Assessing Soil Nutrient and Biomass Contributions to Peatland Formation

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ABSTRACT

Peat formation is a key factor in carbon sequestration in Peat Swamp Forest (PSF). The study aims to analyze alternative pathways for peat formation based on soil nutrient availability and dried biomass accumulation. A randomized complete block design was used with two treatment factors across three blocks: (A) sampling plots representing land covers and (B) dried biomass levels. Data were analyzed using two-way ANOVA and Tukey Honestly Significant Difference (HSD) test at a 5 % significance level. Results showed a high supply of dried below-ground biomass did not correspond to increased rooting litter production under high soil nutrient conditions. Instead, most of the biomass was transported upwards into above-ground biomass. All land cover types generated above-ground biomass with significant differences in peat formation potential across all measured parameters. Peat formation was strongly influenced by land cover type (e.g., peat forest), environmental factors, seed bank composition, and species competition. Restoration strategies, including revegetation, rewetting, and revitalization, are crucial to promoting the establishment of peat-forming species. This research provides valuable insights for enhancing PSF restoration efforts and facilitating recovery toward a near-natural condition.

Keywords: Addition; Organic carbon; Peat development; Soil nutrients

INTRODUCTION

The Peat Swamp Forest (PSF) belongs to a unique territorial ecosystem (Imanudin et al., 2019), with groundwater that delays the complete decomposition of dead leaves and timber. This produces a thick layer of acidic peat over time. These forests are being heavily logged in large regions. PSF retain and accumulate enormous amounts of carbon, far more than trees on mineral soil or non-peatland. As organic matter decomposes more slowly than it is produced, the excess material builds up as peat, which acts as a natural carbon sink. As the greatest near-surface stocks of terrestrial organic carbon, their stability has significant implications for climate change. Ecologically significant tropical peat swamp forests are among the most endangered, least researched, and poorly known biotypes (Syakina et al., 2024a; Syakina et al., 2024b).

There are at least five PSF ecosystem values (benefits): direct values, indirect values, optional values, bequest values, and existence values (Wildayana & Armanto, 2017; Wildayana & Armanto, 2018b). Direct values include using PSF as food sources, building materials, bridges, firewood, fences, medicines, climbing sticks, and fodder. Indirect values include PSF functions, such as keeping food cycles, road infrastructure, flora/fauna habitats, flood, drought, erosion, and climate control.

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Protection of biodiversity, habitat, and agro-tourism can be optional values (Wildayana & Armanto, 2018a; Wildayana & Armanto, 2018c). Bequest values consist of the uses of PSF as shoreline safety, forestry nurseries, and inheritance. Existence values include the uses of PSF as buffering zones, protected forests, and habitats for wild, rare, and protected species (Armanto & Wildayana, 2022).

The impact of human intervention on PSF is increasingly negative and can lead to the extinction of PSF (Armanto, 2019a). Most PSFs are degraded due to drainage, logging, fire, oxidation, and pollution (Zuhdi et al., 2019). In South Sumatra, Indonesia, human exploitation has destroyed almost 25% of PSF, in which this destruction was caused by 50% of plantations, 27% by forestry, 10% by food agriculture, and 7% by industrial development and settlements (Wildayana & Armanto, 2021; Armanto, 2019b). This is receiving a lot of international attention, and, at the same time, policy and funding initiatives for restoration from the local to the landscape scale are being promoted (Byg et al., 2023).

The understanding of ecological restoration is still in its infancy, especially in its application, resulting in an imbalance between PSF restoration activities and good ecological applications (Armanto et al., 2023a; Armanto et al., 2023b). In addition, despite the many activities currently underway and information being acquired, the results of ecological restoration research have not been published (Wildayana & Armanto, 2018d; Wildayana & Armanto, 2018e). The Indonesian government has established the Peat Restoration Agency (BRG) to restore at least 2 million hectares of PSF between 2016 and 2020, with an additional 1.2 million hectares scheduled for 2020 to 2024. This agency will now be known as the Peat Restoration Agency and Mangroves (PMRA, 2022; Armanto et al., 2022). This is in response to the problems caused by PSF degradation.

