

Soil macrofauna abundance and soil characteristics of limestone post-mining land in Bogor, West Java, Indonesia

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Abstract. *Wasis B, Putra FR, Winata B, Putra EI, Applegate G. 2025. Soil macrofauna abundance and soil characteristics of limestone post-mining land in Bogor, West Java, Indonesia. Biodiversitas 26: 5314-5323.* Limestone mining can lead to the loss of soil fauna and a decline in soil quality on post-mining land. Soil, as a key component of forest ecosystems, exhibits distinct characteristics across site types. Revegetation is an important strategy to restore ecosystems and biodiversity through tree planting. This study, which aimed to assess the abundance of soil macrofauna, characterize site conditions, and evaluate the influence of soil properties on macrofauna abundance in the limestone post-mining area of PT Solusi Bangun Indonesia, Narogong, Bogor District, West Java, Indonesia, has yielded significant findings. Soil macrofauna were collected using hand sorting and hand capture methods, while biodiversity indices were calculated. Undisturbed soil samples (ring samples) were used for physical property analysis, and disturbed samples (0-20 cm depth) were used for chemical and biological analyses. Data were analyzed using Least Significant Difference (LSD) and negative binomial regression analysis. Macrofauna abundance in Old Revegetation 2010 (OR) sites (54 ± 18.4 individuals) was significantly higher than in Open post-mining land (O) (0.5 ± 0.7) and Young Revegetation 2018 (YR) sites (3.5 ± 2.1) researched in 2023. Porosity, organic carbon, soil pH, soil respiration, and dry litter weight showed significant positive correlations with macrofauna abundance, while soil temperature had a significant negative correlation. These findings, which underscore the importance of revegetation and the role of soil macrofauna as an indicator of post-mining soil quality recovery, are of significant interest to the scientific community and conservation practitioners.

Keywords: Biodiversity indices, limestone mining, revegetation, soil quality

INTRODUCTION

Soil is a key component of forest ecosystems, exhibiting distinct characteristics that vary among site types. Based on its properties, soil can be classified into physical, chemical, and biological categories. Physical properties, such as texture, structure, color, bulk density, permeability, porosity, and particle density, can be directly observed and laboratory analysis (Wasis et al. 2019). Chemical properties, including Cation Exchange Capacity (CEC), base saturation, pH, organic carbon, and nutrient content, require laboratory analysis (Grahmann et al. 2022). Biological properties refer to soil biota and associated processes, such as respiration, microbial abundance, and the presence of soil fauna (Bazyari et al. 2021).

According to Jenny (1941), the dynamics of soil properties are influenced by soil-forming factors, such as climate, parent material, topography, time, and organisms (Tan 2009). Soil fauna serve as bioindicators of soil quality and play vital roles in ecosystem functioning, such as organic matter decomposition, nutrient cycling, and soil structure formation (Dubey et al. 2020).

Their abundance and diversity are influenced by environmental factors, including air and soil temperature, soil pH, and moisture availability (Johnston and Sibly 2020). Soil fauna are categorized by body size, with macrofauna

measuring 2-20 mm, encompassing groups such as earthworms, ants, and termites (Sofa et al. 2020).

Mining activities, such as limestone extraction, can profoundly alter soil conditions because the mining method used is open-pit mining, which causes direct damage to the soil and environment. Operations typically involve vegetation clearance, overburden removal, excavation, loading, and transportation (Solé et al. 2023). Mining activities trigger soil and environmental damage to the soil (soil solum, bulk density, permeability, and soil fauna) and vegetation (land cover) (Wasis et al. 2018). PT Solusi Bangun Indonesia (SBI), operating in Narogong, West Java, is a major limestone mining company whose activities have resulted in post-mining land with diminished ecosystem function.

Post-mining land reclamation involves land management, spreading topsoil, preparing planting holes, applying organic fertilizer, and revegetation planting, including cover crops and trees. Revegetation is a common strategy for restoring areas after mining, as it reconnects vegetation cover to help rebuild biodiversity and ecosystem functions. The plants that grow through revegetation produce organic matter and litter, which change environmental conditions by boosting nutrient availability, creating favorable microclimates, and supporting the recovery of soil fauna populations. However, open and unvegetated post-mining

lands usually lack these resources, which results in lower macrofauna populations (Józefowska et al. 2023).

Despite the importance of soil fauna in ecosystem restoration, research on macrofauna communities in tropical limestone post-mining landscapes remains limited. Most studies in Indonesia focus on revegetation success using vegetation or soil chemical properties, without integrating biological indicators. Yet, soil macrofauna offer a sensitive and integrative measure of soil recovery, responding to changes in both abiotic and biotic conditions. Globally, macrofauna such as earthworms (Phillips et al. 2019) and termites (Davies et al. 2021) have attracted attention, but these taxa alone do not capture the full complexity of macrofauna communities. The need for comprehensive assessments that include diverse taxa is urgent and essential for understanding ecological processes and guiding effective land rehabilitation.

