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Litter layer and earthworms as an indicator of coffee production in the coffee and pine based agroforestry system

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Abstract. Critical support for successful coffee-based agroforestry production is the amount of litter input and the activity of macro-organisms. The purpose of this study was to analyze the relationship between the amount of litter on the soil surface, the population of earthworms, and the growth and production of coffee. The research was conducted between June 2019 and March 2020 at the Universitas Brawijaya Forest, East Java, Indonesia. For the coffee plants, a proportional random sampling method was used to capture the range of plant sizes within the study location. The range of diameters at breast height (DBH) recorded were divided into ten decils and four replicates within each decil. For each plant, DBH was transformed into tree biomass and fresh coffee bean weight was also measured. Litter weight and depth were measured using a 50 x 50 cm quadrat frame. A sampling of earthworms used the TSBF monolith method. There was a positive relationship between litter thickness, litter weight, the number of earthworms, and earthworm biomass against the dry weight coffee bean, while the four variables have no significant relationship with coffee tree biomass. We concluded that litter layer and earthworm biomass can be used as a simple indicator of coffee production.

1. Introduction

The primary soil quality indicators used by medium to large farming operations are based on physical and chemical attributes [1,2]. These approaches are often inaccessible to smallholder farmers who cultivate small parcels of land as subsistence farms [1] [2]. These groups also neglect biological attributes as soil quality indicators, despite the role biology plays in supporting production under more sustainable agricultural systems [3]. It is necessary to understand soil resources as a dynamic living system that emerges from balance and interaction among soil biological, chemical, and physical components [3].

The services of soil microorganisms weigh heavily in agricultural success because they are directly related to soil quality and represent indicators sensitive to changes in this system [2]. Therefore, evaluating and increasing the contribution of biological processes to agricultural crops, grazing land, and forest production are of fundamental economic and environmental importance. In coffee production systems, research efforts have generated advances in technological practices. An example is plant breeding with cultivars developed to be increasingly resistant to pests and diseases, responsive to management practices, and resultant higher production [4]. However, when dealing with aspects related to the soil, most studies on coffee growing are limited to physical and chemical attributes, with little analysis of biological attributes. Considering the urgent need to increase the sustainability of coffee production, the assessment of soil biological indicators may become an indispensable tool for coffee crop management. They may assist in predicting the rates and direction of changes in soil quality, therefore, supporting decision developed microbiological indicators, including using arbuscular mycorrhizal fungi as soil quality indicators in coffee plantations [5, 6].

Simple biological indicators such as the measurement of litter biomass and earthworm populations may be suitable soil quality indicators for agroforestry systems. Agroforestry systems generally have high litter inputs due to tree canopies covering all or part of the soil surface. The level of cover (thickness) of the litter layer is determined by the equilibrium between inputs and the rate of decomposition, which is governed by litter quality and forest floor microclimate. The slower the decomposition rate, the longer litter is present on the soil surface, and often the greater the depth of the litter layer [7]. However, slow decomposition rates can be unfavorable litter quality for earthworms, with high lignin and phenol content and a high C : N ratio reducing palatability for earthworms. Coffee-pine-based agroforestry systems have varying amounts and types of litter input based on the trees and crops growing on them. Pine litter has high lignin and phenol content and high C : N ratio, making it less likely to be utilized by soil macrofauna [8] and more resistant to degradation, both biologically, enzymatically, and chemically [9]. However, coffee litter has a lower C : N and lower content of lignin and polyphenols is likely to be more favorable by soil fauna. This is reflected in the litter layer, where the amount of coffee litter on the ground is much less than the amount of pine litter even when differences in the inputs are considered. The litter layer and the tree canopy in agroforestry systems can directly impact the forest floor microclimate, causing the soil surface to be more humid and lowering temperatures and light intensity. This can make conditions more suitable for earthworms.

