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The Seasonal Pattern of Stem Diameter Growth and Litter Accumulation Based on Meteorological Conditions in *Pinus merkusii* Plantation Forest on Sulawesi Island, Indonesia

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Abstract

This study focused on stem diameter growth and litter accumulation as one possible approach to understanding tree productivity and growth under meteorological conditions. We selected a 62-year-old pine (*Pinus merkusii*) planted forest located on Sulawesi Island, Indonesia, to be studied for two years. Dendrometer bands were set up on nine individuals to track stem diameter growth, and litter traps were installed at eight locations to measure the amount of litter. Meteorological data, including air temperature, precipitation, air humidity, and solar radiation, were recorded using instruments positioned near the pine stand, while soil moisture was measured at four different depths. Results showed that the stem diameter did not change during the dry season but increased during the wet season. The increase in stem diameter varied among individuals, but the increase stopped at the end of the wet season and the beginning of the dry season. The observed increase in stem diameter may have included short-term water expansion of the tree body, which was considered to disappear during the dry season and could be interpreted as hypertrophic growth of the stem. Litter production, which included branches and cones, was 8.45 $Mg \cdot ha^{-1} \cdot y^{-1}$. By the end of the eight-month dry season, the monthly litter amount increased to approximately 1.5 times the average annual production. The monthly increase in stem diameter showed a significant positive correlation with monthly precipitation. The monthly litter volume had a significant positive correlation with monthly maximum air temperature and a significant negative correlation with monthly average soil moisture in the deeper layers. This study suggests that in areas with distinct dry and wet seasons, *P. merkusii* trees had greater growth in assimilative organs such as stems during the wet season, while they minimized water loss through transpiration by shedding more litter at the end of the dry seasons.

Keywords

Stem Diameter Growth, Litter Accumulation, *Pinus merkusii*, Meteorological Conditions

1. Introduction

Studies into tropical tree growth have demonstrated a substantial and detailed relationship between tree dimensional increments, mainly focusing on stem diameter growth and meteorological conditions in these regions. These limited but insightful studies indicate that as tropical trees increase their stem diameters, this growth is strongly influenced by various factors, such as air temperature, rainfall, and air humidity. Understanding this robust connection is important, as it describes how trees adapt and respond to their environment, affecting their ecophysiology and productivity. On the other hand, limited studies illustrate a robust relationship between stem diameter growth and litter production in the tropics. It was crucial to comprehend the meteorological conditions that drive litterfall production and understand the changing patterns in a forest ecosystem in response to climate change.

Previous research has mainly concentrated on the ecological impact of litter. However, there was limited and conflicting research on how litterfall components respond to meteorological conditions, and it is now apparent that investigating litter production can offer valuable insights into effective plantation management. For example, leaf litter enables plants to adapt to adverse growth conditions, such as colder temperatures or drier soil (Rowland et al., 2018). Previous studies have also created regression models to determine the main factors affecting litterfall and estimate litterfall production. These models usually have limited abiotic and biotic characteristics (Chave et al., 2010; Kirman et al., 2007; Starr et al., 2005). The prediction of litter accumulation was not adequately characterized due to the complex nonlinear relationships involved. Litter production in forests varies in response to both abiotic and biotic factors. These factors include geographic location (such as latitude, longitude, and altitude) (Starr et al., 2005), meteorological conditions (for example, air temperature and precipitation) (Chave et al., 2010; Kirman et al., 2007; Starr et al., 2005), and vegetation structure (such as forest type, stand age, tree species, tree density, tree height, and stem diameter at breast height) (Liu et al., 2019). Litterfall adds the nutrients accumulated from its biomass, influencing forest productivity and tree growth (Pitman, 2013). The falling of litter was crucial for bringing back organic matter and nutrients from aboveground biomass to the forest floor. This process was closely connected to the soil carbon pool (Wang et al., 2016). Increased amounts of aboveground litter can significantly impact the movement of carbon and nutrients below the soil surface, as the amount of litter that falls each year is strongly linked to soil respiration (Davidson et al., 2002; Raich & Nadelhoffer, 1989).S

The litter found on the forest floor impacts the nutrient levels, moisture content, air temperature, and pH of the soil (Sayer, 2005). Some studies have looked into the pattern of litterfall and its connection with meteorological variables like air temperature and precipitation (Dai et al., 2021; Giweta, 2020; Lin et al., 2003; Putra et al., 2023). Moreover, recommendations from previous studies (Liu et al., 2019) mentioned that soil moisture might also influence the dynamics of annual litter production. Therefore, it was important to study how soil moisture affects litter production carefully.

Pinus merkusii Jungh et de Vriese, which constitutes 21% of the total tree species planted in UNHAS Educational Forest, has been a primary focus of reforestation and afforestation efforts led by the Indonesian Government's Ministry of Forestry since the 1960s. This species was the only native pine in Indonesia, known for its resilience and adaptability. As a needle-leaved pioneer tree from the *Pinaceae* family, it thrives at elevations between 200 and 2000 meters above sea level and can withstand annual rainfall between 1200 and 3000 mm (Sallata, 2013). The *P. merkusii* is also known for thriving in sandy and red soils. This light-demanding tree is necessary for combating erosion and preserving land deformation, especially on hilly terrains (Forest Inventory and Planning Institute, 1996). While growth was initially slow, the species gains momentum after the first five years and can harvest resin after 15 years. Natural regeneration was robust, particularly in open areas, contributing to widespread species presence. The *P. merkusii* taproots can reach a depth of more than 5 meters at maturity. It blooms from May to June, and its cones mature from October to November the following year, adding to its ecological significance (Forest Inventory and Planning Institute, 1996).

The pine species commonly shed their leaves to minimize transpiration due to the decreased soil moisture during the dry season (Giweta, 2020). Therefore, we predicted more litter would fall in the dry rather than the rainy season. Based on the structural parameters of vegetation, such as tree abundance, size, and species diversity, litter production provides essential information on ecosystem functioning, i.e. it relates to soil organic carbon incorporation, decomposition dynamics, and nutrient cycling (Aragão et al., 2009). The primary factors affecting litterfall production, as suggested by previous studies, are climate-related characteristics, particularly air temperature and precipitation (Bhatti & Jassal, 2014; Geng et al., 2022; Martínez-Alonso et al., 2007; Zhang et al., 2020). Even evergreen trees lose their leaves, few coniferous trees shed a coherent amount of leaves within a certain period of time. During the dry season, pine also sheds some leaves to reduce the evapotranspiration rate on the crown surface (Putra et al., 2023). Considering only climate factors when assessing litterfall production may result in a biased prediction due to excluding biotic features (Liu et al., 2019).

Forest litter accumulation above the ground was expected to rise due to higher atmospheric carbon dioxide (CO_2) levels, increasing air temperatures, and changing rainfall patterns. Since litterfall represents a significant carbon transfer from vegetation to soil, alterations in litter inputs will likely have far-reaching effects on soil carbon dynamics. These disruptions to the carbon balance could be significant in tropical regions, as tropical forests hold nearly 30% of the world's soil carbon, making them a crucial part of the global carbon cycle (Sayer et al., 2007). Despite this, the impact of heightened aboveground litter production on belowground carbon dynamics is poorly understood.