Post-mining areas in tropical limestone ecosystems face unique challenges. Soil formation is slow, nutrient levels are often low, and microclimatic extremes can hinder biological recovery (Anwar et al. 2016). In such environments, macrofauna can act as early indicators of soil health improvement, reflecting changes in habitat quality, organic matter availability, and microclimate control (Sanchez et al. 2021). However, literature on macrofauna dynamics in tropical limestone post-mining settings, particularly in Southeast Asia, remains limited.

This study addresses this knowledge gap by analyzing soil macrofauna abundance and diversity in relation to soil physical, chemical, and biological properties across four post-mining land types at PT Solusi Bangun Indonesia: open post-mining land, young revegetation, old revegetation, and secondary forest. An integral approach was used, combining field surveys of macrofauna with laboratory

analysis of soil characteristics. The specific objectives were to quantify and compare soil macrofauna abundance across land types, characterize soil physical, chemical, and biological properties, and determine the relationships between soil properties and macrofauna abundance.

By linking soil macrofauna communities to measurable soil parameters, this research provides insight into the ecological recovery of post-mining land and identifies potential biological indicators for monitoring rehabilitation success. Findings from this study strengthen the scientific basis for restoration practices in tropical limestone landscapes. They may guide management strategies aimed at improving degraded soils through targeted revegetation and habitat enhancement.

MATERIALS AND METHODS

Research sites

Data and samples were collected at PT Solusi Bangun Indonesia, Narogong, Bogor, West Java, Indonesia (Figure 1). Sampling plots were established by purposive sampling based on vegetation condition and litter thickness on four post-mining limestone: Open post-mining (O) ($6^{\circ}27'58.63''\text{S}$, $106^{\circ}56'41.83''\text{E}$), Young Revegetation 2018 (YR) ($6^{\circ}27'41.01''\text{S}$, $106^{\circ}56'51.34''\text{E}$), Old Revegetation 2010 (OR) ($6^{\circ}27'37.44''\text{S}$, $106^{\circ}56'45.59''\text{E}$), and Conservation Area Forest (CAF) ($6^{\circ}27'49.87''\text{S}$, $106^{\circ}56'28.37''\text{E}$). The research was conducted from October to December 2023. The study was conducted at a single point in time and emphasized differences in land cover without regard to seasonal or climatic differences (no rain).

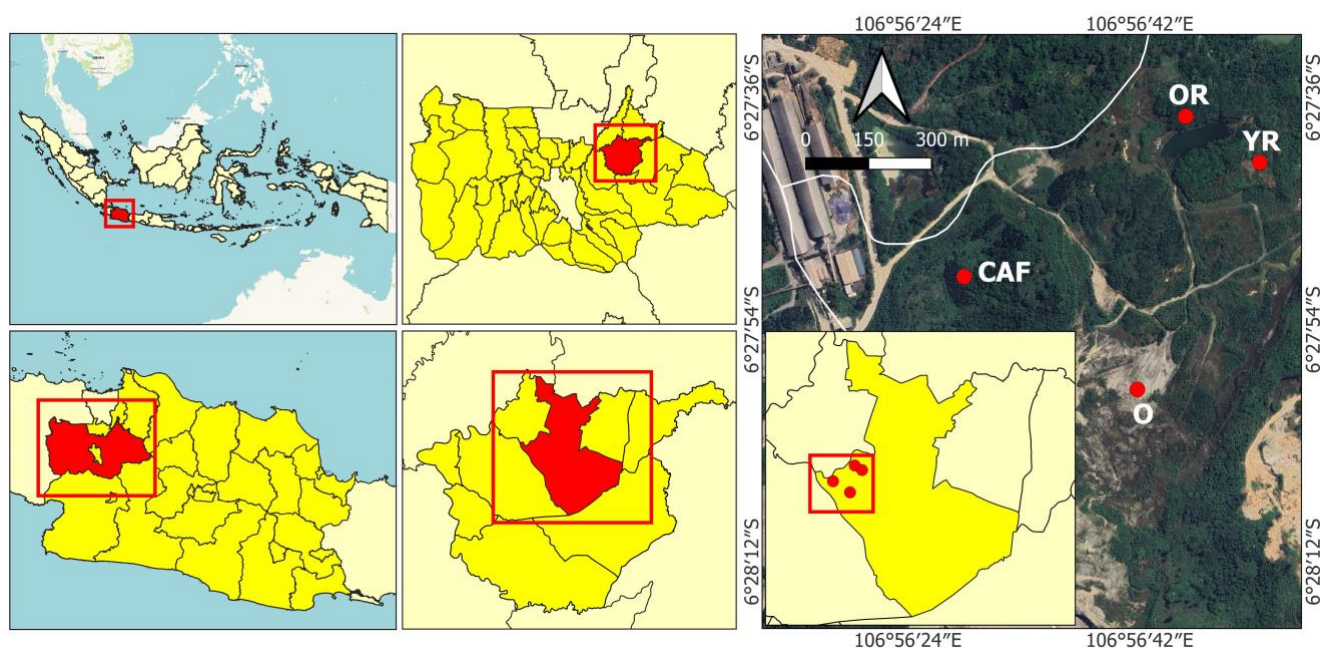


Figure 1. Map of the research sites in PT Solusi Bangun Indonesia, Narogong, Bogor District, West Java, Indonesia. O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

