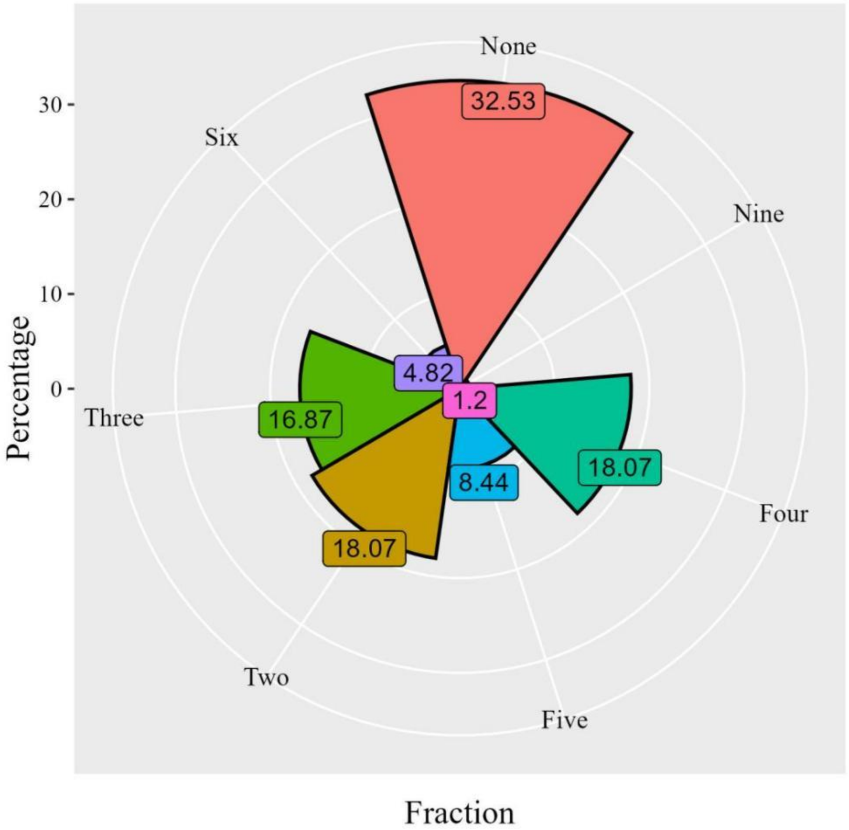

Figure 5: Quantity of fractions into which the litterfall and litter stock was divided in the published articles developed in Amazonia in the last 40 years (1980-2019).

3.3. Litterfall and litter stock in Amazonia

The average litter stock in the ecosystems varied from 4.94 ± 2.07 Mg ha^{-1} to 11.05 ± 4.67 Mg ha^{-1}, with the lowest result in the Agroforestry System – AFS and the highest in Mixed Plantation – MIP. For SCF, PAS and MIP, the litter stocks averages were 7.11 ± 4.50 Mg ha^{-1}, 7.38 ± 4.17 Mg ha^{-1} and 11.05 ± 4.67 Mg ha^{-1}, respectively. In the case of litterfall, the average of SCF was 7.18 ± 3.08 Mg ha^{-1} year^{-1}, while in the PAS and MIP ecosystems, the litterfall was 2.09 ± 1.14 Mg ha^{-1} year^{-1} and 6.29 ± 1.14 Mg ha^{-1} year^{-1}, respectively. For MOP, and AFS, the results were high to litterfall and low to litter stock. As for the Alluvial Forest – ALF ecosystem, we found litterfall results of 8.91 ± 3.84 Mg ha^{-1} and did not find studies that had quantified litter stock (Figure 6).