According to [10] and [11], complex coffee-based agroforestry systems had an important role as a buffer for subsurface biodiversity, including for earthworms and termites. Earthworms are important soil fauna and can be used as an indicator of soil sustainability. Earthworms are ecosystem engineers that play an important role in influencing the hydrological function of the soil [12]. Conversion of forest land to coffee-based agroforestry led to a decrease in litter input from 2.06 Mg ha^{-1} to about 1.5 Mg ha^{-1}, thereby reducing soil cover, reducing the amount of food for earthworms and soil organic matter content [13]. The decrease in litter thickness did not, however, affect earthworm population density. A study by [12] also found no significant difference between the size of the earthworm population in a monoculture coffee system compared to a shade coffee system, with an average population of 82 individuals m^{-2}. The conversion of forest land to agroforestry land even increased the earthworm population, with the highest earthworm population of 149 individuals m^{-2} reported in Sumberjaya, Lampung, Indonesia. Higher density of earthworms is desirable. The greater the number of individuals, the more burrows produced during their movement, increasing the number of macro-pores in the soil, facilitating the flow of water and nutrients, and improving plant growth.

In light of the relationships between litter dynamics, earthworms, and soil health, including water infiltration and nutrient recycling, the purpose of this study was to analyze the relationship between the amount of litter on the soil surface and the population of earthworms with coffee yields. The aim is to explore if simple measurements of these factors could be used as a low-cost and accessible method to monitor coffee-based agroforestry systems' health.

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2. Material and Method

2.1. Site Location and Research Design

This research was conducted at UB Forest land in Sumbersari Village, Karangploso District, Malang Regency, East Java, Indonesia (7°49'S and 112°34'E). The site is located on Andisol soil on the slope of the Arjuna Volcano. The research was conducted from June 2019 to March 2020.

The study was conducted using a sample of 40 individual coffee plants, which were divided into ten deciles (categories) based on stem diameter at breast height (DBH). The coffee plant was selected using a proportional random sampling method to represent plant growth in each category. For each decil (1 to 10), four individuals were selected, D1 being the representative of the DBH of the coffee plant with the smallest plant growth (<15 mm), while D10 is the DBH of the largest coffee plant (>43,8 mm), and each decil with interval 3,1 mm. The selection of individuals was restricted to 6 years old Arabica coffee cultivars (*Coffea arabica L.*), with a spacing between coffee plants of 1.5 m x 1.5 m and a spacing of pine shade trees of 3 m x 2 m.

2.2. *Measurement of research parameters*

2.2.1. Coffee stem diameter and coffee production

The determination of plant biomass was carried out by measuring the diameter of the coffee stem at 120 cm above the soil surface (DBH) with four plants selected per decil (Table 1). The DBH value was then converted to coffee biomass with the equation [14]:

$$DW = 0.281 \text{ x DBH}^{2.06} \quad (1)$$

where, DW = biomass dry weight (kg $plant^{-1}$) DBH = Diameter at Breast Height (cm)

Coffee production was measured by harvesting all fully ripe coffee cherries per plant (red color) over four observation periods (every 7–10 days) during the coffee harvest from June to October 2019. The fresh fruit from each observation period was then weighed and summed together to determine the total wet weight production of coffee from each tree. The Dry weight per coffee bean was then calculated using a ratio of fresh fruit bean to dry weight coffee bean of 6:1 (based on personal communication with Abdullah).

2.2.2. The thickness and weight of litter

Determination of sampling locations for litter measurements are determined by following the location of coffee growth and production measurement. The thickness of the litter on the soil surface was measured by measuring the thickness of the litter under the selected individual stands of trees. The measurement of litter weight was carried out in an area of 0.5 m x 0.5 m in pairs in each research plot using the destructive sampling method [15]. At each litter measurement location, ±100 g of wet sample (Sw) was taken to determine 105 oC (Sd) oven-dry weight. The total weight of the litter is calculated by Formula [16], namely:

$$TL = (L - (L\, x \left(\frac{\text{Sw} - \text{Sd}}{Sw}\right)))x \left(\frac{\text{A}}{a}\right) \quad (2)$$