PSF ecological restoration generally aims to maintain and increase carbon sequestration, prevent fires, protect water and air quality, ecosystems, and species, and protect all living things (Holidi et al., 2019; Wildayana, 2017). Hence, peat formation is the primary key to carbon sequestration in the PSF area. The development of peat-forming vegetation is a prerequisite for forming PSF (Barry et al., 2021). Swamp grass and swamp bush spread rapidly after restoration or fire. Under favorable conditions, these species can cover the entire PSF surface in 2-3 years, depending on the extent to which natural PSF species survive (Armanto et al., 2025a; Armanto et al., 2024). Research on surface peat accumulation has been carried out in many restored PSF places, and a comprehensive study on this issue is currently being carried out (Armanto et al., 2025b; Armanto, 2019c). Field surveys of the restored PSF carried out ten years after the restoration revealed varying degrees of waterlogging on the PSF surface (Kaban et al., 2024; Jing et al., 2020), with the new peat surface becoming thicker where fluctuations in the Ground Water Table (GWT) were minimal and shallow (Armanto & Wildayana, 2023).

The availability of nutrients characterizes vegetation growth. The availability of these nutrients can be caused naturally, for example, in river valleys (Lázaro-Lobo et al., 2023), or can be caused by anthropogenic eutrophication. Nutrient availability can be used to control patterns of biodiversity and the movement of dominant species. A fertile PSF can accumulate peat effectively, depending on other supporting factors, such as hydrological, biogeochemical, or microbiological constraints. The research aimed to analyze alternative possibilities for peat formation based on the available soil nutrients and dried biomass. The research novelty is to give an alternative for forming PSF based on soil nutrients and biomass availability.

MATERIALS AND METHODS

Location and Time of Research

The research was conducted in Pedamaran Sub-district, OKI District, South Sumatra, Indonesia, which is included in the Peat Hydrological Unit (KHG) of the Sibumbung-Burnai River, covering an area of 87,000 ha (Figure 1). The research was conducted from 2022 to 2024.

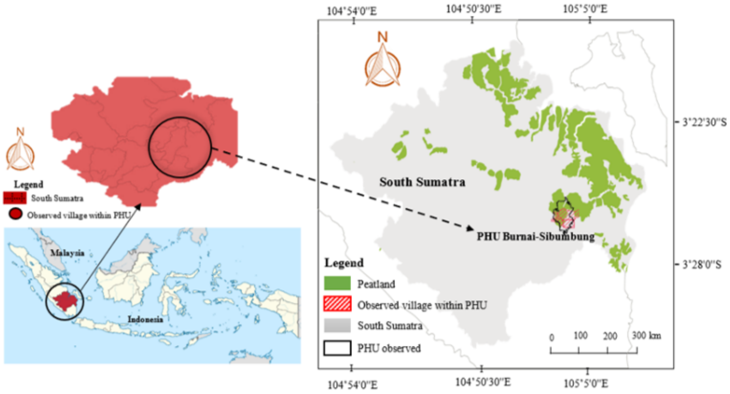

Figure 1. Research location in South Sumatra Province, Indonesia

Research Methods and Experiment Design

In a complete randomized block design, a factorial trial was applied using two treatment combinations in three blocks: factor A (sampling plots, land cover) and Factor B (dried biomass). Blocks were made according to the three-peat depths, including shallow, moderate, and deep. Factor A (sampling plots, land cover) consisted of four sampling plots as natural treatments, namely peat forest (L0), restored PSF (L1), swamp bush (L2), and swamp grass (L3). Factor B (dried biomass) consisted of above-ground dried biomass, namely dried leaves (T0); grass stalks, dried twigs, wicker, wood (T1); and below-ground dried biomass, namely root litter (T2).

Soil and Biomass Sampling

All sampling plots were located in adjacent areas with a distance of < 2000 m and elevation in the 0-3% range. Soil sampling and dried biomass data were acquired using the quadratic approach located in each treatment combination. Plot sizes were determined to be 10×10 m for peat forest and restored PSF and 5 m x 5 m for swamp grass and bush.

Data Analysis

Plant tissue samples were taken from sampling plots, and all soil samples were analyzed in the laboratory. The collected plant tissues were weighed to obtain the fresh weight. Before analysis, they were washed with ion-free water to remove dust and other impurities, dried in an oven with a fan, and cut into pieces for faster drying. The oven was set at 70 oC. Dried samples were weighed to obtain dried biomass and milled using a machine grinder with a filter with a fineness of 0.5 mm. Methods of plant tissue analysis is summarized in Table 1. Dried biomass content was calculated from the organic C content with the following formula:

$$\text{Dried biomass (\%)} = 1.74\% \times \text{organic C (\%)}$$

The conversion factor was obtained by assuming 58% organic C in the dried biomass.