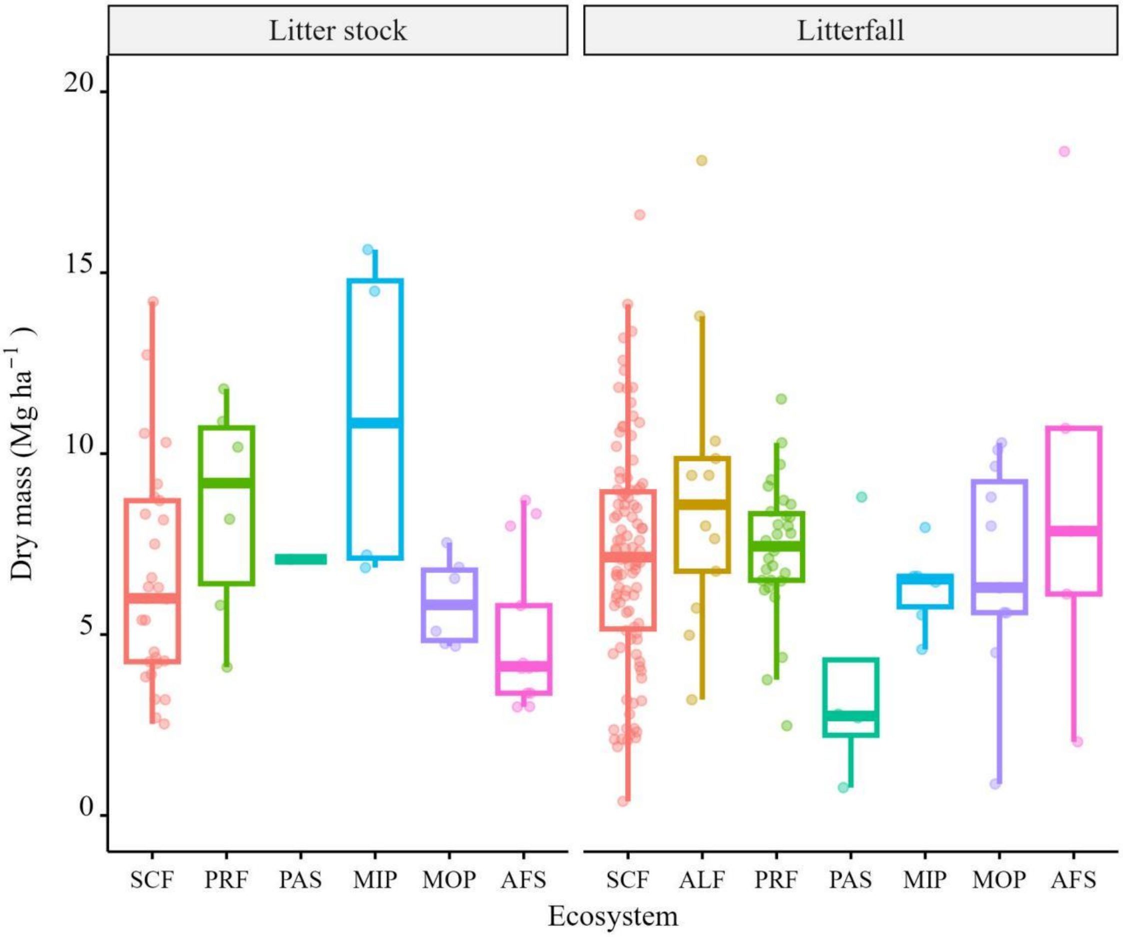

Figure 6: Litterfall and litter stock in Amazonian ecosystems obtained from the average values of works published over 40 years (1980 - 2019). Where: SCF = Secondary Forest; PRF = Primary Forest; PAS = Pasture; MIP = Mixed plantation; MOP = Monospecific planting; AFS = Agroforestry system; ALF = Alluvial Forest.

