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Soil organic matter and nitrogen in varying management types of coffee-pine agroforestry systems and their effect on coffee bean yield

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Abstract. *Sudharta KA, Hakim AL, Fadhilah MA, Fadzil MN, Prayogo C, Kusuma Z, Suprayogo D. 2022. Soil organic matter and nitrogen in varying management types of coffee-pine agroforestry systems and their effect on coffee bean yield. Biodiversitas 23: 5884-5891.* Coffee cultivation in agroforestry systems is mostly planted without soil fertility management. While there are several management interventions to improve soil quality in agricultural practices, it is not clear whether particular treatments, such as adding organic fertilizers and nitrogen fertilizers could increase coffee production in agroforestry settings. This study aimed to analyze soil organic matter and nitrogen in varying management types and its effect on coffee bean yield in a coffee-pine agroforestry setting in East Java, Indonesia. We evaluated four types of coffee management (treatments) namely: (i) no management, (ii) pruning coffee plant branches, (iii) a combination of pruning and addition of fertilizers with a planting distance of pine trees of 3 x 2 m, and (iv) pruning under pine trees with a planting distance of 6 x 2 m. The soil organic matter, total and available soil nitrogen were measured at 0-0.2 m and 0.2-0.4 m soil depths. We measured coffee bean yield to 100 coffee plants per plot. The coffee bean yield in the no-management treatment reached 376 kg ha^{-1}, while the yield under the other three treatments increased up to 3.9 times compared with no-management. This increasing coffee bean yield did not correlate with soil organic matter in topsoil, with a correlation between coffee bean yield and total ant available soil nitrogen being positive and negative, respectively. We concluded that the limitation of N in the coffee-pine agroforestry system would require management intervention in the form of adding nitrogen fertilizers to increase coffee bean yield.

Keywords: Agroforestry, coffee management, coffee yield, soil nitrogen, soil organic matter

INTRODUCTION

Coffee is one of the major commodities in Indonesia, making this country the fourth-largest coffee producer in the world (Krishnan 2017; Rosiana et al. 2018). Unlike other countries, most coffee production in Indonesia is produced through a simple or multistrata agroforestry system with some of them cultivated in forest areas (Supriadi and Pranowo 2015). Coffee-based agroforestry system in Indonesia is usually developed by planting coffee along with shade trees and herbs (Kusumawati et al. 2022). The kind of shade trees is a key factor in determining the sustainability of coffee farming. Planting shade trees is the main measurement for soil conservation in coffee agroecosystems (Fitriani et al. 2018). The coffee agroforestry system is well known as multistrata/complex and simple agroforestry (Suprayogo et al. 2010; Fitriani et al. 2018). The multistory canopy in coffee-based agroforestry provides environmental services through water and soil conservation which is better than coffee without shade. Coffee with shade trees also maintains soil nutrients, reduces and minimizes the risk of landslides and improves soil fertility by increasing the amount of nitrogen in the soil (Waktola and Kidist 2021).

On the other hand, there are several challenges in coffee-based agroforestry on forest land including (i) the low level of knowledge of the farmers regarding coffee-based agroforestry cultivation, (ii) limited business capital, and (iii) uncertainty regarding the status of land being managed by the farmers (Zakaria et al. 2017; Supriadi and Pranowo 2015). Such challenges make the coffee plants under the agroforestry system often managed without soil fertility management, resulting in relatively low coffee production. Therefore, Suprayogo et al. (2020) suggested some efforts to increase coffee production under forest stands (e.g. pine), namely: (i) the branching of coffee plants, (ii) using pruned branches and understory plants as mulch, (iii) adding organic and inorganic fertilizers to add with mulch. The pruning of coffee plant branches can facilitate the provision of sufficient nutrients by reducing unnecessary plant parts to maximize plant growth and development (Gokavi et al. 2021). Also, the addition of mulch and fertilizers certainly affect soil organic carbon and nutrients which improve soil fertility. Eventually, changes in soil fertility will increase coffee production.

Changes in farmer management in coffee-based agroforestry can cause differences in the input of organic matter in the soil. It is generally assumed that improved management in coffee-based agroforestry will result in an increase in above-ground carbon stocks which is proportional to the increase in soil organic matter. Differences in the inputs of organic matter in the form of litter, pruning residues, understorey plants for mulch and organic fertilizers change the decomposition pathway. However, a study by Noponen et al. (2013) revealed that the differences in agroforestry management did not always result in an increase in soil organic matter and even there were some cases of a decrease in soil organic matter. Reach by Sauvadet et al. (2019) which compared two coffee-based agroforestry management (i.e. conventional vs. organic methods) for 7 years, reported that adding organic matter had more effect on nutrient availability than on total soil carbon.