Procedure

Determination and establishment of sample plots

Sampling plots measuring 20 m × 20 m were established by purposive sampling (selected due to limited field conditions) based on vegetation condition and litter thickness on four post-mining limestone sites of PT Solusi Bangun Indonesia, Narogong, West Java, Indonesia (Wasis 2012; Wasis et al. 2019): open post-mining land (O), revegetation in 2018 (YR), revegetation in 2010 (OR), and post-mining land used as a conservation area (CAF). Sample plots (20 m × 20 m) were made at each research site for analysis of vegetation, air temperature and humidity, and light intensity. Vegetation analysis was carried out by inventorying vegetation types, the number of individuals of each type, and measuring height and diameter for poles and trees (Kusmana et al. 2022).

Collection of litter, soil samples, and soil fauna

Litter, soil samples, soil fauna, and soil temperature were taken from 1 m × 1 m sample subplots with purposive sampling placement made as many as 3 pieces (Figure 2). Litter was taken and put entirely into clear trash bags to weigh and store the soil fauna contained in the litter. Disturbed soil samples were taken from 5 points with a depth of 0 to 20 cm from the soil surface on each 1 m × 1 m sample subplot, which were then composited and 1 kg soil was taken for analysis of soil pH, C-organic, and soil respiration (Wasis et al. 2019). Undisturbed soil samples were taken using one sample ring in each 1 m × 1 m sample subplot for analysis of soil content and porosity (Wasis 2012).

Soil fauna collection was conducted using hand sorting and hand capture techniques to capture soil fauna in the litter, soil surface, or in the soil in the 1 m × 1 m sample subplots (Wasis et al. 2019). Captured soil fauna were then collected and put into bottles or plastic containers containing 70% alcohol to preserve them. Analysis of soil and litter samples and further analysis of soil macrofauna were performed at the Forest Influence Laboratory and Forest Entomology Laboratory, Department of Silviculture, Faculty of Forestry and Environment, Institut Pertanian Bogor, Indonesia.

Identification of soil fauna

Soil fauna that are successfully taken and collected are then identified using a stereo microscope or Dino-Lite. Before identification, soil fauna are separated based on their size and morphological characteristics (species). The identification process uses basic identification keys sourced from fauna identification books (Borror et al. 1992).

Data analysis

This study analyzed data on several environmental parameter indices (Table 1), soil macrofauna and vegetation analysis (Table 2), and performed statistical analysis. ANOVA analyzes the abundance of soil macrofauna to determine whether there were statistically significant

differences in the average soil macrofauna abundance. After that, a post-hoc test was conducted with Least Significant Difference (LSD) using R-Studio software to determine the effect of different research sites on the abundance of soil macrofauna, with a significance level ($\alpha=0.05$). Correlation (the data used follows a normal distribution) tests were conducted using data from edaphic element analysis results, with soil fauna abundance data analyzed using IBM SPSS Statistics 26 software. Furthermore, the analysis was performed using a Generalized Linear Model (GLM) with a negative binomial distribution (log link) to address overdispersion and to determine the factors that significantly influenced the abundance of soil macrofauna, starting with checking multicollinearity in the explanatory variables, modeling the abundance of soil macrofauna, to hypothesis testing with the negative binomial simultaneous test and partial test of the negative binomial model at 95% confidence interval using R-Studio software.

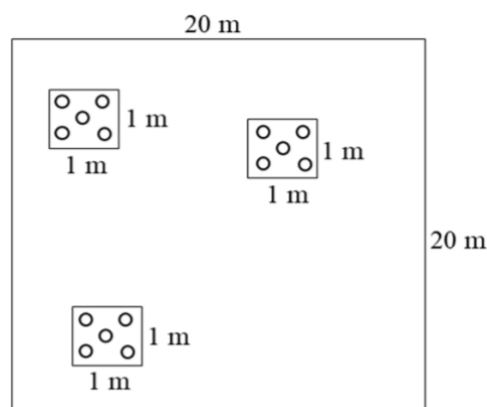


Figure 2. Illustration of subplots for collecting litter, soil samples, and soil fauna

Table 1. Diagnostic identification of environmental parameters

Parameters	Methods
Bulk density and porosity	Ring sample (Wasis 2012)
Soil temperature	Digital thermometer (3 replicates per 30 minutes)
Soil pH	pH meter
C-organic	Dry sobering method (Susanti et al. 2021; Wasis et al. 2024)
Soil respiration	Incubation and titration (Wasis and Naiborhu 2021)
Litter wet weight	Collecting and weighing litter
Dry weight and water content of litter	Drying (oven) and weighing
Air temperature and humidity	Thermohygrometer (3 replicates per 30 minutes)
Light intensity	Luxmeter (4 cardinal directions)

Table 2. Soil macrofauna and vegetation data analysis

Indices	Data processing methods
Abundance (Wasis et al. 2024)	Number of individuals of a species found at the research site
Species diversity (H') (Magurran 2004)	$H' = - \sum p_i \ln p_i$
Species richness (D _{Mg}) (Magurran 2004)	$D_{Mg} = \frac{S-1}{\ln N}$
Species evenness (E) (Magurran 2004)	$E = \frac{H'}{\ln S}$
Density per growth rate (Kusmana et al. 2022)	The number of individuals of a vegetation divided by the sample plot area

RESULTS AND DISCUSSION

Abundance of soil macrofauna

The real difference in the abundance of soil macrofauna is thought to be caused by differences in vegetation conditions, microclimate, and site characteristics at each research site. Explain that revegetation is able to create an acceleration of land cover succession (Table 3).