3.4. Litterfall and litter stock of nutrients in Amazonia

The PAS, MIP, and MOP ecosystems did not present well-defined patterns for some litterfall and litter stock nutrients. In the ALF ecosystem, we did not find studies that quantified litterfall nutrients. For nitrogen content, we observed that in Amazonia, the Primary Forest (PRF) (111.63 ± 26.64 kg ha^{-1}) and AFS (144.45 ± 47.47 kg ha^{-1}) presented the higher numbers in litterfall, whereas the higher numbers in litter stock were found in PRF, (124.20 ± 51.12 kg ha^{-1}), FSC (113.73 ± 103,69 kg ha^{-1}), and MIP (156.89 ± 39.12 Mg ha^{-1}) (Figure 7). For phosphorus, the higher litter stock numbers occurred in MOP (4.46 ± 1.60 kg ha^{-1}) and the higher litterfall numbers occurred in AFS (6.15 ± 3.18 kg ha^{-1}) (Figure 7b). We noticed the SCF presented low average nutrient numbers for litter stock (5.25 ± 5.70 kg ha^{-1}), especially regarding potassium (Figure 7c). However, for this very element, the average production number was among the highest (26.41 ± 33.18 kg ha^{-1}). In Amazonia, the calcium litter stock in MOP and AFS had an average of 35.18 ± 32.90 Mg ha^{-1} and 56.66 ± 38.14 kg ha^{-1}, respectively (Figure 7d). To produce this nutrient, we found distinctive patterns for SCF (47.60 ± 30.98 kg ha^{-1}), PRF (44.67 ± 37.95 kg ha^{-1}), PAS (55.08 ± 30.52 kg ha^{-1}), and MOP (45.24 ± 18.16 kg ha^{-1}). For magnesium, we observed a low litter stock in SCF (6.95 ± 6.48 Mg ha^{-1}) and a high litterfall in MOP (15.83 ± 2.87 kg ha^{-1}), SCF (13.52 ± 5.95 kg ha^{-1}), and PRF (13.29 ± 5.85 kg ha^{-1}) (Figure 7e). We did not observe well-defined patterns for sulfur (Figure 7f).