Collected data were analyzed using two-way ANOVA with the SPSS Statistics 26 and the Tukey HSD (Honestly Significant Difference) Test at a significance level of 5% to determine whether there was a significant difference between treatments according to the parameters observed, namely dried biomass, organic C, total N, P, K, Ca, and Mg. The collected data and field phenomena were then extensively described and explained using tables and figures and then compared to the parameters measured from each research plot and a more detailed comparison of above-ground biomass with below-ground biomass.

Table 1. Methods of Plant Tissue Analysis

Parameter and units	Methods
Water content (%)	Oven drying
Dried biomass (kg ha^{-1})	Weigh, oven drying
Total biomass (kg ha^{-1})	Calculation: 1.74% x C organic (%)
Organic C(kg ha^{-1})	Ash method
Total N (kg ha^{-1})	Wet ash with H_2SO_4, spectrophotometer
C/N ratio	ratio calculation
Total P, K, Ca, Mg (kg ha^{-1})	Wet ash with HNO_3 & H_2SO_4, spectrophotometer

Note: C (Carbon); N (Nitrogen); P (Phosphorus); K (Potassium); Ca (Calcium): Mg (Magnesium); H2SO4 (Sulfuric acid); HNO3 (Nitric acid)

RESULTS AND DISCUSSION

Specific Descriptions of Sampling Plots

The climate of the research area is categorized as a wet climatic type of B since it has roughly seven to nine rainy months, an annual average precipitation of 2,600 to 3,300 mm, and an uneven distribution of rainfall (Stasiun Klimatologi Kayu Agung, 2025). The plains physiographic group included all sampling plots, which ranged in elevation from 0 to 3 m above sea level and in peat depth from 1.20 to 7.50 meters. Table 2 provides a detailed description of sample plots.

Table 2. Specific explanation of sampling plots

Description	Peat forest (L0)	Restored PSF (L1)	Swamp bush (L2)	Swamp grass (L3)
Wildfires	1 time	2 times	3 times	4 time
Sites	104°57′54.65″ E 3°25′20.43″ S	104°57′52.38″ E 3°25′22.84″ S	104°53'35.12" E 3°25'53.37" S	104°57'18.58" E 3°26'37.31" S
Age (years)	10-15	5-10	3-5	1-5
Height (m)	6.00-9.00	3.25-6.00	1.50-3.00	0.25-1.00
Main species	Meranti, Punak, Jelutong, Ramin, Pelawan, Medang	Jelutong, Ramin, Bush, Grass	Gelam, Pakis Udang, Kumpai, Medang, Belidang, Seduduk	Purun Tikus, Kumpai, Teki-Tekian, Seduduk, Belidang
Peat depth	3-7 m	2-5 m	1-4 m	1-4 m
GWT*/	-50 cm	-55 cm	-45 cm	-50 cm
Status	Undrained, undisturbed, unrestored	Undrained, undisturbed, restored	Drained, disturbed, unrestored	Drained, disturbed, unrestored
Field condition				

Note: */ GWT (Ground Water Table)

Peat Forest (L0)

The peat forest experienced a fire once in 2006, then was restored, even though it was not optimal, by planting Red Meranti (*Shorea balangeran*) and Punak (*Tetramerista glabra* Miq). Other growing species are Jelutong (*Dyera lowii* L.), Ramin (*Gonystylus bancanus* L.), Pelawan (*Tristaniopsis merguensis* Griff.), and Medang (*Blumeodendron kurzii* (Hook.f.) J.J.Sm). The peat forest is stable and can be protected due to degradation processing energy (rainfall and drainage).

Restored PSF (L1)

These PSF experienced two fires in 1997 and 2006 and have experienced less than optimal restoration with the planting of Jelutong (*Dyera lowii* L.) and Ramin (*Gonystylus bancanus* L.). The lower part of the tree is overgrown with swamp grass and swamp bush in the form of Kumpai *(Hymenachine amplexicaulis Rudge),* Pakis Udang (*Stenochlaena palustris*); Belidang *(Eleusine indica),* Seduduk *(Melastoma malabatrihcum);* and Teki-tekian *(Cyperus rotondus).* PSF restoration showed a low leaching process because the restored PSF had not been burnt since it was restored. The restored PSF is stable and can be protected due to degradation processing energy (rainfall and drainage).