Canopy formation alters microclimatic conditions underneath it (moisture, temperature, precipitation, light). The development of plant crowns can change conditions under the canopy, such as increasing soil moisture, lowering air temperature, and creating a layer of organic litter and humus, which supports the life of soil macrofauna (Lenk et al. 2024). The abundance of soil macrofauna is a reliable bioindicator of soil recovery in post-mining landscapes. The presence of soil macrofauna boosts the decomposition of litter and organic matter, ultimately enhancing the nutrient cycle of post-mining land. This study shows that plant diversity has an impact on soil fauna abundance, indicating that post-mining land reclamation should involve planting a variety of species. This aligns with Zhang et al. (2022), who emphasize that plant diversity is crucial for the sustainability of soil fauna communities.

Composition of soil macrofauna

Composition and biodiversity of soil macrofauna. Table 4 shows that the conservation area forest research site has the highest number of individuals. In contrast, the open post-mining land research site has the fewest number of individuals.

Order Araneae has the highest number of families among other orders, namely 9 families. Borrer et al. (1992) explained that this order is commonly known as spiders, which are a large and widespread group and are found in many habitat types. The majority of spiders have 8 eyes, but some species have fewer than 8 eyes.

The Thomisidae family is the most numerous in the order Araneae. This family is commonly known as crab spiders, which have a crab-like shape and walk laterally or backwards (Figure 6.A). The anterior two pairs of limbs are usually fatter than the posterior two pairs (Borrer et al. 1992). The second most abundant family, Salticidae or jumping spiders, has a stout body with short limbs, eyes in

three rows, the anterior middle eye is larger than the others, the body is hairy and often brightly colored or iridescent (rainbow-like) (Borrer et al. 1992). The family Oxyopidae, also known as lynx spiders, can generally be recognized by eight eyes in an ovoid cluster and an abdomen that tapers at the end (Borrer et al. 1992).

All species of the order Araneae are predators, especially of insects. However, because of its predatory nature, the Araneae order has an ecological role as a population controller of other animals, especially insects in an ecosystem. In addition, spiders can be potential biological control agents for various pest insect species because spiders are polyphagous. The existence of spiders is closely related to the presence of other animals for their energy sources (Koneri and Saroyo 2015).

The diversity of spider individuals is believed to be influenced by the number of other soil macrofauna, particularly herbivorous insects, at each research site. This is evident in the relatively higher number of spider individuals alongside soil macrofauna, which depends on environmental factors such as climate, soil conditions, and food availability (Wan et al. 2025). The number and arrangement of eyes can also provide clues for identifying family differences (Morehouse et al. 2017).

The results showed that the Formicidae family had a total of 170 individuals, which was the family with the highest total number of individuals. Formicidae was also the most abundant in the young revegetation (Figure 3) and old revegetation (Figure 4) study sites. This family is able to live in various terrestrial habitats, and the number of individuals exceeds most other land animals. The characteristic feature of Formicidae is the pedicel on the metasoma, which consists of one or two internodes and has a bulge that points upward (Figure 7) (Borrer et al. 1992).

The presence of this family was almost widespread throughout the research site, except in the Open post-mining land research site (O). This is believed to be influenced by the diverse types of ant food; most ants are carnivorous, some eat plants, some consume fungi, and others feed on plant fluids (Borrer et al. 1992). The variety of species and food types allows ants to serve several roles, such as decomposing organic matter, acting as predators, controlling pests, and aiding in pollination and seed dispersal. Ecologically, their presence benefits other animals and plants because they play a crucial part in the food chain (Del Toro et al. 2015).

Termites are the second family that has the highest number of individuals, namely 93 individuals, which are cellulose-eating social insects from the Termitidae family (Figure 5). This family lives in colonies with several levels or castes, namely reproductives, workers, and soldiers, which are characterized by different morphologies. Termites have a soft, white body and a wide abdomen associated with the thorax (Figure 8). Some termites live in moist underground habitats and others in dry above-ground habitats. Drywood termites live on pieces of tree trunks, trees, and buildings made of wood (Borrer et al. 1992).

Termites are known as destroyers because they often damage and eat parts of wooden buildings, wooden household furniture, wooden poles, books, and fabrics. However, in

forest ecosystems, termites have great benefits as catalysts for the breakdown of dead trees and other plant products into substances that can be reused by plants (Borror et al. 1992). This study shows that soil fauna abundance can be used as a bioindicator of environmental recovery in post-mining land. Cayuela et al. (2020) state that soil fauna play an important role at all trophic levels of the soil food web and regulate processes that are crucial for soil function, such as nutrient cycling, immobilization, and/or degradation of toxic compounds, soil structure formation, greenhouse gas emissions, and carbon turnover.