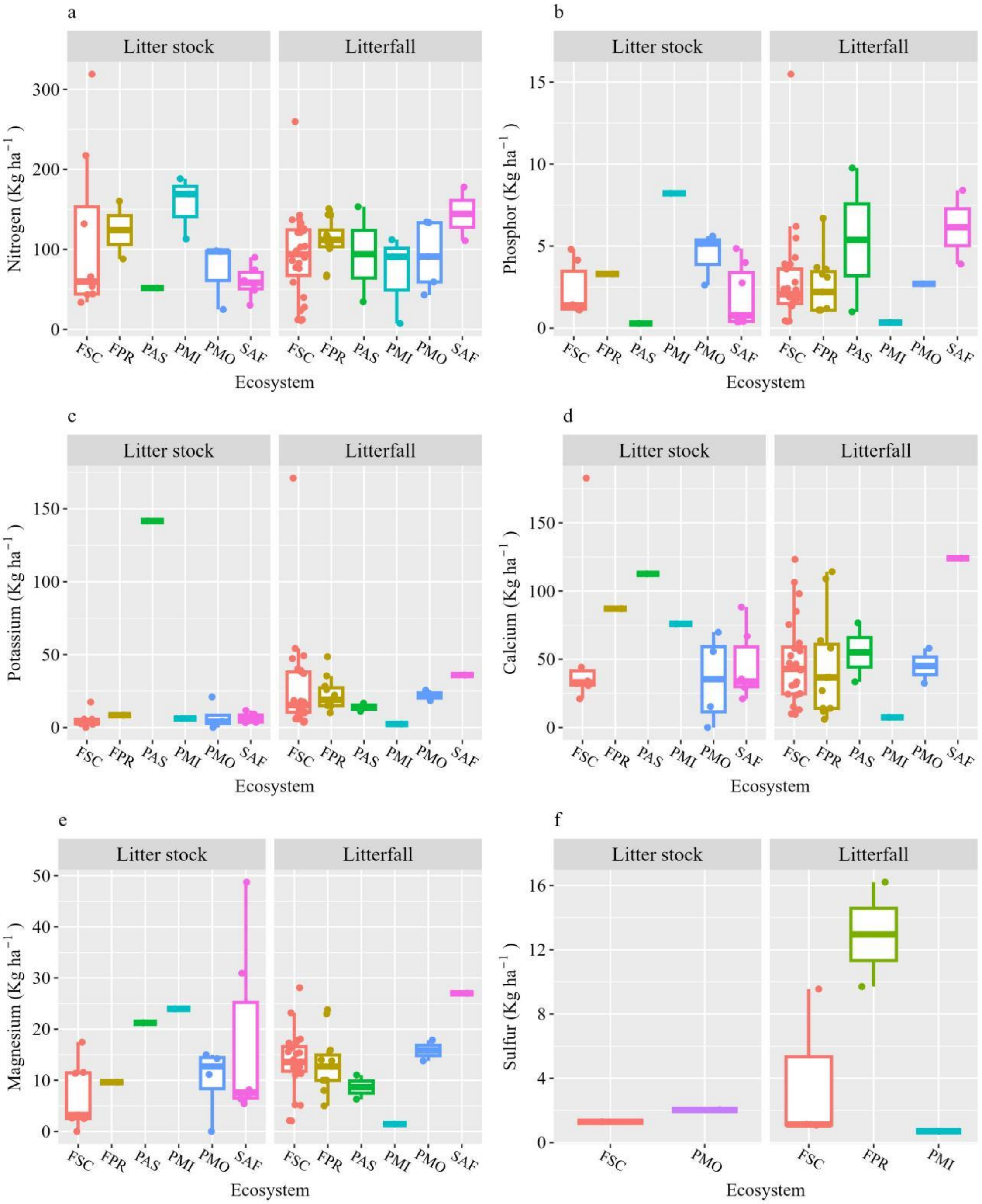

Figure 7: Litterfall and litter stock nutrients in Amazonian ecosystems obtained from the average values of works published over 40 years (1980 - 2019), as indicated by (a) nitrogen, (b) phosphorus, (c) potassium, (d) calcium, (e) magnesium and (f) sulfur. Where: SCF = Secondary Forest; PRF = primary forest; PAS = Pasture; MIP = Mixed Plantation; MOP = monospecific planting; AFS = Agroforestry System.

3.5. Cluster analysis

The cluster analysis showed a satisfactory cophenetic correlation coefficient (0.79), similar to the value usually considered adequate (0.8). Thus, we find that ecosystems are grouped into five groups, of which three are constituted of only one ecosystem, PAS, ALF, and AFS, respectively (Fig 8). The MOP and SCF ecosystems have shown similar characteristics. MIP and PRF are similar in themselves as to litter stock and to litterfall and to nutrients, therefore, constitute another ecosystem group (Figure 8).