This study addressed a recommendation identified in earlier studies conducted by Liu et al. (2019), Giweta (2020), and Putra et al. (2023). It examined the relationship between litterfall and stem growth, considering how these factors are influenced by changes in soil moisture and meteorological conditions. We analyzed monthly stem diameter growth, seasonal litter data, and daily meteorological data to assess their effects on forest growth and health. Instead of differentiating fallen litter by its organ, we measured the total weight of accumulated litter biomass by season, taking a holistic approach. This accumulated litter will eventually decompose into humus on the forest floor. The study was conducted over a year, aligning with local seasonal changes. By evaluating the total amount of litter biomass produced, we aimed to understand the role of fallen litter in the forest ecosystem. This information can be particularly valuable for developing sustainable forest management practices that promote forest growth and regeneration while minimizing environmental impact.

2. Materials and Methods

2.1. Study Site

The study site features distinct local climatic divisions that reflect its lowland tropical climate. The dry season spans a duration of eight months, beginning in early April and continuing until late November. This dry season is divided into two phases: the first dry season, which runs from early April to late July, and the second dry season, occurring from early August to late November. The rainy season takes place from early December to the end of March. These climatic variations significantly contribute to the rich diversity and complexity of the site's ecology, ultimately influencing natural processes of vegetation growth in the region. The study was carried out in UNHAS Educational Forest, located on Sulawesi Island, Indonesia, between the coordinates 119˚44'34"E to 119˚46'17"E and 04˚58'7"S to 05˚00'30"S (**Figure 1**). This region was a tropical lowland forest comprising both plantation and natural vegetation (Putra et al., 2023). In 2022, the study area experienced an annual precipitation of 1890 mm, with a mean air temperature of 25.0˚C. The maximum air temperatures were recorded in August (31.2˚C) and September (32.8˚C). The study area covers a total of 1453.54 ha. A significant portion of this land, amounting to 68.09% (or 989.67 ha), was designated as a

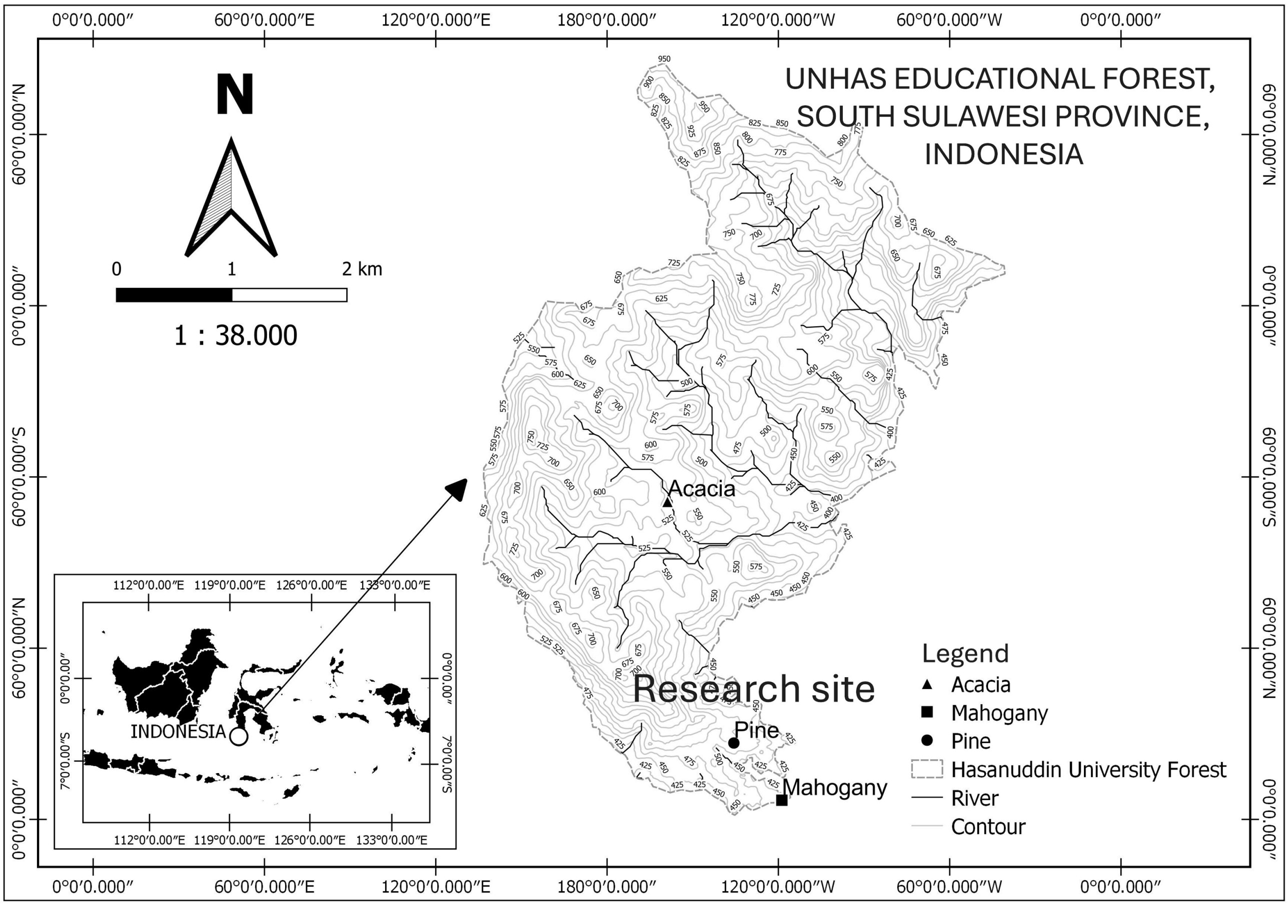

Figure 1. Study area in UNHAS Educational Forest.

natural mixed forest. The evergreen conifer forest, such as *P. merkusii* forest and other species, comprises 21.09% (306.61 ha). However, this area has experienced poor management. Smaller areas include evergreen broadleaf hardwoods such as *Swietenia macrophylla* forest at 0.17% (2.47 ha) and *Acacia auriculiformis* forest at 0.34% (5.01 ha), demonstrating efforts to diversify the forest composition. Shrubland accounts for 4.31% (62.58 ha), while open areas comprise 2.54% (36.94 ha), likely used for grazing and recreational activities. Agricultural land includes paddy fields at 1.98% (28.80 ha) and other cultivated fields at 1.17% (16.95 ha). Additionally, residential areas occupy a modest 0.31% (4.52 ha).

Plot locations were chosen based on representativeness and field conditions. The altitude at 494 msl closely resembles natural forests due to the absence of long-term forest management activities since their establishment. This has allowed the trees to grow naturally, resulting in vegetation that matches the size and composition of the surrounding natural forests. Previous research revealed that the *P. merkusii* stand was 62 years old, with average stem diameter and tree height of 66.52 cm and 24.0 m, respectively. The stem biomass potential was 208 $Mg \cdot ha^{-1}$. The *P. merkusii* forest occupies a total area of 307 ha. Tree distance was irregular, and there were understorey stands in the plots. Additionally, the stand had a basal area of 22.9 $m^2 \cdot ha^{-1}$ and a stand density of approximately 304 $trees \cdot ha^{-1}$ (Dalya et al., 2023).