Swamp Bush (L2)

Swamp bush has burned three times in 1997, 2006, and 2015. Swamp bush is dominated by Gelam (*Melaleuca cajuputi* Powell); Medang (*Litsea* spp); Kumpai *(Hymenachine amplexicaulis Rudge);* Pakis Udang (*Stenochlaena palustris*); Belidang *(Eleusine indica);* Seduduk *(Melastoma malabatrihcum);* and Teki-tekian *(Cyperus rotundus).* Once it was used by native farmers for subsistence farming (sonor system) to grow paddy and regional vegetables, swamp shrubs in peat domes finally developed after being neglected for five to ten years.

Swamp Grass (L3)

Swamp Grass has experienced fires four times in 1997, 2006, 2012, and 2015. Native farmers once used the sonor system of subsistence farming to grow paddy and regional vegetables on swamp grass under peat domes. After being abandoned for five to ten years, the grass eventually turned into swamp shrubs. The energy of rainfall, which severely reduces soil fertility and increases the risk of fires, mainly contributes to the ongoing degradation of peat. The natural plants that makeup swamp grass are mostly Purun Tikus (*Eleocharis dulcis* Hensch), Kumpai *(Hymenachine amplexicaulis Rudge);* Belidang *(Eleusine indica);* Pakis Udang (*Stenochlaena palustris*); Seduduk *(Melastoma malabatrihcum);* Teki-tekian *(Cyperus rotondus); Zalaca* spp, *Pandanus* spp, *Crunis* spp, and creeping species (namely *Uncaria* spp).

Dried Biomass Production

The amount of soil-dried biomass is influenced by the degree of decomposition, type of land use, and soil characteristics. Biomass, C, and N produced by plant residues (kg ha^{-1} $year^{-1}$) are presented in Table 3. Annual dried biomass production increased to natural levels within ten years after restoration, mainly due to the rapid growth of peat forest, swamp grass, and swamp bush. The average annual above-ground dried biomass production rate was around 9.985 - 25.275 kg ha^{-1} $year^{-1}$ during the first ten years. The peat forest could supply around 25.275 kg ha^{-1} $year^{-1}$ of dried biomass, compared to swamp grass supplying only 9.985 kg ha^{-1} year^{-1} (only 40% compared to dried biomass supply from peat forest), and dried leaves providing the most dominant contribution to dried biomass supply.

Table 3. Biomass, C-organic, and N contributed by plant residues (kg ha^{-1} year^{-1})*/

Interactions	Biomass	Organic C	N total	C/N
L0 T0	11,260±451^{g}	6,526±267^{i}	326.54±44.01^{g}	19.98±6.09^{a}
L0 T1	11,250±443^{g}	6,525±266^{i}	34.88±11.23^{f}	187.10±34.01^{d}
L0 T2	2,765±161^{b}	1,604±156^{a}	21.57±8.04^{b}	74.36±22.23^{b}
L1 T0	9,430±267^{f}	5,471±201^{h}	188.64±35.45^{e}	29.00±10.43^{a}
L1 T1	8,173±234^{e}	4,740±190^{g}	25.34±10.11^{d}	187.10±35.66^{e}
L1 T2	2,567±172^{a}	1,489±192^{a}	20.02±7.42^{c}	74.35±23.77^{b}
L2 T0	3,240±178^{c}	2,236±169^{c}	12.96±4.21^{a}	172.50±32.89^{d}
L2 T1	5,100±204^{d}	2,958±168^{e}	20.40±7.96^{c}	144.00±30.78^{c}
L2 T2	6,700±207^{e}	3,886±187^{f}	23.45±8.71^{d}	165.71±31.66^{cd}
L3 T0	2,115±171^{a}	1,459±89^{a}	8.46±3.33^{a}	172.49±33.79^{d}
L3 T1	3,120±177^{bc}	1,810±92^{b}	12.48±4.44^{b}	145.00±28.99^{c}
L3 T2	4,750±189^{b}	2,755±173^{d}	16.63±5.67^{c}	172.50±30.66^{d}

Note: */ Mean values followed by the same superscript within the same column are not significantly different at the 5% (level $p < 0.05$).
Source: Results of two-way ANOVA and Tukey HSD Test

At the 5% significance level, almost all of the interactions between treatment combinations were statistically significant. The maximum total dried biomass supply was shown by the treatment combination of peat forest with dried leaves (L0 T0) and peat forest with grass stalks, dried twig, wicker, and wood (L0 T1) each valued around 11.260 kg ha^{-1} year^{-1} and 11.250 kg ha^{-1} year^{-1}, respectively. The minimum value of the treatment combination of swamp grass with dried leaves (L3 T0) was around 2.115 kg ha^{-1} year^{-1}. From this, it was illustrated that dried leaves dominated the supply of total dried biomass to the PSF.