Where:

TL = total weight of dry litter (kg m^{-2})
L = average wet litter weight of the two traps (kg)
A = area in 1 m^2 (m^2)
a = the size of the litter trap (0.5 m x 0.5 m)

2.2.3. The number and weight of earthworms
Earthworm sampling was carried out using the hand-sorting method, while the collection was carried out using the Monolith Tropical Soil Biology and Fertility Program (TSBF) method. Sampling was carried out using a frame size of 25 cm x 25 cm x 10 cm. Earthworms were taken at three depths for each monolith, namely 0-10 cm, 10-20 cm, and 20-30 cm. The samples of earthworms that have been obtained were then cleaned, counted, and weighed.

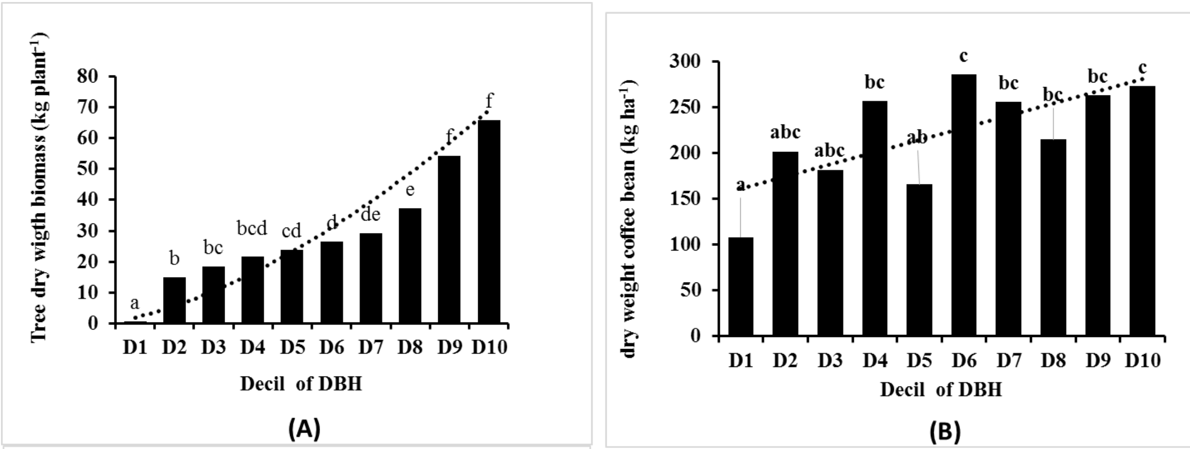
2.3. *Statistical analysis*
Statistical analysis was carried out using the GenStat program. Analysis of variance was conducted to analyze differences in coffee growth and production. If the effect was significantly different ($p<0.05$), then a further test of the Least Significant Difference at the 5% level was carried out. A correlation test (ANCOVA) was conducted to determine the relationship between litter biomass and earthworm biomass with coffee growth and production, if the relationship was significant ($p<0.05$) then the predicted regression line was fitted to data.

3. Result and Discussion

3.1. *Coffee Growth and Production*
The DBH decils were selected to represent the variability present within site. Despite the coffee plants being planted in the same area and all being six years old, a large spread in plant biomass was observed (Figure 1.A). The lowest biomass was 1 kg per plant, and the highest was 66 kg per plant. Coffee plants can have different growth rate and ultimate size due to differences in different cultivars/varieties and environmental conditions where they grow [17]. In this case, it is that environmental factors likely are the determinants as a single variety of coffee was planted. As light availability drives photosynthesis and biomass production, the heterogeneous nature of pine tree canopy shading may have been one factor in determining the growth rate of coffee [18]. As well as pine shading, the distance of coffee plants from the trees can affect the availability of resources (water and nutrients) in the soil and the prevalence of pests and diseases.