2.2. Experimental Design

The plot size was 0.25 ha (125 × 20 meters). We have installed rainfall tipping buckets, air temperature, air humidity, and solar radiation sensors for meteorological monitoring (Figure 2(a)). The gauges were placed in an open area, free from shade and obstruction, at a height of 4.2 m above ground. The distance between the rain gauge and the observation plot was less than 200 m. We utilized dendrometer bands installed on nine individual trees inside the plot to measure the stem diameter at breast height (DBH) growth (Figure 2(b)). We set up aboveground litter traps-tools design, positioning, and determining the number of litter traps. We randomly positioned eight traps to monitor the litter production beneath the tree canopy (Figure 2(c)). Additionally, we inserted the SWC probes to monitor soil moisture on site (Figure 2(d)).

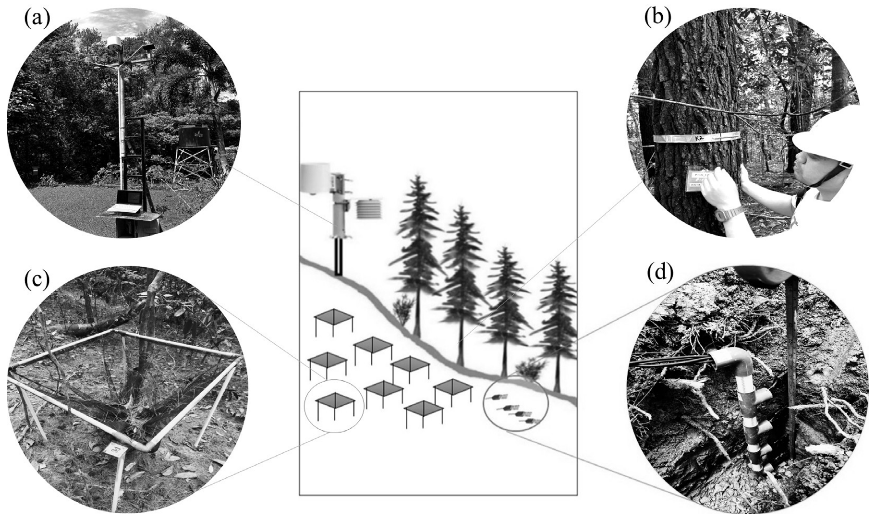

Figure 2. The installation of instruments: (a) Meteorological station; (b) Dendrometer band; (c) Litter trap; and (d) Soil moisture sensor. The sensor probe was inserted vertically into the soil layer to minimize its influence on the water movement of the soil profile.

2.3. Data Collection

2.3.1. Meteorological Variables

Meteorological variables, including air temperature (T_a), precipitation (P), air humidity (RH), and solar radiation (SR), were obtained from the station installed and recorded data for over a year of measurement (April 13, 2023-December 1, 2024). T_a and RH were recorded using a thermometer decagon sensor (ATMOS-14, METER Group, Inc., USA). We did not use relative air humidity (RH) for analysis; instead, we converted it into the actual vapor pressure of air (e_a). We calculated the e_a based on T_a and RH data. On the other hand, precipitation was measured using a tipping bucket-type rain gauge (ECRN-100, METER Group, Inc., USA). We used the pyranometer sensor to measure solar radiation energy (PYR, METER Group, Inc., USA). The station pole height was 4.2 m and installed in an open area free from shading by surrounding trees and other obstructions. The meteorological data was recorded automatically on the Em-50 data logger, which stored data every minute.

2.3.2. Soil Moisture

We used four soil water content (SWC) sensors: 5-TE, METER Group, Inc., USA, to measure soil moisture in varying depths, and the data collection frequency was set to once every minute. Soil moisture was measured at four depths starting from the topsoil ($Z_{0\ cm}$). The sensors were positioned at the following depths: 12.5 cm, which we consider as layer 1 ($Z_{12.5\ cm}$), 22.5 cm for layer 2 ($Z_{22.5\ cm}$), 32.5 cm for layer 3 ($Z_{32.5\ cm}$), and 42.5 cm for layer 4 ($Z_{42.5\ cm}$). According to the activity depth of *P. merkusii*, four monitoring probes were placed 224 m away from the meteorological station. The probes installed in each soil layer can monitor real-time moisture changes. Data analysis involved creating graphs using Microsoft Excel for Microsoft 365 MSO Version 2409.

2.3.3. Stem Growth

Evaluating the dynamics of tree radial growth was essential to enhance our comprehension of how forest species respond to stimuli and variations in meteorological conditions. Hence, dendrometer bands have been applied to study tropical species. We used nine dendrometer bands made of aluminum plates to observe the stem diameter changes, which were classified as large, medium, and small. We classified the three criteria based on tree trunk size as we aimed to observe size variability to accurately capture how trees of a certain size grow over time. It is also possible to more accurately compare growth between groups of trees that are similar in size as well as identify patterns of growth by size. Those were recorded at the end of each month, including repairs to equipment damaged by moisture and deterioration of materials. The dendrometer bands were installed on the trunks at a fixed height of 1.30 m above the ground. The bands were made up and used following the recommendations described in (Flumignan et al., 2023). The DBH was measured using Equation (1):

$$DBH = CBH / \pi \tag{1}$$

where DBH is the stem diameter at the breast height (cm), and CBH is the circumference at the breast height (cm). The DBH data was used to evaluate the stem diameter growth of the individual *P. merkusii* from the different trunk sizes. It was done by determining the diameter increment that occurred between two consecutive readings, using Equation (2):

$$DBH_i = DBH_{final} - DBH_{previous} \tag{2}$$

where DBH_i is the stem diameter increment observed between two consecutive readings (cm), DBH_{final} is the stem diameter at the breast height on the late reading (mm), and $DBH_{previous}$ is the stem diameter at the breast height on the early reading (mm).

2.3.4. Litter Accumulation

The trap capacity was one cubic meter, with a length, width, and height of one meter each. The nets used for litter traps were made of nylon material with a mesh size of 2 mm. The construction of standard-design aboveground litter traps using PVC pipe. We placed each trap underneath the tree canopy and randomly scattered it inside the plot. We collected all the litter inside the frame. Pieces of twigs or branches that cross the frame's border should be cut using a knife or pruning scissors. Then, we placed all the litter on a tarp beside the frame or inside a weighing bag. Where sample bulk was excessive, the green weight of the total sample recorded in the field and a sub-sample of a manageable size (80 - 100 g) should be taken for moisture content determination, from which the total dry mass can be calculated (Pedroni, 2011). Then, we dried sub-samples at 80˚C for 24 hours at a constant weight in the oven. We installed the litter traps in April 2023 and collected the litter captured on the last day of each following month.