Table 3. LSD test results of soil macrofauna abundance

Research site	Abundance (individual/m ²)
Open post-mining land (O)	0.5 ^c ±0.7
Young Revegetation 2018 (YR)	3.5 ^c ±2.1
Old Revegetation 2010 (OR)	54 ^b ±18.4
Conservation Area Forest (CAF)	101 ^a ±7.1

Note: Numbers followed by different letters in the same column mean significantly different based on LSD test at a 95% confidence interval. "±" is standard deviation (SD)

Table 4. Composition of soil macrofauna

Composition	Research sites			
	O	YR	OR	CAF
Number of orders	1	3	9	6
Number of families	1	3	14	14
Number of individuals/m ²	1	7	108	202

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

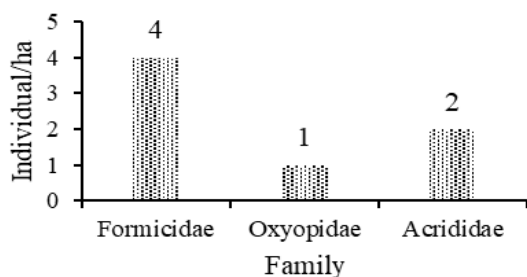


Figure 3. Family composition of soil macrofauna at the Young Revegetation (YR) research site

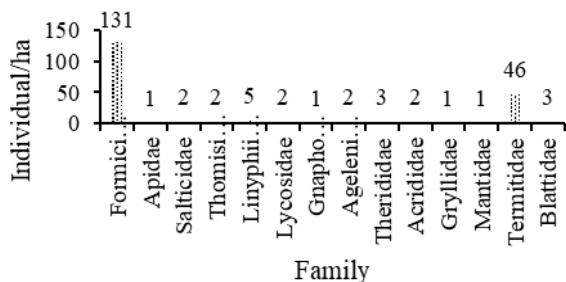


Figure 4. Family composition of soil macrofauna at the Old Revegetation (OR) research site

The role of vegetation on microclimate and soil macrofauna

The OR and CAF research sites had relatively higher densities than other research sites (Table 5), which resulted in a better microclimate. Low vegetation density can lead to increased soil surface temperatures. This can negatively affect living organisms and cause changes in the surrounding microclimate. Additionally, low vegetation density can result in a loss of biodiversity. The elements of the environment that will be affected by the microclimate include air temperature, soil temperature, wind direction and speed, air humidity, and the intensity of irradiation received by a surface. Plant species that are not fast-growing, such as teak (*Tectona grandis*), found in the Young Revegetation 2018 (YR) research site, are believed to influence the slow process of microclimate formation. This proves that post-mining vegetation restoration through revegetation with the planting of adaptive species is more effective in accelerating vegetation cover, increasing diversity, and restoring ecosystem functions (Navarro-Ramos et al. 2022). Meanwhile, natural succession occurs slowly due to nutrient-poor soil and extreme conditions, making it difficult for biodiversity and ecological functions to recover optimally (Isnaniarti et al. 2017).

Vegetation density also influences the production of litter produced at the research site. The Open post-mining research site (O) had no litter at all due to the lack of vegetation or vegetation other than understorey. Tree density affects litter production; the higher the tree density, the more litter is produced (Wasis et al. 2024). The Conservation Area Forest (CAF) had a smaller vegetation density than the Old Revegetation 2010 (OR), however, the weight of litter produced was greater (Table 5).

The uniqueness in this study is thought to be influenced by the type of plants growing in the Old Revegetation 2010 (OR) research site, which is dominated by the sengon buto (*Enterolobium cyclocarpum*) species, with a smaller leaf size, which tends to produce lighter litter weight than other species, such as *Swietenia mahagoni* (mahogany), *Mangifera indica* (mango), *Nephelium lappaceum* (rambutan), and *Diospyros blancoi* (bisbul) in the CAF research site. The smaller the size of organic matter, the faster the rate of decomposition increases because it will be more easily decomposed by microorganisms, so that the amount of litter remaining on the forest floor will be less. This research strongly recommends that revegetation should use diverse and endemic leaf-size trees. Soil fauna diversity increases with plant species richness (Zhang et al. 2022).

The surprising disparity in the abundance of soil macrofauna at the Old Revegetation 2010 (OR) and Conservation Area Forest (CAF) research sites, despite the similar temperature and humidity values (Table 6), has sparked our interest. This finding challenges the conventional understanding that climatic factors such as humidity have a positive relationship with the abundance of soil fauna, while ambient temperature and light intensity show a negative correlation, as suggested by Wasis et al. (2023). This study, in line with Lubbers et al. (2019), demonstrates that reclamation and revegetation of post-mining land can enhance soil quality, soil fauna abundance,

carbon sequestration, and microclimate and climate change. Lubbers et al. (2019) also suggest that soil fauna activity can be a major controller of Greenhouse Gas (GHG) emissions from the soil.