C Fixation and C/N Ratio

C fixation

C fixation describes how much C can be bound by PSF over ten years. Almost all treatment combinations were significantly different at the 5% significance level. The maximum total supply of C fixation was shown by the treatment combination of peat forest with dried leaves (L0 T0) and peat forest with grass stalks, dried twig, wicker, and wood (L0 T1), which were around 6,526 and 6,525 kg C ha^{-1} year^{-1}, respectively. The treatment combination of restored PSF with root litter (L1 T2) of about 1.489 kg C ha^{-1} year^{-1} showed the minimum value. It was concluded that dried leaves dominated the supply of total C fixation to the PSF. C fixation contributed by root litter was generally very low, with the lowest starting order of restored PSF, peat forest, swamp grass, and swamp bush, which was around 1,489; 1,604; 2,755; and 3,886 kg C ha^{-1} year^{-1}, respectively.

C/N Ratio

The C/N ratio pattern did not follow the C distribution pattern and was more likely to follow the land covers. A high C/N ratio was indicated by swamp grass and swamp bush. Almost all treatment interactions had significant differences at the 5% significance level. The maximum C/N ratio was shown by the treatment combination of swamp grass with root litter (L3 T2) and swamp grass with dried leaves (L3 T0) of around 172.50 and 172.50, respectively. The treatment combination of peat forest and dried leaves (L0 T0) showed the minimum value, valuing 19.98.

Addition Potential of Soil Nutrients

One of the functions of surface peat accumulation was to increase soil nutrients and form peat. In nutrient-poor PSF, the annual nutrient supply increased to natural levels within ten years of restoration, mainly due to the rapid growth of peat forest and swamp grass from swamp bush.

Figure 2 illustrates that all treatment combinations were significantly different from one another at the 5% significance level. The maximum values of all parameters observed (N, P, K, Ca, and Mg) were generally shown by the treatment combination of peat forest with dried leaves (L0 T0), and the minimum values were demonstrated by the treatment combination of swamp grass with grass stalks, dried twig, wicker, and wood (L3 T2) or swamp bush with grass stalks, dried twig, wicker, and wood (L2 T2).

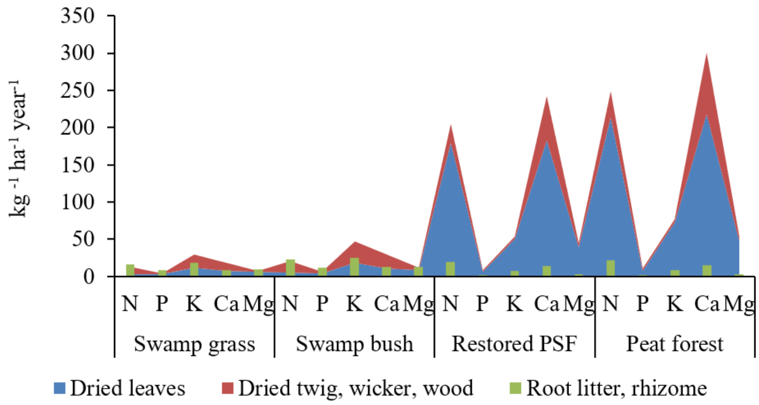

Figure 2. Amount of soil nutrients contributed by dried biomass (kg ha^{-1} year^{-1})

Comparing Dried Biomass Supply in the Above and Below Ground

Production of above-ground dried biomass increased as nutrient levels increased by over 500-800% in peat forests and restored PSF. Dried leaves from peat forests showed significantly higher dried biomass production at the 5% significance level than other land covers. These findings were comparable to those of Hinzke et al. (2021a).