With increasing coffee plant diameter, there is a tendency to increase dry coffee bean production (Figure 1.B). The lowest average yield was 108 kg ha^{-1} in D1, while the highest average harvest weight was 286 kg ha^{-1} in D6. This production is still far below Indonesia's average production of 750 kg ha^{-1}. However, excluding D1, there are limited significant differences between the other Decil, suggesting that plant biomass is not the only factor influencing bean yield (Figure 1.C).

Coffee biomass production is normally one of the success factors for plant production, resulting in increased production of dry weight coffee beans. For the smallest coffee plants in this study, coffee bean yield was significantly lower than all the other size classes. This supports other research [19], which shows that smaller plant diameters produce less fruit than larger plant diameters. In the larger decil, however, In the larger decil, however, the relationship coffee biomass and dry weight coffee beans was weak ($F=7.8$, $P=0.028$, $R^2= 0.47$) (Figure 1.D). This is likely due to a combination of other factors that influence yield. Yield is affected by environmental conditions in which coffee plants grow. At least three environmental factors can impact yield, namely the nutrient content in the soil, soil moisture, and sunlight. These may vary between areas and may also change over time. Management of the coffee plants can also impact yield. Pruning for example, can increase yields by removing unproductive side branches, focusing the plants efforts on bean production. This is unlikely to affect the DBH of the main stem but will increase yields. Also, according to [20], the effect of stem diameter on fruit production physiologically does not occur directly but through canopy conditions related to the process of receiving sunlight which then physiologically affects fruit production. Together these factors may explain the weakness of the relationship in this study.



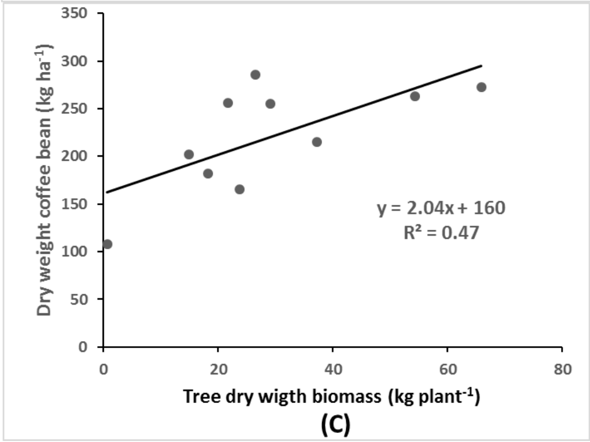


Figure 1. Variation of (A) Biomass of Coffee Plants, (B) Coffee Production and (C) Relationship between Biomass and coffee production in Coffee-Pine-based Agroforestry (Note: Decil which has the same letter notation, is not significantly different in the Least Significant Difference test 5% level.)

3.2. *Relationship between litter and earthworm*

The results of the regression analysis showed that the thickness of the litter had positive effect on the earthworm biomass (F=4.28, P=0.058) (Figure 2.A), but no effect with the number of earthworm (F=0.04, P=0.852) (Figure 2.C). In comparation, the weight of the litter had a significant positive effect on earthworm biomass and number. The relationship is slightly stronger between litter weight and earthworm biomass (F=6.48, P=0.032, R^2= 0.32) (Figure 2.B) than with earthworm number (F=3.75, P=0.073, R^2= 0.21) (Figure 2. D).

Our results indicate earthworm presence is positively associated with the litter mass cover in the field in this agroforestry system. It is known that the population, distribution, and activity of earthworms are influenced by the quality of input of organic matter, soil moisture, and temperature [21]. The type of vegetation present is a key factor [22] as it influences both the type and amount of the litter. In this agroforestry system, the pine litter has relatively high lignin and phenol content and is slow to decay [15]. Such litter, which is slowly weathered, supports a continuous supply of food for earthworms [23] [21] [24] being saprophagous [25]. Coffee litter has a lower lignocellulose content providing an additional food source to the pine litter alone. The level of litter input also affects the population and biomass of earthworms. According to [26], the population density of earthworms is highly dependent on soil physico-chemical factors and the availability of sufficient food. The availability and type of vegetation determine the species diversity and population density of earthworms. Litter found on the soil surface will also affect soil temperature and moisture, promoting cooler temperature and higher moisture levels, which are positively associated with earthworm biomass [27]. Therefore, it is likely that the combinations of food abundance and diversity of earthworm, together with soil microclimatic condition, explain the observed relationship between litter weight and earthworm biomass.