2.4. Data Analysis

We computed descriptive statistical parameters for the collected data, including the mean, standard error, and coefficient of variation (CV). The Lilliefors test assessed the normality and homogeneity of variances in the experimental datasets. We used nonlinear regression analysis with a polynomial model to analyze the influence of meteorological variables on litter production. Specifically, nonlinear regression was utilized to identify the impact of meteorological conditions on stem growth and litter fluctuations in both the dry and wet seasons. Polynomial regression can yield more precise predictions by accommodating these nonlinear relationships in Equation (3), particularly when the dependent variable is affected by several complex interacting factors (O'Brien & Silcox, 2024). We can establish a curve that closely conforms to the actual data through polynomial regression, accurately depicting growth and litter production trends. The performance of regression models was assessed using the goodness-of-fit statistics (Cysneiros et al., 2021): root mean squared error (RMSE, Equation (4)) and coefficient of determination (R^2, Equation (5)) as follows:

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \beta_3 x^3 + \beta_n x^n \quad (3)$$

$$\text{RMSE} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2} \quad (4)$$

$$\text{R}^2 = \frac{\left(n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)\right)^2}{\left(n\left(\sum x^2\right) - \left(\sum x\right)^2\right)\left(n\left(\sum y^2\right) - \left(\sum y\right)^2\right)} \quad (5)$$

where y = the dependent variable for monthly mean dry litter (D_L); x = the independent variable; β_0 = the constant of the polynomial regression; β_i = the regression coefficient corresponding to the variable; y_i = the actual value for the i^{th} observation; $\hat{y}_i$ = the predicted value for the i^{th} observation; and n = is the number of observations. The prediction accuracy was assessed using mean error (ME, Equation (6)) and mean absolute percentage error (MAPE, Equation (7)) (Sileshi, 2014):

$$\text{ME} = \frac{1}{n}\sum_{i=1}^{n}\left|y_i - \hat{y}_i\right| \quad (6)$$

$$\text{MAPE} = \left(\frac{1}{n}\sum_{i=1}^{n}\left|\frac{yi-\hat{y}_i}{yi}\right|\right)\times 100\% \quad (7)$$

We performed an analysis of both biotic and abiotic factors to evaluate their influence on monthly litter production, utilizing the coefficient of determination (R^2). We also consider the relationships of the variables substantial enough to impact the accumulation of litter on the forest floor. The monthly mean dry litter (D_L) prediction accuracy was high when the RMSE and MAPE values were low.

3. Results

3.1. Temporal Pattern of Meteorological Variables

The monthly average maximum air temperature during the first dry (April to July), second dry (August to November), and rainy seasons (December to March) was 29.8˚C, 32.0˚C, and 29.8˚C, respectively. The highest maximum air temperature reached 36.2˚C in October 2023. The average minimum air temperature during the first dry, second dry, and rainy seasons was 17.7˚C, 18.3˚C, and 20.9˚C, respectively (**Figure 3(a)**). The minimum air temperature reached 16.6˚C in August 2023. The monthly average solar radiation during the first dry, second dry, and rainy seasons was 151.02, 193.44, and 99.39 $W \cdot m^{-2}$, respectively (**Figure 3(b)**). The average relative air humidity during the first dry (April to July), second dry (August to November), and rainy seasons (December to March) was 87.8, 71.9, and 90.6%, respectively (**Figure 3(c)**). The precipitation during the first dry, second dry, and rainy seasons was 502.0, 172.0, and 2012.2 mm, respectively. The highest monthly precipitation intensity was 916.0 mm in January 2024, and the maximum daily precipitation intensity was 151.4 $mm \cdot d^{-1}$ (**Figure 3(d)**).

3.2. Soil Moisture Changes

Daily changes in soil moisture in all layers showed differences that were influenced by water availability (**Figure 4**). Under moist conditions (SWC = 40% - 45%), the soil water content shows a fluctuating pattern. When it rains, the soil in layer 1 to layer 3 shows the fastest response due to the infiltration. The infiltration process was influenced by soil texture, slope, and soil depth. Furthermore, the content of organic matter in the form of litter also affects the infiltration rate in the soil. The more organic matter content, the better the infiltration process in the soil. This can also slow down the surface runoff rate on the forest floor. During this period, the average soil moisture in each layer (layers 1 to 4) was 29.25%, 32.71%, 30.76%, and 16.43%, respectively. After the rain, from July to October 2023, the water movement in layer 2 showed a staircase-like pattern, even in dry conditions, in contrast to the water movement in other layers (**Figure 4**). We assume this was due to the capillarity of groundwater due to evaporation or other factors that need to be further studied.

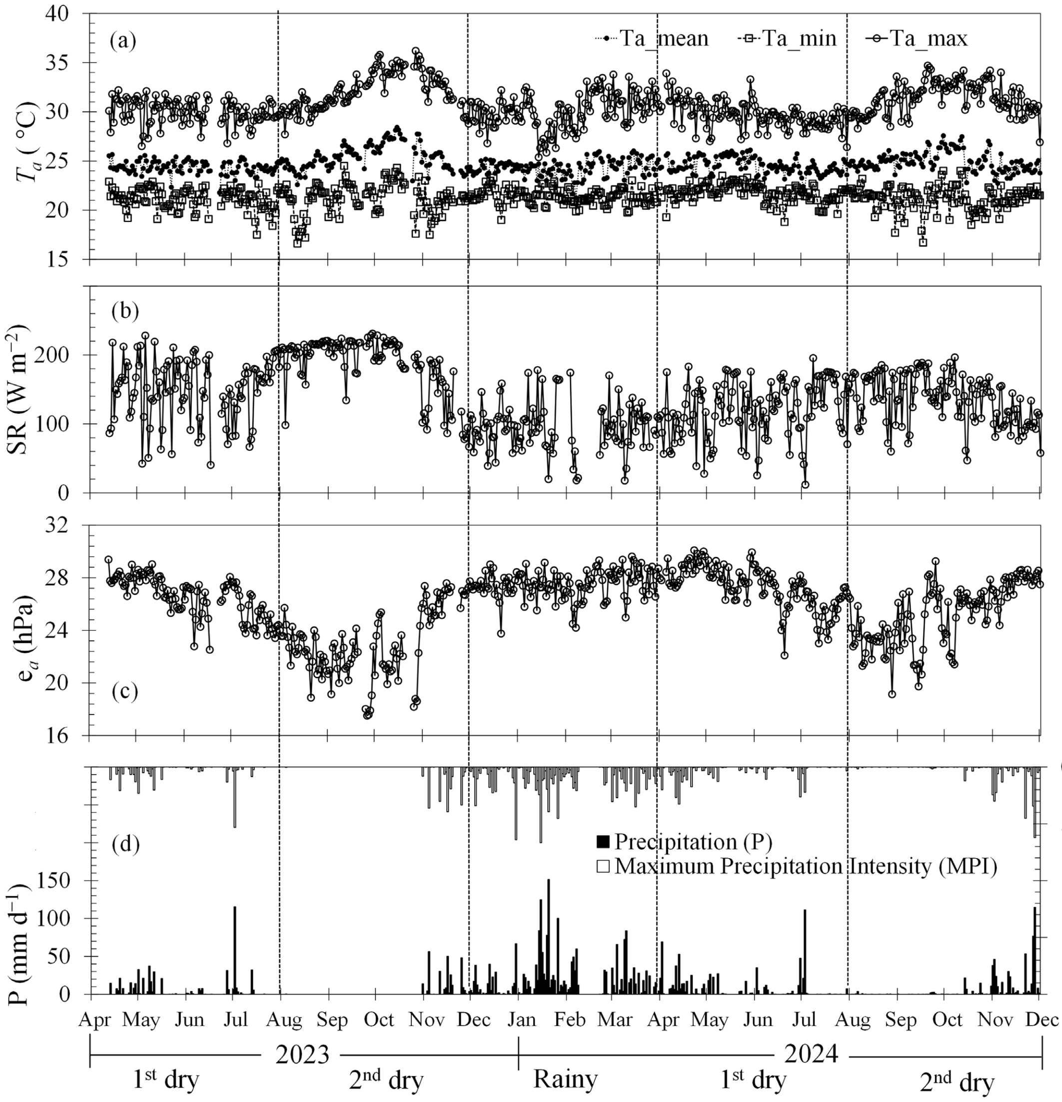

Figure 3. The variations of meteorological conditions from April 13, 2023 to December 1, 2024: (a) Daily minimum air temperature (T_a_min); mean air temperature (T_a_mean); maximum air temperature (T_a_max); (b) Daily average solar radiation (SR); (c) Daily average vapor pressure of air (e_a); and (d) Daily precipitation (P); hourly maximum precipitation intensity (MPI). The long vertical dashed line indicates the local seasons.