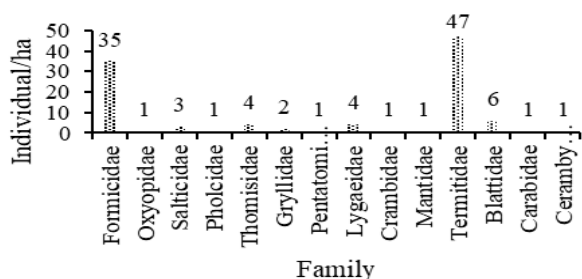


Figure 5. Family composition of soil macrofauna at the Conservation Area Forest (CAF) research site

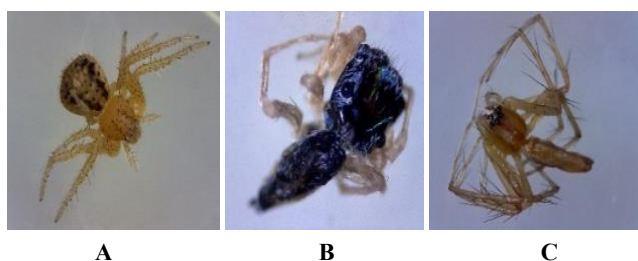


Figure 6. Several families of the order Araneae. A. Thomisidae (1.5× magnification), B. Salticidae (0.8× magnification), C. Oxyopidae (1.5× magnification)



Figure 7. The Formicidae family. A. Species 1 (3.5× magnification), B. Species 2 (1.5× magnification), C. Species 3 (0.8× magnification), D. Species 4 (1× magnification)

Diversity of soil macrofauna

Based on the analysis of the species Diversity Index (H'), the Old Revegetation 2010 (OR) research site has the highest value. However, the Old Revegetation 2010 (OR) research site and Conservation Area Forest (CAF) as having medium species diversity, while the other research sites were classified as low. Ecologically, a moderate or low value (H') indicates a low or decreasing level of ecosystem stability, while a high value of the Diversity Index (H') will influence the stability of an ecosystem.

The results of the analysis of the Species Richness Index (DMg) show that all research sites have low species richness because the index value is less than 2.5, except for the Old Revegetation 2010 (OR), which has a medium index value. After all, the value is between 2.5 and 4 (Table 7). The value of the Margalef Richness Index (DMg) is strongly influenced by the total number of individuals found in a particular area, so that the DMg value in one area with another area is very different even though the number of species found has the same value.

The value of the species Evenness Index (E) obtained ranged from 0 to 0.87. The Young Revegetation 2018 (YR) research site had the highest evenness value because the 7 soil macrofauna individuals found were almost evenly distributed among 3 types of families (Table 7). However, none of these research sites showed a perfectly even distribution of species because none had a value of 1 on the species Evenness Index. This is in accordance with Magurran (2004), which states that the value of the species Evenness Index (E) has a range of values between 0 and 1; the value of 1 represents that all species in an ecosystem have the same or evenly distributed abundance.

The influence of soil physical properties on soil macrofauna abundance

The physical properties considered as characteristics of the footprint include bulk density, porosity, and soil temperature. The first step is to check for multicollinearity in explanatory variables. Initial detection of multicollinearity is done by calculating the Pearson correlation coefficient between the explanatory variables. If a large coefficient value is obtained, there is a possibility of multicollinearity in the data. The test results clearly show that the bulk density and porosity variables are perfectly negatively correlated at -1, indicating perfect multicollinearity. In this case, an increase in bulk density will cause a decrease in porosity and vice versa. Since these two variables contain very similar information, only one of them needs to be retained in the model. Therefore, to avoid problems in coefficient estimation and ensure model stability, only one variable is selected to be included in the model.

Next, the content weight variable was removed from the model, resulting in the following negative binomial regression model.

$$\ln(\mu) = 17.12 + 0.06x_1 - 0.64x_2$$

After obtaining the model, the results of the partial significance test of each explanatory variable using the Wald test. The value of the test statistic G in the physical properties model was 23.074, with a value of

$\chi^2_{(\alpha=0.05, k=2)} = 5.99$, so that based on the test criteria, it was concluded that there was at least one explanatory variable of soil physical properties that had a significant effect on fauna abundance. The results of testing the partial significance of each explanatory variable using the Wald test showed a p-value <0.05 for the variables x_1 and x_2 (Table 8). This means that, at the 5% real level, porosity and soil temperature have a significant influence on macrofauna abundance. The model shows that each addition of one unit of porosity (x_1) will increase macrofauna abundance by $\exp(0.06) = 1.06$, assuming other explanatory variables remain constant. Meanwhile, every one unit increase in soil temperature (x_2) will decrease macrofauna abundance by $\exp(-0.64) = 0.53$, assuming other explanatory variables remain constant.