In a coffee-based agroforestry system, coffee production is often limited by the natural supply of nitrogen. Adequate nitrogen supply in the soil is important for growth and biomass production (Chatterjee et al. 2019). Coffee trees provided with a larger amount of N soil had a higher concentration of N per unit leaf area, light-saturated rate of leaf photosynthesis and bean yield compared to coffee trees grown in low N supply (Bote et al. 2018). Therefore, to maintain and increase soil fertility in coffee plantations, integrated soil fertility management by optimizing nutrients from the soil, recycling residues from shade trees, and application of fertilizers in an optimum quantity and frequency, and balanced nutrients (e.g. N-based) is necessary (Bhattarai et al. 2017). The concentration of mineral N (ammonium- and nitrate-nitrogen) in soil rhizosphere is fundamental to improving coffee growth and development, which is required in particularly large quantities in coffee leaves and fruit prior to fruit filling (Bruno et al. 2011).

Here, we examined the potential for improving farm management in the coffee-pine agroforestry system by focusing on how to improve soil fertility to increase coffee production in the context of the humid tropics of East Java, Indonesia. We hypothesized that better farm management in coffee-pine agroforestry would improve soil fertility and has an impact on coffee yield. In particular, we investigated soil organic matter and total nitrogen stocks, and soil nitrogen availability because of their critical importance for soil fertility management in the agroforestry system.

MATERIALS AND METHODS

Study area

This research was conducted at Andisol from April 2021 to October 2021 in the *Kawasan Hutan Dengan Tujuan Khusus Universitas Brawijaya (KHDTK-UB)* or usually called University Brawijaya Forest (UB Forest), Sumbersari Hamlet, Tawang Argo Village, Karangploso Sub-district, Malang District, East Java Province, Indonesia (Figure 1). The elevation of UB Forest ranges from 700-1100 m a.s.l with an annual air temperature of 21.9ºC and mean annual precipitation of 4,725 mm, average humidity of 58% and with a dominant slope of 15 - 25% (BMKG of Malang District, 2019; Kurniawan et al. 2019). Laboratory work was carried out in the Chemical Laboratory, Faculty of Agriculture, Universitas Brawijaya, Malang, Indonesia.

Procedures

This study used Completely Randomized Design (CRD) with four different levels of management (treatments). The study was conducted on four research plots. Four research plots were a coffee-pined based agroforestry cultivated by small farmers around the UB Forest and the size of each plot was 130x40 m. A description of the different levels of management is presented in Table 1.