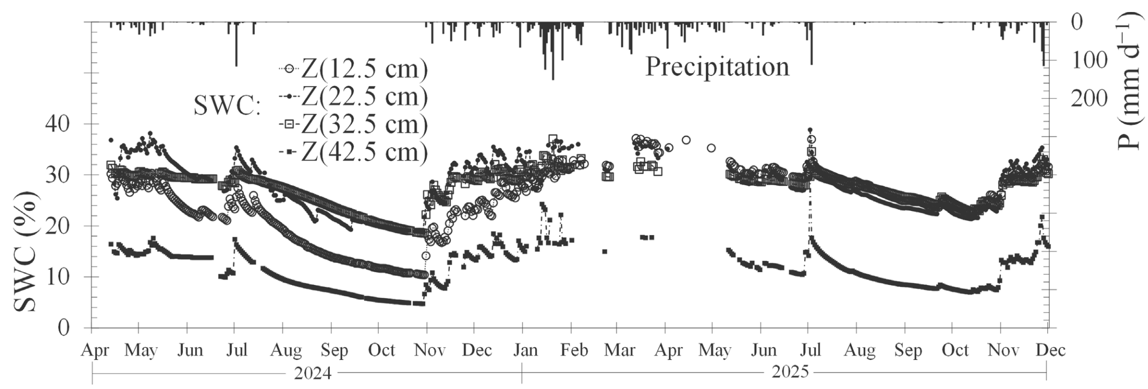

Figure 4. Daily variation of soil moisture changes in four different soil layer depths of *P. merkusii* from April 13, 2023 to December 1, 2024.

Under dry conditions (SWC = 10% - 20%), soil moisture in all layers showed a significant downward trend (July to November 2023), resulting in a decrease in soil moisture content. During this period, the average soil moisture in each layer (layers 1 to 4) was 18.84, 26.38, 26.03, and 10.28%, respectively. The highest soil moisture was shown in layer 2, layer 3, layer 1, and layer 4, respectively. The low moisture condition in layer 1 might be due to environmental factors, as it was directly exposed to external conditions. We also suppose that layers 2 and 3 represent the process of clay accumulation that allows water to be bound by the clay particles, causing the entry of water into the next layer (layer 4) to be slow. The deeper the soil (up to one meter deep), the slower the infiltration process will be, affecting reduced soil moisture.

The boundary at which water becomes unavailable to plants is said to be 10% - 15% (Raveendra Kumar et al., 2017), which occurred in layer 4 in this study from the middle of July to last November 2023 and 2024. The ideal condition for trees to obtain water is when the water in the soil is at field capacity. On the other hand, the effective rooting depth of *P. merkusii* reaches five meters (Forest Inventory and Planning Institute, 1996). In other words, this study suggests that *P. merkusii* can only obtain water at a depth of less than one meter in dry conditions.

During dry conditions, soil moisture may continue to decline in the long term. The results showed the same trend of decreasing soil moisture patterns from July to November 2023 and 2024. From February to May 2024, data leakage occurred due to water seeping into the data logger, which caused the battery storage to become wet. This damage was caused by rainwater seepage, which disrupted the functionality of the data logger and resulted in data loss during the specified period.

3.3. Stem Diameter Growth in *P. merkusii*

Stem diameter growth (DBH_i) was less apparent during the dry season but became significant during the rainy season (December 2023 to June 2024). From April to November, we observed changes in DBH based on small, medium, and large tree diameter sizes. Small-diameter trees (**Figure 5(a)**) showed a significant increase in DBH, probably due to heavy rainfall. These trees grew the most during wet periods, suggesting that *P. merkusii* was quite sensitive to dried conditions. Medium-diameter trees (**Figure 5(b)**) had a moderate growth pattern. We think this was also influenced by rainfall. The DBH_i in medium trees was less than that of small trees. In contrast, large-diameter trees (**Figure 5(c)**) grew the slowest and showed the most stable increase in DBH. Their growth response to rainfall was low, suggesting that factors like nutrient accumulation and tree conditions may matter more.

Our study found that the average mean stem diameter growth of *P. merkusii* on Sulawesi Island was 0.99 $cm \cdot y^{-1}$ in 2023 and increased to 1.88 $cm \cdot y^{-1}$ in 2024. Our analysis showed that small trees have a greater diameter growth rate than medium and large-tree pines. Specifically, small trees experienced diameter

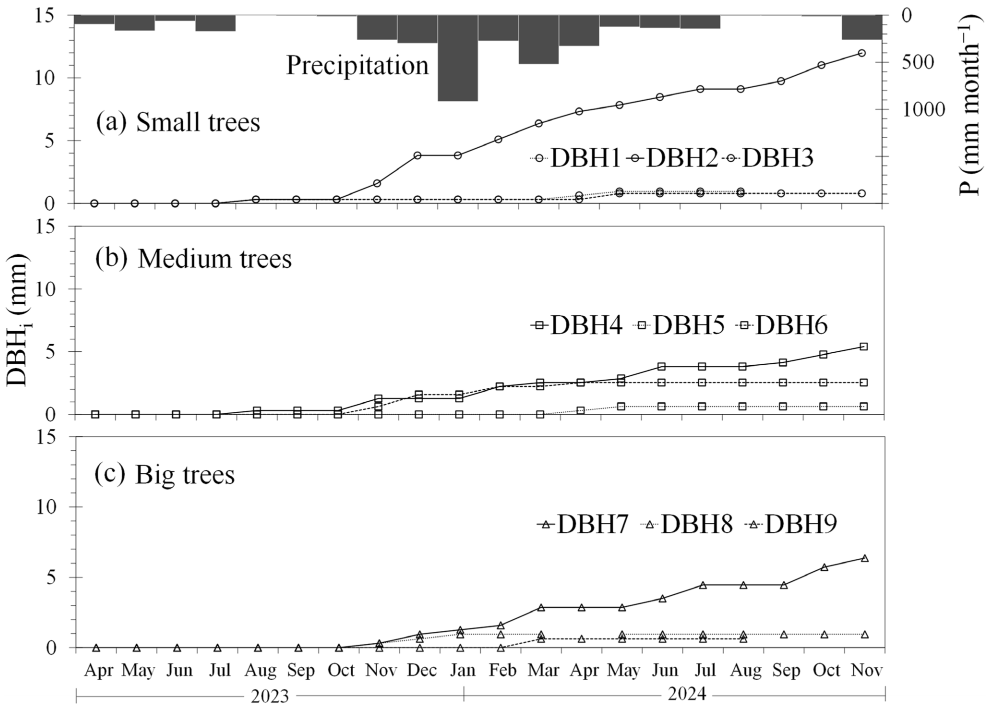

Figure 5. Monthly variation of stem diameter growth (DBH_i) individuals' trees of *P. merkusii*.

increases of 1.5 cm·y^{-1} in 2023 and 2.2 cm·y^{-1} in 2024. In contrast, medium-trees showed increases of 0.96 cm·y^{-1} and 1.38 cm·y^{-1} for the respective years. Meanwhile, large trees had growth rates of 0.53 cm·y^{-1} in 2023 and 2.02 cm·y^{-1} in 2024. In the dry season, the average seasonal stem diameter increments of *P. merkusii* were as follows: small trees were 0.19 cm, medium trees were 0.16 cm, and large trees were 0.05 cm each season.