With sufficient availability of organic matter, the activity of soil organisms, including earthworms, increases the availability of nutrients, supporting soil nutrient cycles and the formation of micro and macro soil pores [28]. Often the higher the number of earthworms, the higher of soil fertility level, as indicated by the availability of nutrients and organic matter content. The burrowing activity of earthworms can prevent soil compaction in a field. Worms translocate nutrients to the soil surface by eating organic soil or organic material in the deeper soil layers and then releasing it at the soil surface in the form of worm casts. Through casting, worms also promote the formation of stable soil aggregates and place nutrients and organic matter in the rhizosphere. These functions all help to support soil health and thus plant growth.

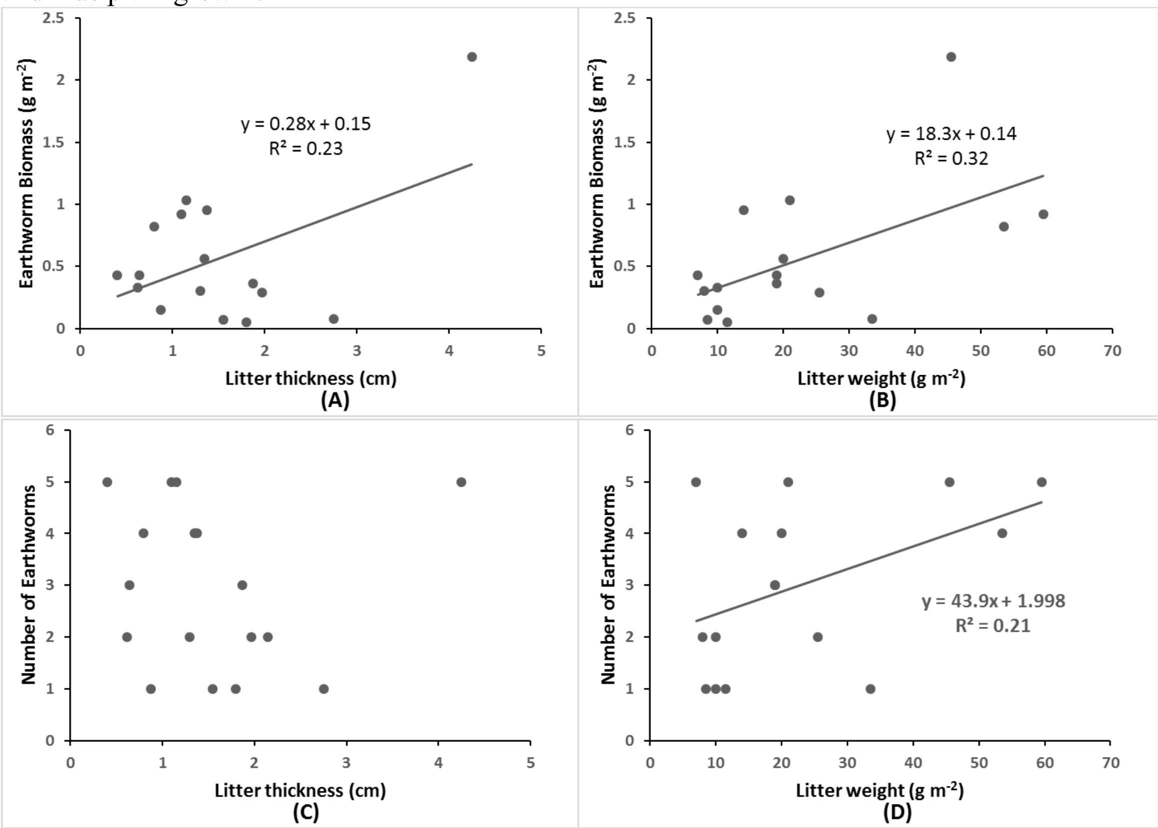


Figure 2. Relationship between (A) litter thickness and earthworm biomass (B) Litter weight and earthworm biomass (C) litter thickness with the number of earthworms and (D) Litter weight and the number of earthworm in coffee pine-based agroforestry systems.

3.3. *Litter and Earthworms as indicators of coffee growth and production*

The results of the regression analysis showed that litter thickness and litter weight had no significant effect on coffee plant biomass (F=0.65, P=0.727 and F=0.30, P=0.589 respectively) (Figures 3.A and 3.B), but they did have a positive correlation with dry coffee beans weight (F=1.22, P=0.282 and F=5.58, P=0.027 respectively) (Figures 3.C and 3.D). Although the relationship for litter thickness was very weak with an $R^2 = 0.005$.