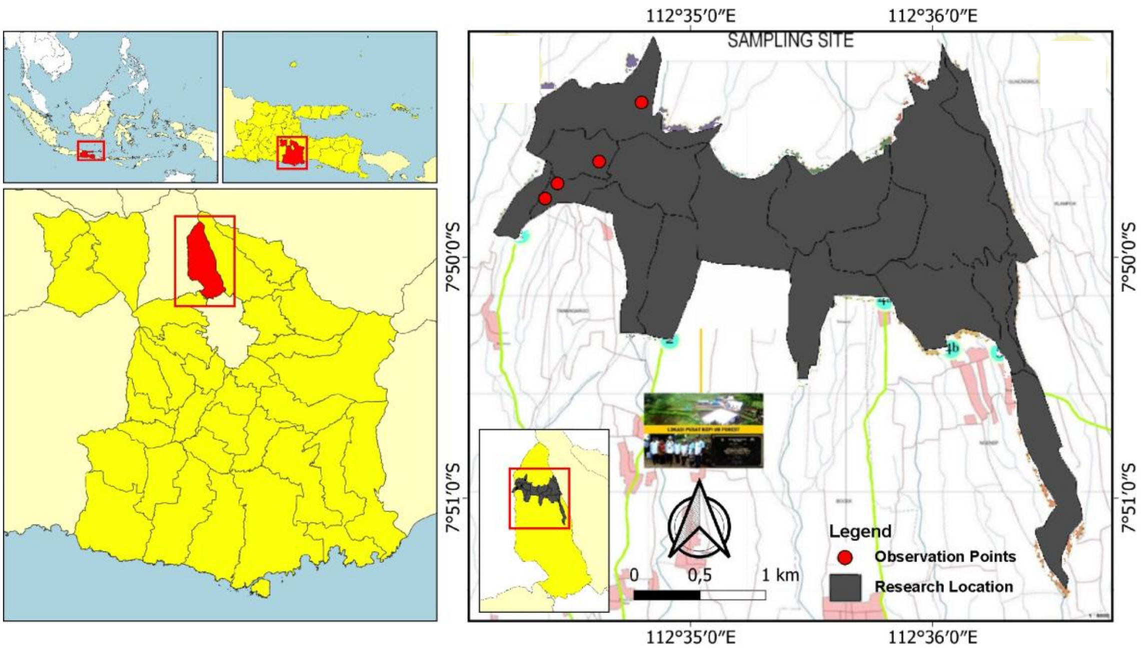


Figure 1. Map of research location: (A) the position of University Brawijaya Forest (UB Forest), Sumbersari Hamlet, Tawang Argo Village, Karangploso Sub-district, Malang District, East Java Province, Indonesia, and (B) observation points at UB Forest area

Table 1. Description of management intervention (treatment) in the research location

Plots	Management intervention
NM (No Management)	• No fertilization • Coffee crops were not maintained • Shade plants in the form of pine trees with a spacing of 3 meters x 2 meters
PM (Pruned Stems Management)	• No fertilization • Regular pruning of coffee branches • Cover crops were used as mulch • Shade plants in the form of pine trees with a spacing of 3 meters x 2 meters
PFM (Pruned Stems and Regular Fertilizers Management)	• Fertilization with manure at a dose of 1 kg/coffee plant which was applied twice a year and NPK fertilizer at a dose of 25 quintals/ha which was applied once a year • Regular pruning of coffee and the residues of the pruning were used as mulch • Shade plants in the form of pine trees with a spacing of 3 meters x 2 meters
SPM (Standard of Perum Perhutani Management)	• No fertilization • Regular pruning of coffee • Shade plants in the form of pine trees with a spacing of 6 meters x 2 meters

Note: Perhutani is a state-owned forestry corporation in Indonesia

Four research plots were sampled purposively, each plot had 3 replications, so the total observation point was 12 points. Samples were taken at the beginning of every month during the study. The observation point was used as a location for soil sampling, using a soil drill at a depth of 0-0.2 m and 0.2-0.4 m. Soil samples were analyzed to determine the content of soil organic matter, total soil nitrogen, an available soil nitrogen (ammonium (NH_4^+) and nitrate (NO_3^-). The Walkey and Black (1934) method was used to determine the content of soil organic matter, Kjeldahl method (1883) for total nitrogen content and Spectrophotometric method for available nitrogen content (Devani et al. 1989) with wavelengths: of 690 nm for NH_4^+ and 517 nm for NO_3^-. Calculation of coffee bean yield used a plot area with a size of 20x20 m. Coffee beans were harvested from each coffee tree and carried out in stages according to the maturity level of the coffee beans (red color) then the wet coffee beans were weighed and 100 samples of coffee plants were taken from each research plot to determine the oven-dry bean weight. The equations used to calculate coffee bean production are as follows:

Coffee bean water content:

$$\frac{\text{Wt of wet bean (100 beans) (g)} - \text{Wt of dry bean (100 beans) (g)}}{\text{Wt of dry bean (100 beans) (g)}} \times 100\%$$

Dry coffee bean yield per plot (g):

$$(\text{Wt of wet bean per plot (g)} - (\text{Wt of wet bean per plot (g)}) \times \text{Coffee bean water content}$$

Coffee bean yield (kg ha^{-1}):

Dry coffee bean yield (kg) × 25

Data analysis

The data obtained were analyzed by variance using Analysis of Variance (ANOVA), if the results obtained showed significant results, then continued with the Fisher's LSD (Least Significant Difference) 5% level test. Futhermore, correlation and regression tests were carried out to determine the relationship between research's variables.

RESULTS AND DISCUSSION

Coffee bean yield

The result showed that coffee bean yield significantly increased ($p < 0.05$) with the treatments of management of pruned stems (PM), and standard of Perum Perhutani (SPM) (Figure 2). The highest improvement was achieved through pruning the stems of coffee and adding fertilizer (PFM).