In the wet season, the diameter increments for small, medium, and large trees were recorded to increase by 0.45 cm, 0.24 cm, and 0.32 cm per season, respectively. Darmawan et al. (2018) reported that the average breast height diameter of *P. merkusii* on Northern Sumatra Island at the age of 40 years is approximately 38 cm. At this age, the branch-free trunk height ranges from 8 to 10 meters. Consequently, the mean diameter growth rate is about 0.95 cm per year (0.37 inches per year), indicating that *P. merkusii* is a fast-growing wood species.

Additionally, Buckley et al. (2007) found that *P. merkusii* from the Phu Khao Khouay National Biodiversity Conservation Area, northeast of Vientiane, showed a negative correlation with rainfall in June of the previous year and a positive correlation with maximum air temperatures in August and September. The annual radial increment also showed a significantly negative correlation with the percent cloud fraction, suggesting that light availability may adversely affect growth rather than be positively influenced by high air temperatures. Moreover, Teck and Hilt (1990) reported that the growth rates for the diameters of red pine, white pine, Virginia pine, and loblolly pine were 0.35, 0.40, 0.29, and 0.31 cm·y^{-1}, respectively. The differences in diameter growth among these pine species can be attributed to various factors, including genotype, environmental and meteorological conditions, and the interactions between these variables.

3.4. Seasonal Litter Accumulation in *P. merkusii*

The results showed that litter accumulation varies every month (Figure 6). In 2023, litter accumulation started to continuously increase from May until it peaked in October, then decreased in the following months until December. At the beginning of 2024, entering the rainy season, the accumulation of litter decreased gradually until July. It increased significantly, reaching the highest peak in August and October and decreasing slightly in November. Data analysis showed litter accumulation peaking in October 2023 (1.07 Mg·ha^{-1}). The average monthly litter production during 2023 and 2024 was 0.75 Mg·ha^{-1} and 0.69 Mg·ha^{-1}, respectively. At the end of the dry season, monthly litter production increased to about 1.5 times the annual average of monthly production. This pattern suggests a seasonal litter fall phenomenon, probably influenced by climatic factors and tree physiology. A year-to-year comparison showed that October consistently recorded the highest litter production. However, there was a slight decline in 2024 (0.91 Mg·ha^{-1}). This decline could be due to weather variability between years or changes in forest dynamics. The data also suggested an increasing trend in litter accumulation before the rainy season, which may be due to seasonal leaf and litterfall.

In contrast, the first dry season of 2024 showed lower litter compared with 2023, which may reflect the impact of meteorological conditions on forest growth and litterfall. Overall, the annual litterfall of *P. merkusii* amounted to 8.45 Mg·ha^{-1}. According to local climatic divisions, the monthly average litter production during the first dry, second dry, and rainy seasons was 0.65, 0.82, and 0.72 Mg·ha^{-1}, respectively. We also found that the litter that fell during the dry season was mostly reproductive organs such as cones. This is one of the reasons for the significant increase in litter weight compared with other months.

Putra et al. (2023) reported that the peak litter production of *P. merkusii* litter on Sulawesi Island occurs in the dry season, with an annual litterfall of 12.88 Mg·ha^{-1}. Gunadi (1994) also reported that the *P. merkusii* forest plantation on Mount Merapi in Central Java had an annual litterfall of about 9.0 Mg·ha^{-1}. Bruijnzeel (1985) observed that in the same region of Central Java, dense *P. merkusii* plantations produced a significantly higher annual litterfall of 10 Mg·ha^{-1}, of which

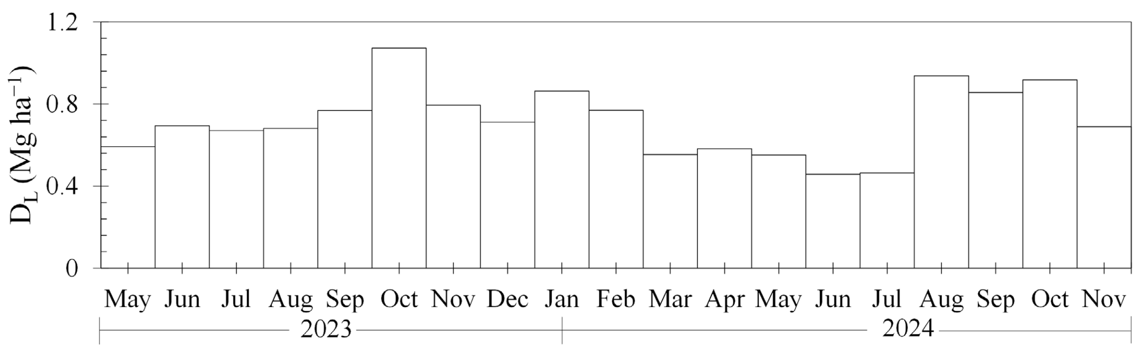

Figure 6. The monthly variation of accumulated litter (DL) in *P. merkusii*.

5.5 Mg·ha^{-1} came from needles. Berg et al. (1999) also measured litterfall in several pine forests across a European transect, explicitly focusing on Scots pine. Their findings indicated an annual litterfall ranging from 1.21 Mg·ha^{-1} to over 6.60 Mg·ha^{-1}, which is relatively low compared with our study.

In comparison, the annual litterfall reported by Putra et al. (2023) was higher than that measured in our studies and some previous studies. This discrepancy may be attributed to various environmental factors, including meteorological conditions, litter trap site selection, the model and size of the aboveground litter traps used, tree density, basal area, and the age of the stands. Nonetheless, all studies consistently demonstrate that *P. merkusii* produces a significant amount of litter in the dry season.

3.5. Analyzing How a Litter Accumulation Relates to DBH$_i$, SWC, and Meteorological Conditions

Analyzing the overall data from the graph showed complex relationships of monthly litter accumulation (D_L) to various environmental variables, offering a comprehensive understanding of the factors influencing seasonal litter patterns of *P. merkusii* (**Figure 7**). This study showed that during the dry season of 2023, the D_L trend corresponded to the rise in the average T_a, reaching its peak in October. When the rainy season began in December, there was a significant decrease in D_L, and T_a also tended to decrease. T_a affects D_L from August to October with a significant positive relationship and from November to January with a significant negative linear relationship. Although *P. merkusii* is not a deciduous conifer, this research showed that the conifer sheds its leaves, branches, and cones in a maximum amount at the end of the second dry season (October). However, this study suggested that precipitation (P) did not affect D_L beneath the pine canopy. The R^2 value for monthly precipitation (P) was 0.272, indicating a weak to moderate positive correlation. This suggests that while rainfall does affect litter accumulation, other factors may play a more significant role. The daily maximum precipitation intensity (MPI) had an R^2 value of 0.332, showing a moderate positive correlation. Although intense rainfall events can increase litterfall due to physical damage to foliage, our study suggests that the relationship between these two variables was not particularly strong. The monthly average vapor pressure of air (e_a) displayed a weak correlation with an R^2 value of 0.239, suggesting that while higher humidity levels promote tree growth, e_a did not significantly affect litter fall during this study.