This absence of a correlation between plant biomass and litter thickness or weight suggests that other environmental factors may need to be considered as indicators for coffee growth. Several environmental factors affect plant growth in agroforestry systems, including the level of shade, water availability, and light intensity that can vary spatially even in a small area [29]. Although not in this study, trials on the impacts of reducing shade levels on coffee plant biomass are ongoing in UB forest, as it is thought that high shade levels may be limiting productivity. In addition, according to [30], nutrient imbalances can impact tree growth responses.

The relationship between litter weight and dry weight coffee bean, however, does suggest that litter weight may be a useful low-cost indicator of coffee production. This relationship could be due to improved soil fertility linked directly to the higher litter accumulation. According to [31], litter is dead material located on the surface of the soil, which will later undergo decomposition. Litter found on the soil surface becomes food intake for soil macro-organisms that decompose the litter into minerals and nutrients for plants. In the coffee agroecosystem, litter is produced by shade trees, coffee trees, and ground cover weeds collectively restore and recycle nutrients, playing an important role in the sustainability of the coffee production system [32]. Decomposition of these inputs is a key process forming of soil organic matter and nutrient cycling [33]. In the agroforestry system, the use of weed residues as an organic mulch in the planting area is also expected to improve the soil's physical, chemical, and biological properties, which can further increase crop production. This activity is likely to increase the population and biomass of earthworms which can be used as indicators of soil fertility [34].