Soil organic matter and relation with coffee bean yield

Soil organic matter was significantly different by coffee plant pruning (PM) (except at 0.2-0.4 m soil depth) and fertilization (PFM) management compared with no management (NM) for both soil depths ($p < 0.05$) (Figures 3A and 3B). Nonetheless, the standard Perum Perhutani (SPM) with pine trees of 40 years old showed an increase in soil organic matter, compared with no management (NM) (Figures 3A and 3B).

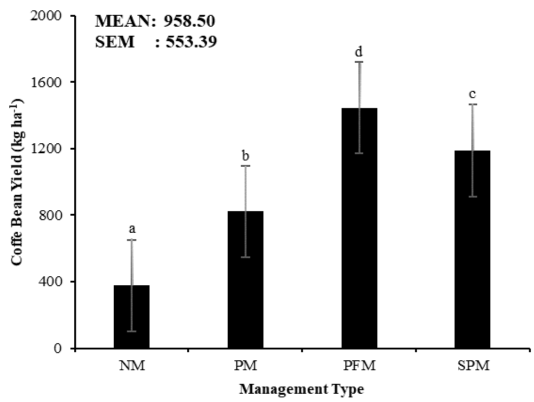


Figure 2. The comparison of coffee bean yield in four coffee-pine agroforestry treatments: no management (NM), pruned stems (PM), pruned stems + regular fertilizers (PFM), and standard of Perum Perhutani (SPM)

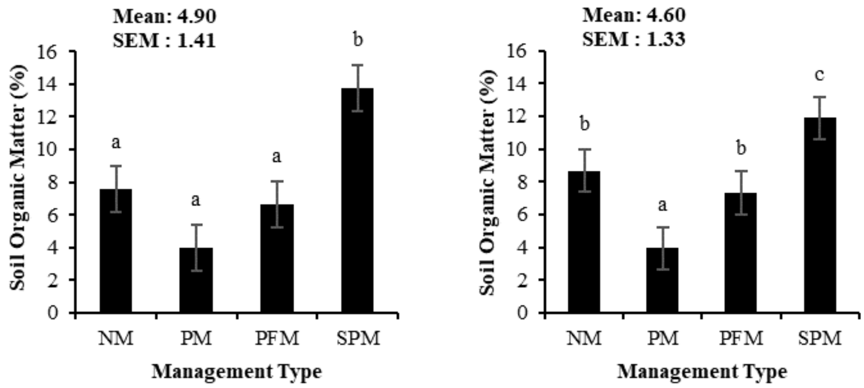
In this coffee-pine-based agroforestry system, there was a weak correlation between soil organic matter at both 0-0.2 m and 0.2-0.4 m soil depths with coffee bean production (*r = 0.020* and *0.14, p >0.05*) (Figure 4).

Total soil nitrogen

The result of the analysis showed that there was no significant increase in total soil nitrogen by coffee plant pruning (PM), pruning and fertilization application (PFM), and standard of Perum Perhutani (SPM) for both soil depths ($p > 0.05$) (Figure 5A and 5B). In this pine-coffee-based agroforestry system, total soil nitrogen at both 0-0.2 m and 0.2 m-0.4 m soil depth showed a significant positive correlation with coffee bean production ($r = 0.68$ for 0-0.2 m soil depth and $r = 0.57$ for 0.2-0.4 soil depth) (Figure 6).

Available soil nitrogen

Available soil nitrogen (NH_4^+ + NO_3^-) was not significantly different by coffee plant pruning (PM), pruning and fertilization application (PFM), and standard of Perum Perhutani (SPM) compared with no management (NM) in both rainy season and dry season ($p > 0.05$ for both seasons) (Figures 7A and 7B).



A B

Figure 3. The comparison of soil organic content at two soil depths: (A) 0-0.2 m soil depth, (B) 0.2-0.4 m, across four coffee-pine agroforestry treatments: no management (NM), pruned stems (PM), pruned stems + regular fertilizers (PFM), and standard of Perum Perhutani (SPM)