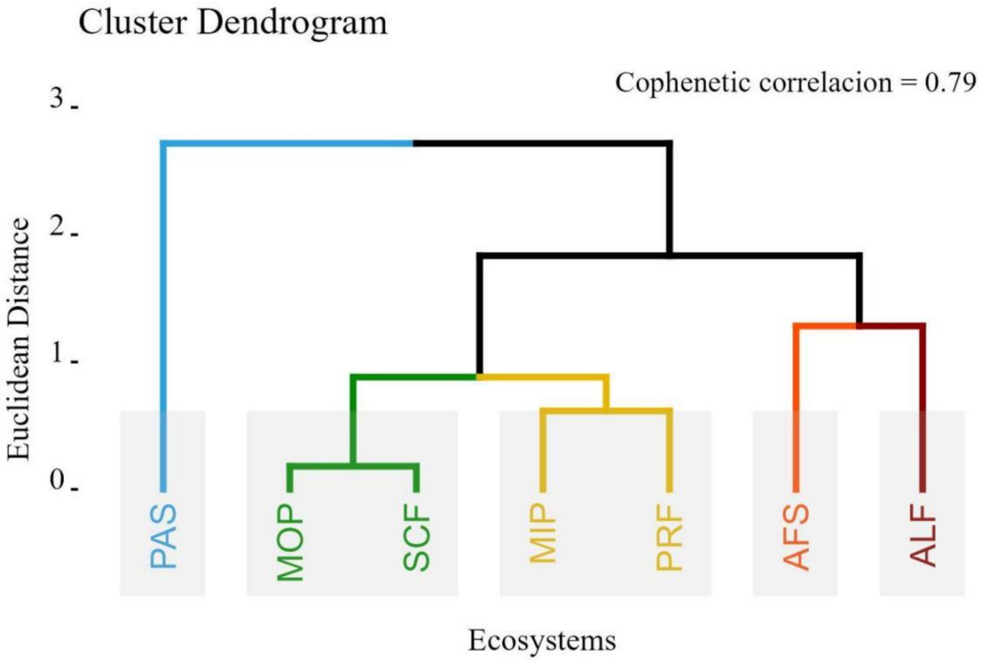

Figure 8: Cluster analysis for different ecosystems as a function of litter stock, litterfall and nutrient content in Amazonia.

4. DISCUSSION

4.1. Features of published scientific work on the litterfall and litter stock

Compared to other bibliometric analyses [38-40], the low number of research articles published in Amazonia, in a 40-year period, reveals the insufficiency of scientific research on the subject. Although Peru, Bolivia, and Ecuador are on the list of countries with the highest deforestation rates from 1990 to 2015 [41], few studies on litter flow and litter have been published in these locations. This data is alarming for local scientific research, as understanding the factors associated with litter deposition can help devise strategies to recover degraded areas, as litter is an indicator of restoration [42-43].

The predominance of publications in Brazil may be explained by the extensive area the Amazonia biome occupies in the country and by the intensive contribution of public institutions to developing research in this area [44]. In this scenario, we can infer that the eventual political, economic, and environmental obstacles in Brazil can reflect immediately in the development of scientific research in Amazonia.

In journals with the largest number of published articles about litterfall and litter stock in Amazonia, we realized that most of them came from universities and institutes for scientific research. Moreover, partnerships with international research centers and the implementation of measures intended to attract foreign resources such as the Amazonia Fund [45] are essential for this work's development. Investment in forestry research contributes significantly to the reduction of deforestation, given the high extension of deforested areas which could be rehabilitated and used for agriculture and the expansion of cattle raising, for example, without the need to deforest new ecosystems [46]. However, it is important to emphasize the time it takes to carry out an experiment, as well as to write an article and submit it to a journal, make the resources destined to forestry research in any given year reverberate in research articles that are published in subsequent years. As an example, the results of high investments made in 2014 were perceptible only in the interval from 2015-2019 [47].

Due to the weakening and lack of care for public environmental institutions, the increase of deforestation in Amazonia in recent years [48] is notable. The consequences are catastrophic, because, in addition to the loss of biodiversity and the interruption of cycles (e.g., hydrology and carbon) essential for the ecosystem's maintenance, the Amazonian forest becomes increasingly more susceptible to fires [49]. This happens due to the loss of its natural firebreak, that is the dense canopy and high humidity characteristic of primary Amazonian forests [23,50]. The increase in irradiation in the understory brings about a rise in the microclimate, promoting conditions for the spreading of fire [48]. Thus, studies on the litter stock and litterfall in a forest ecosystem are essential to plan fire prevention, given the knowledge regarding the dynamics of this combustible material. Nevertheless, only two found articles discussed the effect of fire on the soil’s litter layer [51, 52].