Figure 8. Documentation of the Termitidae family. A. Worker caste (1.5× magnification), B. Soldier caste (1.2× magnification)

Table 5. Vegetation density at the research site

Research site	Density (individual/ha)			
	Seedling and understory	Stake	Pole	Tree
O	2,500	0	0	0
YR	47,500	6,800	0	0
OR	175,000	3,200	800	575
CAF	75,000	3,200	300	75

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

Table 6. Measurement results of climatic parameters and wet weight of litter at the research site

Parameter	Research site			
	O	YR	OR	CAF
Temperature (°C)	41.5	40.8	30.7	31.0
Humidity (%)	37.67	40.67	65.67	65.00
Light intensity (lux)	61,265	47,272	920	31,884

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

Table 7. Diversity of soil macrofauna at the research site

Indices	Research site			
	O	YR	OR	CAF
H'	0	0.93	1.61	1.17
D _{Mg}	0	1.03	2.78	2.45
E	0	0.87	0.61	0.44

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

The Young Revegetation 2018 (YR) research site showed the highest content weight value, while the lowest value was produced at the Conservation Area Forest research site (CAF) (Table 8). The addition of organic matter in the soil that occurs due to the decomposition process of litter in the soil is a factor in decreasing the value of soil content weight. This negative effect indicates that the higher the abundance of soil macrofauna, the lower the soil content value will be due to the activities carried out by soil macrofauna. The value of soil content weight will decrease due to activities carried out by soil macrofauna. The highest porosity value in this study was produced at the conservation area forest site (Table 8). At the same time, the lowest value was produced at the Young Revegetation 2018 (YR) research site. The decrease in soil porosity was caused by an increase in soil density (bulk density) due to the use of heavy equipment in the mining process. Wasis et al. (2024) explained that the positive relationship means that the more the presence of soil fauna, the more the soil porosity will increase. This is in line with the opinion of Mamabolo et al. (2024a) that soil cultivation is known to have a negative impact on soil fauna, soil function, and physicochemical properties through intense soil structure disturbance.

The Open post-mining land (O) and Young Revegetation 2018 (YR) research sites have higher soil temperatures than other research sites due to the openness of the land, so they have relatively few soil macrofauna abundances (Table 8). Soil macrofauna will be abundant at optimal soil temperatures. Research by Wasis et al. (2024) revealed that the negative correlation value indicates that the abundance of soil fauna tends to increase along with a decrease in soil temperature.

The influence of soil chemical properties on soil macrofauna abundance

The chemical properties considered as site characteristics consist of pH and organic carbon. Initial detection of multicollinearity was performed by calculating the Pearson correlation coefficient between explanatory variables. Based on the test results, it can be seen that the organic carbon and soil pH variables have a negative correlation of -0.85, indicating a fairly strong relationship between the two. To confirm whether multicollinearity affects the stability of the model, it is necessary to check the VIF value. If the VIF is greater than 10, it indicates high multicollinearity that needs to be addressed.

Since there are no VIF values greater than 10, it can be concluded that the multicollinearity in the data is still acceptable, allowing the analysis to proceed without further intervention. The resulting negative binomial regression model is as follows:

$$\ln(\mu) = -63.36 + 1.10x_3 + 8.06x_4$$

Furthermore, the results of the partial significance test of each explanatory variable using the Wald test. The value of the G test statistic in the soil chemical properties model was 24.016, with a value of $\chi^2_{(\alpha=0.05, k=2)} = 5.99$, so that based on the test criteria, it was concluded that there was at least one chemical explanatory variable that had a

significant effect on fauna abundance. The results of testing the partial significance of each explanatory variable using the Wald test showed a p-value <0.05 for variables x_3 and x_4 . This means that, at the 5% real level, C-organic and pH have a significant influence on macrofauna abundance. The model shows that every addition of one unit of C-organic (x_3) will increase macrofauna abundance by $\exp(1.10) = 3$, assuming other explanatory variables remain constant.

The Open post-mining land (O) and Young Revegetation 2018 (YR) research sites have slightly alkaline soils, while the Old Revegetation 2010 (OR) and Conservation Area Forest (CAF) research sites have neutral soil properties (Table 9) (Nazir et al. 2017). Soil fauna tend to prefer living in soil with a neutral pH, but some soil fauna can survive in both acidic and alkaline soil conditions (Bentacur et al. 2023).

The Conservation Area Forest (CAF) research site has the highest C-organic value (Table 9). Meanwhile, the open post-mining land research site has the lowest C-organic value. The positive effect of organic carbon on soil macrofauna abundance creates a direct relationship, meaning that the higher the organic carbon content in the soil, the greater the abundance of soil macrofauna. The availability of soil C-organic is a source of soil fertility. Low soil fertility indicates a low availability of nutrients, so the role of soil macrofauna as a breaker of soil organic matter can influence nutrient availability in the soil (Sofa et al. 2020).