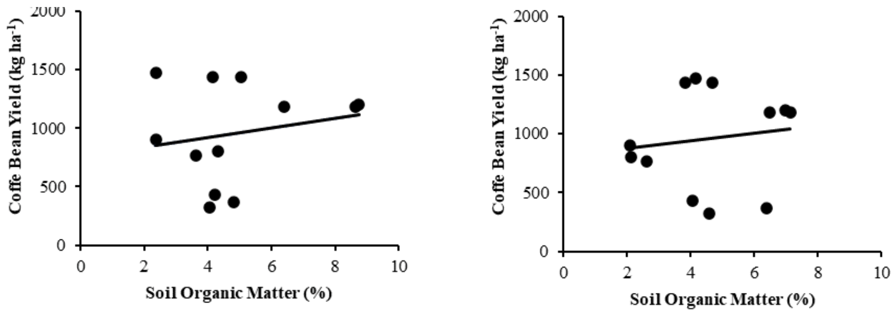


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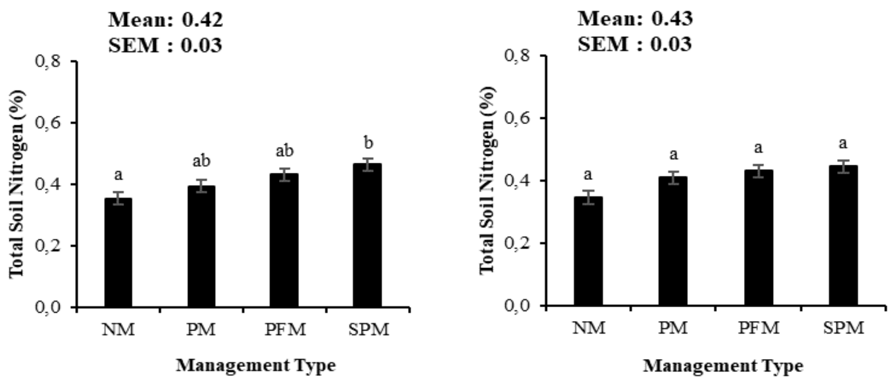
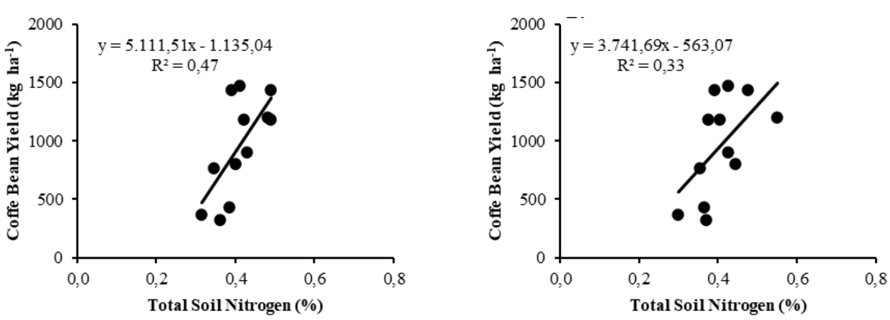
Figure 4. The association between soil organic content and coffee bean yield at two soil depths: (A) 0-0.2 m; (B) 0.2-0.4 m



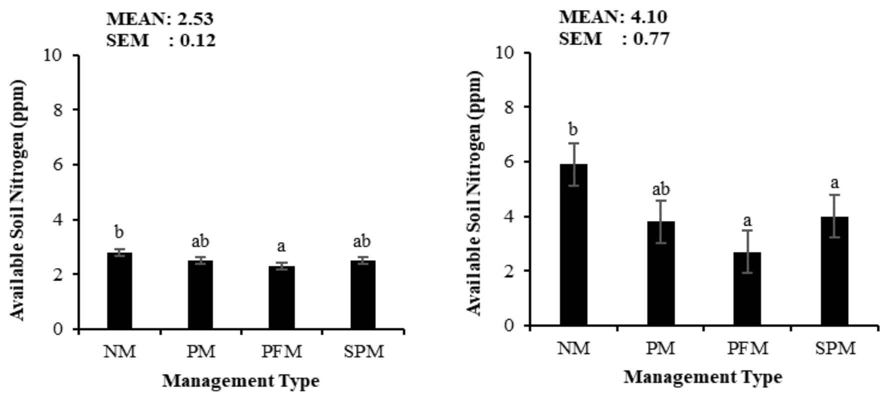
A B

Figure 5. The comparison of total soil nitrogen at two soil depths: (A) 0-0.2 m and (B) 0.2-0.4 m, across four coffee-pine agroforestry treatments: no management (NM), pruned stems (PM), pruned stems + regular fertilizers (PFM), and standards of Perum Perhutani (SPM)