4.2. Litterfall and litter stock in Amazonia

We believe that the preference for studies on litterfall as opposed to studies on litter stock is justified by the observation of information details. That is because, through the periodical analysis of litterfall, one can quantify the dry mass and the nutrients which will be naturally available for the soil in an already known timeframe, besides allowing to identify which biotic and abiotic factors are correlated with the flow of these materials. Concerning litter stock it is not possible to do the same, although both methodologies are significantly important for the comprehension of the forestry ecosystem’s behavior, and for this reason, they should be approached simultaneously, as it was conducted in some of the articles [30, 53, 54]. In this case, studies that simultaneously evaluate both litter flux and litter stock are important as they provide a better understanding of functional ecosystem processes, in addition to enabling to estimate the decomposition rate, which is directly related to the availability of nutrients for the soil-plant system and the time required for this to occur [55]. To quantify litterfall or litter stock, one may use collectors of various shapes (Figure 4a, b, and c), yet for both sampling methodologies the square shape is the most common probably due to the practicality of building it and extrapolating its numbers for areas of different sizes (Figure 4d and e).

The uncommon use of rectangular and conical collectors may be justified by the fact that they are harder to install, manufacture, and even move with in the field. On the other hand, although we did not register the use of rectangular collectors in Amazonia, they are the most appropriate ones, because they comprehend the largest spatial variability of the litter stock [56]. However, the knowledge concerning the influence of the collector’s shape in litterfall estimates is still limited. For litter stock, in addition to these traditional collectors, an equipment called Marimon-Hay, developed, and patented by Brazilian researchers in 2005, was created to facilitate the collection (Figure 9e). This equipment has “teeth” where the litter stock is fixed and collected [57]. One of its advantages is to decrease the overestimations during the collection process, which happens in traditional collectors when removing the litter stock concurrently with the soil particles. Besides it, this equipment also minimizes the risk of accidents related to venomous animals, such as snakes, scorpions, and spiders, since it prevents the handler from having direct contact with the soil. Despite the benefits of using this equipment, we found that its use is still unusual, with only two reports of case studies.

After the collection in the field, the litterfall or litter stock is divided into fractions such as leaves, branches, and reproductive material. The authors of the study determine the number of fractions and usually differs according to the objective of the research. This division process was absent for most articles (Figure 5) and may be justified by the decrease in time spent in processing the whole material, and above all, by the evaluation of the litterfall or litter stock as a subsidy to explain other variables such as macro and mesofauna [13, 58-60].

4.3. Litterfall, litter stock and, nutrients in Amazonia

Variations in the action of biotic and abiotic factors may explain the difference between Amazonian ecosystems regarding litterfall and litter stock. We believe this happened because the litterfall is generally influenced by pluviometry indexes [13, 58-60], where the hydric stress activates the plant defenses system and increases the litterfall of the hormones which are responsible for leaf abscission [61], as well as altering phenological mechanisms [62]. In the case of secondary forests, the inconstancy of the numbers found for the ecosystems may be related to the stochasticity of the trajectory of ecological succession, which interferes directly with the pattern of litter stock and litterfall [63].

In general terms, the secondary forest ecosystem’s structural and functional characteristics recover slowly, and because of that, it needs quick cycling of nutrients causing constant litterfall [64]. It justifies the similar values of litterfall, and litter stock found for these ecosystems. However, in ecosystems that possess a high disturbance degree, such as pasture or young secondary forests, their low density and diversity of species [21], added to edaphic conditions which are restrictive to plant growth, cause a low production as a whole [65]. As the ecological succession advances, the accumulation of biomass is gradually relocated to the shaft [secondary growth] and consequently, the exchange and the storage of nutrients that happens through the precipitation of litterfall tend to find a balance that can be similar or higher than that of a primary forest [66].