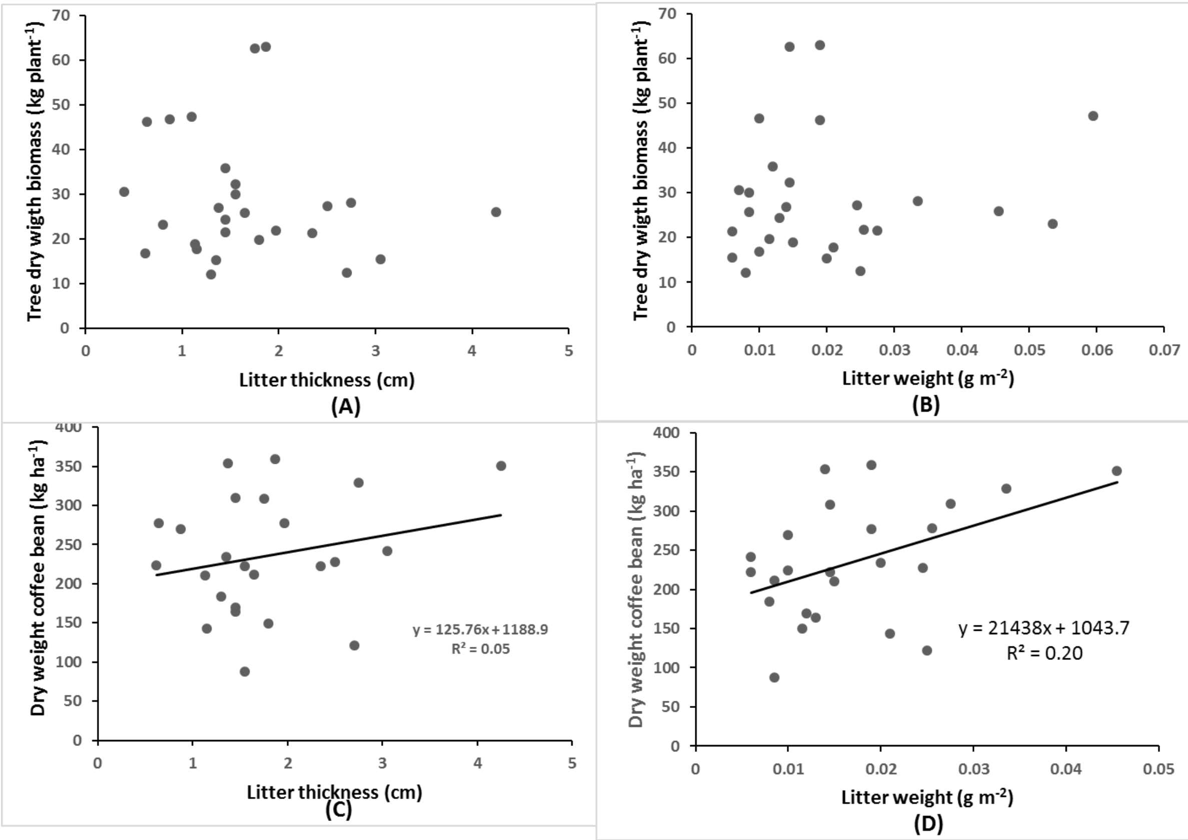


Figure 3. Relationship between (A) Litter thickness and plant biomass weight (B) Litter weight and plant biomass weight, (C) Litter thickness and dry weight of coffee bean (D) Litter weight and dry weight of coffee bean, in coffee pine-based agroforestry systems.

The results of the regression analysis showed that the number and biomass of earthworms were not related to the biomass of coffee plants (F=0.09, P=0.766 and F=0.01, P=0.094 respectively) (Figures 4.A and 4.B), while the number of earthworms and earthworms biomass was positively correlated with the dry weight of coffee beans (F=5.71, P=0.031, R^2= 0.29 and F=1.69, P=0.213, R^2= 0.13) (Figures 4.C and 4.D),.

This indicates that, as with litter biomass, earthworm number and biomass could be valuable indicators that conditions support coffee bean production. The positive relationship between earthworm biomass and number and coffee bean weight may be the result of the direct or indirect relationship.

Plants provide organic matter input through fallen leaves, branches, and twigs and through dead roots, which becomes food intake for earthworms. If increased coffee production is linked to increasing inputs, then it is likely to support higher earthworm numbers. Conversely, earthworms decomposed litter, releasing minerals and nutrients into the soil, and through their action, they increase soil porosity, factors that can promote coffee tree production. Thus there is potentially a direct link between coffee bean weight and earthworm biomass.

Earthworms do play a significant role in maintaining soil fertility physically, chemically, and biologically [35]. Physically, earthworms play a role in mixing coarse or fine organic matter between the top and bottom soil layers [36] [37]. [38] conclude that earthworms impact organic matter decomposition through (1) their effect on microbial biomass and the physicochemical parameters of microbial habitat and (2) the formation of organic matter associations by changing the organic matter types associated with minerals and possibly by creating a closer association of partially degraded organic matter and iron oxides.