Total production of dried biomass (above-ground and below-ground) of all land covers increased with an increase in nutrients by more than 200-300%. The pattern of total dried biomass production was in peat forests with higher levels of nutrients. In contrast, land covers (swamp bush and swamp grass) showed low levels of soil nutrients, so dried biomass production was also low based on the 5% significance level. Hinzke et al. (2021b) reported comparable work for PSF in Kalimantan. As seen in Figure 3 at the 5% significance level, the pattern of total dry biomass production revealed a significant difference between above and below-ground/soil surface layers.

Total production of dried biomass below ground/ (represented by root litter and rhizome weight) of all land covers showed increased saturation, except for peat forest. However, the length and "number of rhizomes differed between land covers. Overall, the dried biomass production below ground showed the same pattern, which was lower than the above-ground dried biomass. These findings were comparable to those of Hinzke et al. (2021a).

A comparison of above-ground biomass production (represented by dried leaves) with below-ground biomass production (shown by rhizomes and root litter) showed an increasing trend of improving soil nutrient levels. This was supported by the works of Hagan et al. (2023). Dried leaves were found to predominate in accumulating an increasing share of the total dried biomass production with improved soil nutrients (Table 4).

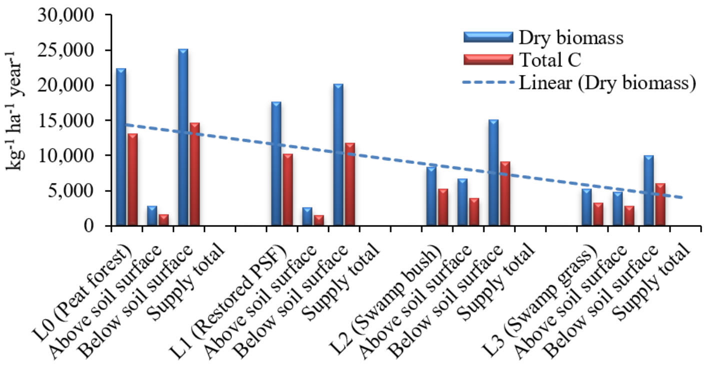

Figure 3. Total supply of dried biomass and C fixation (kg ha^{-1} year^{-1})

Table 4. Percentage of supply total for dried biomass and C fixation

Land covers	Above ground	Below ground	Total supply
L0 (Peat forest)			
Dried biomass (%)	88.97	11.03	100.00
C fixation (%)	44.49	4.96	49.45
L1 (Restored PSF)			
Dried biomass (%)	87.27	12.73	100.00
C fixation (%)	43.64	5.73	49.36
L2 (Swamp bush)			
Dried biomass (%)	55.45	44.55	100.00
C fixation (%)	24.95	20.05	45.00
L3 (Swamp grass)			
Dried biomass (%)	52.43	47.57	100.00
C fixation (%)	23.59	21.41	45.00

Source: Field and laboratory results (2024)

Although C fixation in root litter was low, especially in peat forests and restored PSF, the contribution was high (very dominant) to C fixation by above-ground dried biomass. In contrast, the contribution of root litter in other land covers was not optimal in supplying C fixation to PSF. The opposite was seen in swamp grass and bush, where C fixation in root litter was high (2,755 and 3,886 kg C ha^{-1} year^{-1}, respectively), which could not supply above-ground dried biomass. This phenomenon proved that swamp grass and bush were less able to supply dried biomass for peat formation. This work was positively correlated with that reported by Zhang (2023).

The potential of the below-ground dried biomass (rhizomes and root litter) forming peat was similar to dried biomass production despite increased soil nutrients. This was proven by the fact that even though peat forests and restored PSF were the richest in soil nutrients, there was no additional peat-forming dried biomass below the ground. Yan et al. (2023) showed the same result with this research. The increase in the potential of root litter dried biomass to form peat was dominant in the dried biomass above the ground, followed by an increase in soil nutrient levels. This means that the supply of soil nutrients is more than 200-600% played by above-ground dried biomass compared to below-ground dried biomass. The same result was given by He et al. (2023).

Comparing Soil Nutrients Supply in the Above and Below Ground

From this description, it was clear that swamp grass and swamp bush were minimal in supplying soil nutrients to PSF. These soil nutrients were the main prerequisite for increasing the productivity of dried biomass production for the peat formation. The observed nutrient contents of N, P, K, Ca, and Mg increased back to levels observed in similar natural PSF in about ten years of restoration. These nutrients showed a distinctive distribution pattern in the different topsoil and subsoil layers. The surviving parts of PSF vegetation recycled nutrients released from the root litter exudate; the nutrient contents were the highest above the ground compared to nutrients below the ground.