The monthly maximum air temperature (T_a_max) positively correlated with D_L, with a coefficient of determination (R^2) of 0.502. This suggests that higher peak air temperatures can enhance metabolic activity and increase plant stress, resulting in greater litter fall. The monthly mean air temperature (T_a_mean) showed a moderately positive correlation (R^2 = 0.490), suggesting that rising monthly average temperatures might influence the monthly production of litter. In contrast, the monthly minimum air temperature (T_a_min) showed a weaker correlation

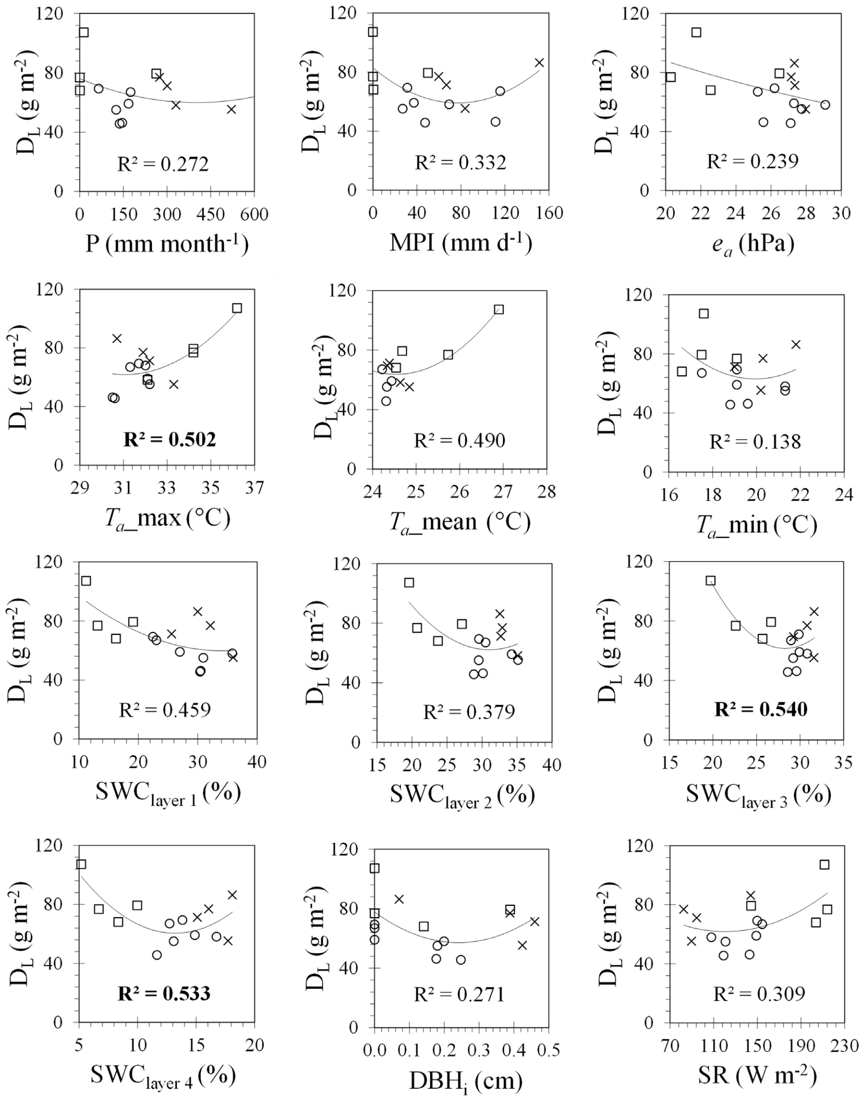

Figure 7. Relationships of monthly litter accumulation (D_L) with monthly precipitation (P), monthly maximum precipitation intensity (MPI), monthly average vapor pressure of air (e_a), monthly maximum air temperature (T_a_max), monthly mean air temperature (T_a_mean), monthly minimum air temperature (T_a_min), monthly average soil moisture in layer 1 to 4 ($SWC_{layer1-4}$), monthly average solar radiation (SR), and monthly stem diameter at breast height increment (DBH_i) of *P. merkusii*. The data was grouped based on local seasons: the first dry season (○), the second dry season (□), and the rainy season (×).

(R^2 = 0.138), suggesting that it has a limited impact on litter accumulation.

Furthermore, the analysis showed a negative correlation between monthly average soil moisture and monthly litter accumulation. Specifically, the soil moisture in the top layer (SWC_{layer1}) had an R^2 value of 0.459, suggesting a moderate to strong correlation to litter fall. Adequate moisture in the topsoil was essential for tree health and litter production. Monthly average soil moisture content in layer 2 (SWC_{layer2}) showed a moderate influence with an R^2 value of 0.379, which certainly also influenced tree growth. The monthly average soil moisture content in layer 3 (SWC_{layer3}) had a negative correlation (R^2 = 0.540), highlighting the importance of deeper soil moisture for tree survival and consistent litter fall. The monthly average soil moisture content in layer 4 (SWC_{layer4}) also showed a positive correlation (R^2 = 0.533), suggesting the role of moisture in the deepest soil layers in maintaining tree health during drier periods.

Other factors, such as monthly average solar radiation (SR), showed a moderate positive correlation (R^2 = 0.309), suggesting the importance of sunlight for photosynthesis and overall plant productivity, leading to more litter fall. Finally, monthly diameter at breast height increment (DBH_i) had an R^2 value of 0.271, indicating a weak to moderate positive correlation. Although tree growth and tree age may influence litter production, this study suggested that other environmental factors were more significant.

4. Discussion

4.1. Influence of Meteorological Conditions on Stem Growth and Litter Accumulation

Studies have found a negative correlation between D_L and SWC. Our study suggested that the decrease in soil moisture corresponds to increased monthly litter accumulation. The air temperature correlates with litterfall, specifically maximum air temperature. A significant increase in air temperature will contribute to the increase in litterfall. In tropical lowland forests, high air temperatures can accelerate litter decomposition, while excessive moisture due to rainfall can lead to anaerobic conditions, slowing the process. While there appears to be a positive linear relationship between solar radiation and litter production, the relationship remains quite weak. Furthermore, despite an apparent positive linear relationship, monthly litter production did not show a strong relationship with either precipitation or maximum precipitation intensity.

The daily changes in water content in four soil layers (**Figure 4**) showed distinct characteristics that help us understand water movement in the *P. merkusii* soil. During the dry season, soil moisture most probably affects the accumulation of litter biomass. This analysis showed that a significant decrease in layers 3 and 4 correlated with increased litter, R^2 = 0.540. The model equation was also tested, and a fairly good predictive value with a small RMSE was found. This certainly makes the model reliably applicable for predicting the value of monthly litter falls through soil moisture decline in tropical lowland *P. merkusii* forests. Our findings also address a suggestion from a previous study (Liu et al., 2019), which recommended measuring soil moisture and its effect on variations in litter accumulation.

Moreover, in wet conditions, soil water content displays a fluctuating pattern. While dry conditions can slowly decompose litter, potentially leading to a build-up of litter biomass. This balance was critical to maintaining the ecophysiology and sustainability of forest ecosystems. In addition, interactions between soil moisture and other factors, such as air temperature and understory presence, might also influence changes in litter biomass. These interactions are complex and can vary depending on the specific conditions of the forest ecosystem, highlighting the importance of much more comprehensive studies to understand the impact of soil moisture on forest litter biomass, such as monitoring the litter decomposition process during the dry season, as well as conducting periodic monitoring of soil moisture changes at deeper depths corresponding to the effective rooting of *P. merkusii* trees.