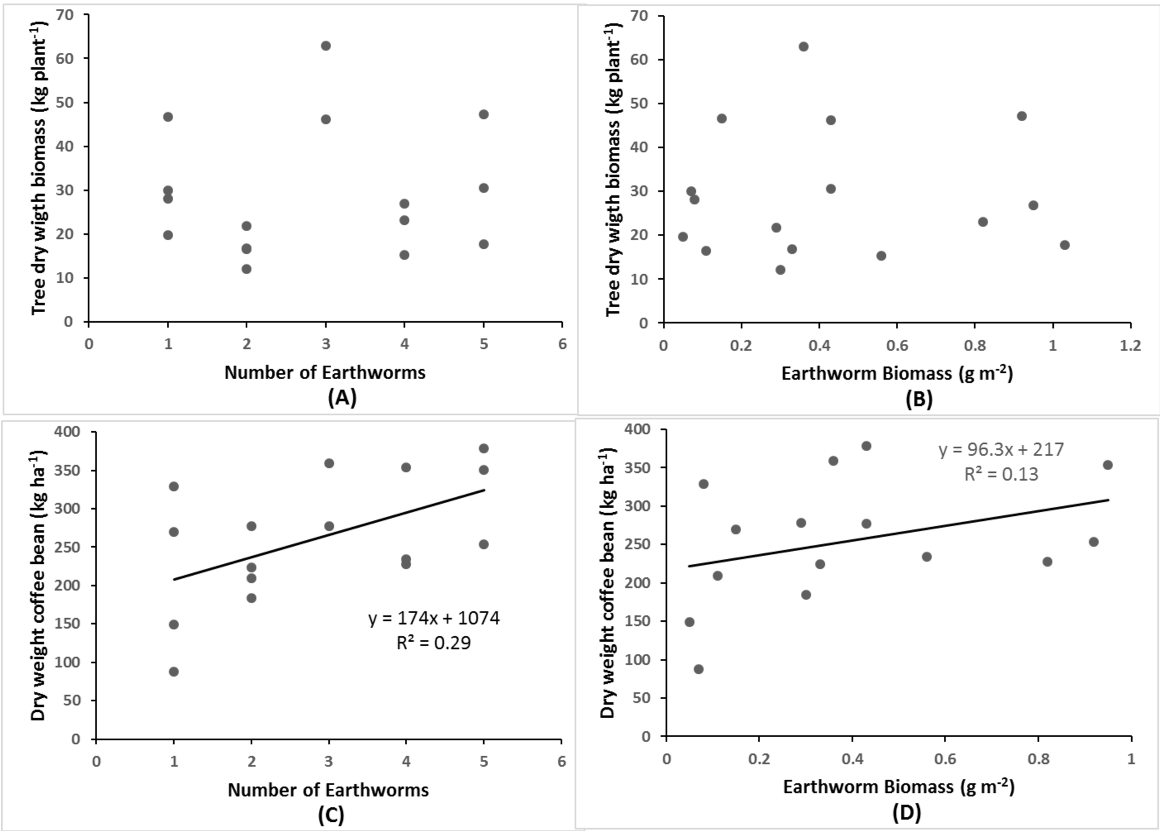


Figure 4. Relationship between (A) The number of earthworms and the weight of plant biomass (B) The weight of earthworms and the weight of plant biomass, (C) The number of earthworms with the weight of dry coffee beans (D) The weight of earthworms with the weight of dry coffee beans in coffee–pine based agroforestry system.

4. Conclusion

This study indicates that in pine coffee-based agroforestry, the size of coffee plants varies, but this has a limited impact on the variation of coffee bean production. Smallholder farmers traditionally manage coffee bean production in coffee pine-based agroforestry with limited guidance and input on cultivation methods from the wider supply chain. Coffee cultivation production in these systems is far below the average Arabica coffee production in Indonesia. Litter weight and earthworm biomass and number are easily measured in the field and can be used as indicators of coffee production capacity in pine–coffee based agroforestry, and therefore may be valuable for assessing management approaches.

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