The production of soil nutrient supply (represented by N, P, K, Ca, and Mg) above the ground increased as the nutrient level increased by more than 300%. In comparison, the production of soil nutrients below the ground only increased slightly (less than 100 %). Dried leaves from peat forests showed significantly higher dried biomass production at the 5% significance level than other dried biomass types (Figure 4). These results supported the work of Ribeiro et al. (2021).

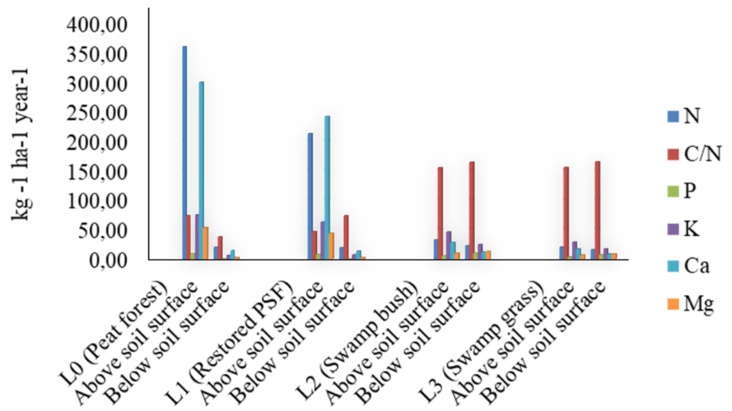

Figure 4. Total supply of soil nutrients to PSF (kg ha^{-1} year^{-1})

The production of soil nutrient supply below the ground was relatively saturated, even though the dried biomass was slightly higher than the ground. It can be concluded that the increase in dried biomass below the ground did not automatically increase above-ground dried biomass (Figure 4). There is a tendency for an increase in above-ground biomass, which is also accompanied by an increase in soil nutrients, especially for all parameters observed; however, this trend does not apply to below-ground biomass because an increase in root and rhizome biomass does not automatically increase soil nutrients. This phenomenon is interesting to study in more detail, as peat formation is more dominant from above-ground biomass. Lin et al. (2020) have found the similar results.

It can be concluded that dried leaves were able to lower the C/N ratio due to the high N content in the dried leaves, while root litter increased the C/N ratio. There is a tendency that the higher the dried leaves, the lower the C/N ratio. Conversely, the higher the root litter, the higher the C/N ratio. The additional potential of soil nutrients can only be contributed dominantly by peat forests or restored PSF and dried leaves. In contrast, root litter contributed minimally (less than a quarter of the total addition potential of soil nutrients). This inability of root litter to reach the additional potential of soil nutrients was due to the very high C/N ratio of root litter, making it difficult for soil microbes to decompose, becoming soil nutrients. These results are in line with Michaelis et al. (2020).

CONCLUSION

This research contributes to sharpening, perfecting thinking, and implementing ecological restoration so that the results of environmental restoration applications can restore or bring Peat Swamp Forest (PSF) closer to its original condition. There is potential for the formation of peat originating from native species, followed by an increase in soil nutrients. Hence, the production of root litter at a high level of soil nutrients was not followed by a higher supply of dried below-ground biomass. Most dried biomass is transported above the ground into dried above-ground biomass. All types of land covers can produce above-ground dried biomass and have the potential to form peat, with significant differences in all parameters studied. The potential for peat formation is highly dependent on the different types of land covers (e.g., peat forests) and environmental factors, the composition of the seed bank, and the ability of species to compete. Restoration actions (replanting, rewetting, and revitalization) aim to accelerate the development of peat-forming species.

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AUTHORS CONTRIBUTIONS

Three authors here have equal and fair duties in developing this research. The first author (MEA) conceptualized and created the primary concept and framework for the manuscript, conducted the comprehensive review and literature review, wrote the original draft preparation, and oversaw the collection and analysis of data from field studies. The second author (EW) contributed to methodology, data analysis, and writing regarding review and editing. The last author (MSI) carried out the field research coordination, qualitative data collection, writing in sections on field research and findings, and ethical considerations in ensuring that all field research activities adhered to ethical standards.

COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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