The average soil moisture in the upper layer was much greater than the lower layer in moist conditions or during the rainy season. The soil layer from layer 1 to layer 2 was closest to the surface, where the main root activity of understory or aboveground vegetation occurs, and water moves upward through evapotranspiration. We were unable to determine whether these results are comparable to previous studies in the same region and climate due to the fact that we had not specifically found any similar studies. Furthermore, optimal soil moisture can enhance litter decomposition, contributing to nutrient cycling and forest floor dynamics. Variations in soil moisture content can significantly alter microbial activity, thus impacting the decomposition process. For example, increased soil moisture can increase microbial biomass, leading to faster decomposition rates of litter. Research in this area not only contributes to our ecological knowledge but also informs forest management practices aimed at conserving these vital ecosystems.

In *P. merkusii* forests, as forest ecosystems, larger tree diameters typically correlate with higher biomass, including litter biomass. This study showed that small—and medium-diameter trees had more increase in girth in response to rainfall than large-diameter trees. The changes in the dendrometer bands during the rainy season might be caused by a radial growth response of the stem in the measurement device. Several possible reasons for this significant stem increase include water-induced expansion and irreversible woody growth (cell wall extension and cell division). During the rainy season, the girth increased ($R^2 = 0.413$), while the amount of litter fluctuated. We also investigated the relationship between the DBH_i and D_L. We conducted a nonlinear regression analysis showing a weak correlation between DBH_i and D_L ($R^2 = 0.271$, see **Figure 7**).

On the other hand, the monthly mean air temperature (T_a_mean) did not have a strong enough relationship with the fluctuation pattern of the monthly increment of all diameter classes ($R^2 = 0.120$). The presence of rainwater entering the bark through stem flow could be the leading cause of the increase in the circumference of *P. merkusii* trunks. The abundance of water also allows trees to grow more than in dry conditions. This happens because trees rely on water not only for hydration but also to transport nutrients from the soil throughout their structure. When rainwater falls in abundance, trees may be able to carry out more active photosynthesis and growth, producing a thicker xylem layer. The woody tissue was responsible for water transport throughout the tree's structural parts, ultimately forming an annual growth cycle.

However, it is necessary to note that while precipitation can contribute to the tree growth, it is not the only factor. Other factors, such as air temperature, soil fertility, and the genetic composition of the tree itself, also play an essential role in the growth process. In addition, events such as drought or severe seasonal in the tropics can also influence stem diameter growth. The dynamics of competition among individual trees also can significantly affect the growth and development of their stems. When several trees are positioned closely together, they compete for essential resources such as sunlight, water, and nutrients from the soil. This struggle for survival can lead to changes in stem growth. For example, trees in shaded areas may exhibit stunted growth or develop elongated stems as they reach the light source.

Based on our results, the monthly stem diameter increase did not have a strong enough relationship with the monthly accumulation of litter falls. In contrast, the increase in stem dimension aligns with the increase in stand age. However, previous research (Liu et al., 2019) mentioned that litter production was closely related to stand age. Mature trees can produce more litter than young trees.

We suggest that longer period studies are needed to see a more robust relationship between stem diameter increments and seasonal litter accumulation on the forest floor. We believe that long-term studies can find gradual changes or trends that might not be apparent in short-term studies. The long-term impact of changing meteorological conditions on stem growth and litter dynamics can be more accurately assessed over extended periods (it would be more than 5 years). More data collected over a longer period increases the robustness and reliability of the study findings. This helps to reduce the influence of outliers or anomalies and provides a clearer picture of the underlying relationship.

This seasonal litter pattern result addressed the earlier prediction that litter production was highest during the dry season, suggesting once again that meteorological variables such as maximum air temperature ($R^2 = 0.502$) and soil moisture ($R^2 = 0.540$) were among the main factors leading to increased litter accumulation on the forest floor of *P. merkusii* plantations. Peak rainfall occurred in January 2024. In comparison, the peak of litter accumulation occurred before the peak of rainfall in October 2023. The peak rainfall appeared to have little effect on litter falling to the forest floor. However, high rainfall can significantly affect the litter decomposition process compared with Devianti et al. (2017). The large quantities of litter that fall a couple of months before the peak of the rainy season suggest *P. merkusii*'s response to the natural decomposition process. *P. merkusii* litter was needle leaf litter with a high lignin and extractive content. It was acidic, making it difficult for microorganisms to break down. The litter will decompose naturally within 8 - 9 years (Mindawati et al., 1998). Furthermore, we suggest that large amounts of litter falling to the forest floor in the dry season also signifies the natural regeneration of trees in response to the readiness of new seeds to germinate during the rainy season.

4.2. Study Challenges and Uncertainties

The challenge of accurately estimating litterfall in forest ecosystems stems primarily from the limitations of available data sources and methodologies. The accuracy of litterfall estimates obtained from field observations was influenced by the number of individual trees and the challenges associated with data collection. Thus, future field studies should prioritize larger sample sizes and extended observation periods. Furthermore, in-depth investigations into the effective rooting of *P. merkusii* trees could serve as a valuable indicator, mainly by installing deeper soil moisture sensors to enhance our understanding of the correlation between soil moisture and accumulated litter production.

The interplay of litter accumulation to stem growth, soil moisture, and meteorological conditions is complex. The coniferous may produce more litter due to the dry conditions. Still, if soil moisture is inadequate, the increased litter may not decompose efficiently, potentially leading to a build-up of organic material.

Our study has shown that decreasing soil moisture conditions and increasing air temperature can demonstrate the highest potential for forest litter production, suggesting that the dry conditions can be harmful to tree growth and litter biomass changes. Understanding the specific impacts of these factors on *P. merkusii* forests is necessary for sustainable forest management and conservation efforts. Further research is needed to quantify the robust relationships among these variables and develop predictive models that inform forest management practices in tropical lowland regions.

5. Conclusion

Based on nearly two-year observations of litterfall production, we found that the highest *P. merkusii* litter production occurs in the dry season, peaking in October ($1.07\ Mg \cdot ha^{-1}$). This was suggested due to the reduced availability of monthly average soil water content in the depth layers (layers 3 and 4) and the increased monthly maximum air temperature (T_a_max), causing the *P. merkusii* response to shed leaves, branches, and cones to minimize evapotranspiration. Our study also suggested that monthly stem diameter growth had little effect on litterfall. Increased rainfall during the rainy season can possibly affect the girth growth of *P. merkusii*. Water ingress into the bark or radial growth of the stem itself may cause circumferential enlargement and changes in stem size. Monthly precipitation and daily maximum precipitation intensity also did not significantly contribute to the increase in litter on *P. merkusii*. The relationship between these two variables was not very strong. The influence of other meteorological conditions on increasing litter production, such as monthly average air temperature, monthly minimum air temperature, monthly average solar radiation, monthly average air humidity, and monthly average soil moisture in the top layer, was not strong enough.

Furthermore, litter production was necessary for the carbon cycle in the soil and as a form of tree response to overcome the unavailability of water in the soil by shedding some organs to reduce excessive evapotranspiration. The amount of litter on the soil surface can also indirectly reduce the occurrence of water runoff on the forest floor. Further research over a sufficient period is needed to understand the evidence response of *P. merkusii* growth and litter production to meteorological conditions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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