For the alluvial forest ecosystems, permanently or periodically flooded, the high litterfall is explained by the constant leaf renovation rate aimed at optimizing the vital functions of plants and is provided by the excess water [27]. The opposite happens in pasture ecosystems, which generally present low litterfall and litter stock, most of which is composed of the ligneous fraction [67, 68]. This contrast was sharpened in the case of the Cluster dendrogram, where ALF and PAS represented different groups. Nonetheless, due to this fraction's high lignin and carbon content, the decomposition and the following nutrient release is slow for these ecosystems. On the other hand, despite the low cycling of nutrients, the litter stock on the soil considerably reduces the impacts of leaching [69].

When related to the forest plantations studied in Amazonia, the AFS is the most productive regarding the biogeochemical matrix because of its greater wealth of species compared to the other ones. However, when comparing it to natural ecosystems, AFS is similar to intersection between Amazonia and Cerrado biomes, characterized by a high mortality rate and, consequently, by the predominance of secondary forests in different succession stages [70] [61]. Thus, the similarity between ecosystems that we were able to ascertain with the Cluster dendrogram can be justified by the low floristic diversity and by the spaced-out canopy, which diminishes the stock and litterfall [71, 72].

As for the MIP, although species diversity is also present, the low production registered is probably because most of the scientific works developed concerning these ecosystems were related to previously degraded areas [20, 25, 28, 73]. As well as the SCF ecosystem, where both present conditions that hinder the development of the plant, even though their soil was prepared in advance. Generally regarding forest planting, conditions that cause nutritional stress are reduced by a process of soil preparation, fertilizing and liming, which are often performed [20]. These techniques have a direct influence on the quality of the litterfall and litter stock, since these ecosystems are the ones that present the higher numbers of produced and stored nutrient content in Amazonia.

The nutritional limitation of Amazonian soils makes nutrient cycling indispensable, especially in ecosystems that have not benefitted from soil preparation. In these cases, the mobility and function the nutrients perform in the plant are essential to determine its content in litter and soil [74]. For example, the plant demands high quantities of nitrogen because this element is linked to its growth [75], making the decomposition of the litter stock the main entry point for this nutrient in the soil [76]. In secondary forests, the remarkable storage of this nutrient in the biogeochemical matrix is derived from the presence of pioneer species which have higher N levels when compared to the species belonging to other ecological groups [76].

As for calcium, its content in Amazonian ecosystems is due to its structural and regulatory function. It is found in large amounts in plants, mainly in the thickest branches, which prevents a fast nutrient retranslocation [77]. Mobility is also a determining factor for magnesium and phosphorus that is due to its high mobility, being retranslocated before leaf abscission and potentializing nutrient use in the plant, thus reducing loss caused by leaching. This is an essential process in Amazonia, especially about phosphorus, since it is the one that most restrict tree growth [78, 79]. Despite the high production levels of this nutrient during the rainy season [20], the decomposition rates in this period are also high, which ensures its fast cycling. In the case of potassium, seasonality interferes considerably in the flow and storage, correlating negatively with rainfall, because it is easily translocated from plant tissues due to its solubility in water [59]. Thus, the high rainfall levels in Amazonia are responsible for the low stock in some nutrients litter layer of the soil, especially in ecosystems with more soil exposure such as forests in the first succession stage, young forest plantations, and pastures.

5. CONCLUSION

In our extensive evaluation, we observed no well-defined pattern regarding the distribution of publications on litter in Amazonia over 40 years. Furthermore, most publications are concentrated in Brazil, lacking representation from other countries within the biome. We found that the average litter stock in Amazonian ecosystems ranges from 4.94 ± 2.07 Mg ha^{-1} to 11.05 ± 4.67 Mg ha^{-1}. Still, due to the insufficient quantity of scientific articles on litter stock and litterfall in Amazonia, some ecosystems such as pasture, forest plantation, and alluvial forests do not have sufficient data to be considered reference values. Nutrient content in the litter layer of Amazonia was observed in the following descending order: N>Ca>K>Mg>P. Therefore, because of the essential role the litter layer plays in maintaining the Amazonian ecosystems, we recommend intensifying scientific research on this subject.

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