Table 8. Measurement results of soil physical properties at the research site

Parameter	Research site			
	O	YR	OR	CAF
Bulk density (g/cm ³)	1.23	1.45	0.99	0.96
Porosity (%)	53.59	45.13	62.64	63.79
Soil temperature (°C)	31.23	29.95	26.33	26.00

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

Table 9. Measurement results of soil chemical properties at the research site

Parameter	Research site			
	O	YR	OR	CAF
Soil pH	7.57	7.69	7.53	7.31
C-organik (%)	1.72	2.50	6.00	8.30

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

Table 10. Measurement results of soil biological properties at the research site

Parameter	Research site			
	O	YR	OR	CAF
Soil respiration (mg CO ₂ /day/100 g soil)	5.30	9.36	18.14	11.86
Litter wet weight (g)	0	234	508.5	1133
Litter dry weight (g)	0	207	441.5	974.5
Litter water content (%)	0	11.52	13.17	14.06

Note: O: Post-open mining, YR: Young Revegetation 2018, OR: Old Revegetation 2010, CAF: Conservation Area Forest

The influence of soil biological properties on soil macrofauna abundance

The biological properties considered as site characteristics consist of respiration, wet litter weight, dry litter weight, and litter moisture content. Initial detection of multicollinearity was performed by calculating the Pearson correlation coefficient between explanatory variables. Based on the test results, it can be seen that the variables of wet litter weight and dry litter weight have a perfect positive correlation of 1, indicating perfect multicollinearity. In this case, an increase in wet litter weight will cause an increase in dry litter weight, and vice versa. Since these two variables contain very similar information, only one of them needs to be retained in the model. Therefore, to avoid problems in coefficient estimation and ensure model stability, only one variable is selected to be included in the model.

Next, the wet litter weight variable is removed from the model, resulting in the following negative binomial regression model:

$$\ln(\mu) = -1.988 + 0.176x_5 + 0.003x_6 + 0.125x_7$$

After obtaining the model, the results of the partial significance test for each explanatory variable using the Wald test. The value of the G test statistic in the soil biological traits model was 18.359, with a value of $\chi^2_{(\alpha=0.05, k=3)} = 7.814$, so that based on the test criteria, it was concluded that there was at least one explanatory variable of biological traits that had a significant effect on fauna abundance. The results of testing the partial significance of each explanatory variable using the Wald test showed a p-value <0.05 for variables x_5 and x_6 . This means that, at the 5% real level, soil respiration (x_5) and litter dry weight (x_6) have a significant influence on macrofauna abundance (Table 10). However, in litter moisture content (x_7) the p-value was >0.05 . This means that at the 5% real level, litter moisture content did not have a significant effect on macrofauna abundance. The model shows that each addition of one unit of respiration (x_5) indicates an increase in macrofauna abundance of $\exp(0.176) = 1.192$, assuming other explanatory variables remain constant. Meanwhile, every increase of one unit of litter dry weight (x_6) will increase macrofauna abundance by $\exp(0.0027) = 1.0027$.

The highest soil respiration was produced by the Old Revegetation 2010 (OR) research site, while the lowest value was produced by the Open post-mining research site (O) (Table 10). Wet weight and dry weight of litter in the research site of the Conservation Area Forest (CAF) showed the highest value. The high weight of litter associated with the presence of vegetation can affect the high abundance of soil macrofauna. The abundance of soil macrofauna depends on the soil organic matter (Warren and Zou 2002; Sayad et al. 2012). Wasis (2012) explains that most of the organic matter in the forest is plant organic tissue in the form of leaves, stems/branches, twigs, fruits, and roots. Dead organic materials on the soil surface can be considered to be litter, which provides humus, serves as a habitat for insects, and supports various other microorganisms. The condition of litter is very influential on the presence of soil fauna; the abundance of litter on the soil surface will

be used as a shelter and, at the same time, become food for soil fauna. The abundance of soil macrofauna can increase due to high litter moisture content, which will reduce temperature and increase soil moisture. This shows that soil macrofauna and mesofauna prefer moist conditions.

Vegetation cover and plant litter cover are the variables that most favorably influence fauna diversity. Mamabolo et al. (2024b) explain that vegetation cover and plant litter cover are the variables that most favorably influence fauna diversity. This is due to soil respiration, which is the process by which soil microorganisms and plant roots release CO₂ from the soil into the atmosphere. Soil respiration is not only influenced by biological factors (vegetation and microorganisms) and environmental factors (temperature, humidity, and pH). Still, it is also more influenced by human-made factors.

In conclusion, the abundance of soil macrofauna in Old Revegetation 2010 (OR) showed significant differences from Open post-mining land (O) and Young Revegetation 2018 (YR). This study described that soil macrofauna abundance can be used as an indicator of soil improvement in post-mining land. Significant positive effects were observed between the interactions of porosity, organic carbon, soil pH, soil respiration, and dry litter weight with soil macrofauna abundance. Meanwhile, significant negative effects were only observed between the interaction of soil temperature with soil macrofauna abundance. This study highlights the need to add organic matter to post-mining land, as this will improve soil properties, soil fertility, and support vegetation growth. It also emphasizes the responsibility of selecting the appropriate plant species for post-mining land, a crucial step that can significantly impact the success of soil restoration efforts. Plants can naturally produce organic matter through the litter they generate, so it is important to select the appropriate plant species for post-mining land and produce litter of small size for easy decomposition, such as the sengon buto species.

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