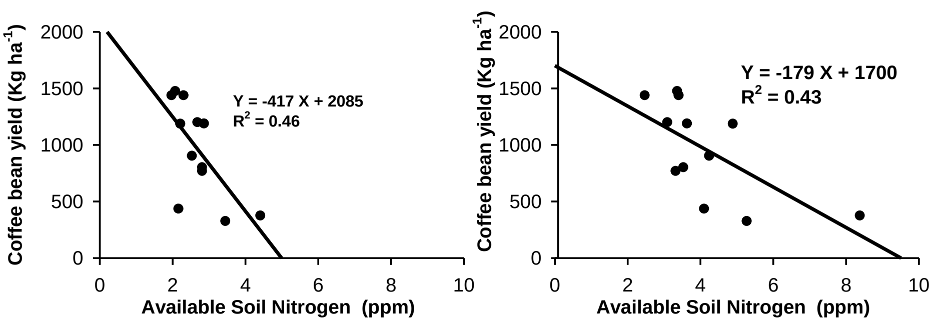
A **B**

Figure 6. Regression analysis between total soil nitrogen (axis X) and coffee bean yield (axis Y) at two soil depths: (A) 0-0.2 m; (B) 0.2-0.4 m



A **B**

Figure 7. The comparison of available soil nitrogen ($NH_4^+ + NO_3^-$) at two soil depths: (A) 0-0.2 m and (B) 0.2-0.4 m, across four coffee-pine agroforestry treatments: no management (NM), pruned stems (PM), pruned stems + regular fertilizers (PFM), and standard of Perum Perhutani (SPM)



A **B**

Figure 8. Regression analysis between available soil nitrogen ($NH_4^+ + NO_3^-$) and coffee bean yield: (A) in the rainy season (April 18th, 2021); and (B) in the dry season (July 25th, 2021)

Discussion

According to Agustian and Simanjuntak (2018), the soil organic matter content in the research plots was classified as high (3-5%) (PM) to very high (>5%) (NM, PFM and SPM) both at the depths of 0-0.2 m (Figure 3A) and 0.2-0.4 m (Figure 3B). It is known that the type of soil at the study site is classified as Andisols soil (Kurniawan et al. 2019) and its formation is classified as a volcanic landform (Kurniawan et al. 2019). Soil formation at the research site was influenced by the activity of Mount Arjuno from the parent material of volcanic tuff and ash which caused the high content of soil organic matter (Kurniawan et al. 2019). This is in line with the study by Anindita et al. (2022) that showed high organic matter content was also found in Andisols. High SOC content in Andisols because this soil is formed from volcanic ash which contains allophanic minerals and amorphous fractions, which can form complexes with humic substances. The affinity of allophane minerals in binding topsoil compounds is very high and more resistant to microorganism attacks. This condition causes the soils of Andisols to be dark in color because they contain humus compounds, especially in the upper layers (Sufardi et al. 2020). High SOC content does not guarantee the humification process that produces complex humus compounds, so the return of organic mass into the soil needs to be carried out continuously to conserve soil organic matter. Based on this, the amount of organic matter and its distribution in the soil is very important to maintain soil quality (Sufardi et al. 2020). The quality and nature of fertility are closely related to the organic C content of the soil, especially soils that develop in humid tropical climates, because the loss of soil organic matter in this region is relatively high. Andisols not only have high organic matter content, low bulk density, high water holding capacity and high total porosity, but this soil is also loose in consistency, less plastic and not sticky (Montoya et al. 2017).

From this study, it is revealed that the high content of organic matter in the research location did not affect coffee production. This is presumably because the organic matter content in the soil is sufficient for plants to support their growth. The high soil organic matter has more influence on maintaining fertility status and soil productivity (Voltr et al. 2021). Besides being influenced by soil type, the high content of soil organic matter in the location is also thought to be influenced by other factors. The research by Wardani et al. (2021) showed that the high soil organic matter content in the coffee agroforestry system was due to land management in the form of not transporting litter and pruning residue out of the land. Organic matter will accumulate due to the decomposition process of litter, which in turn will play an important role in improving soil quality and will increase soil productivity in the long term. Very high soil organic matter content (> 5%) was found in the PFM and SPM plots that carried out the management. In addition, the organic matter content of the soil is not only influenced by the amount of litter, but also the quality of the litter is an important factor in the rate of litter decomposition. Several studies reported that lignin has an important role in the decomposition process, even though its concentration is more influential than other chemical concentrations (Devianti and Tjahjaningrum 2017; Kusumawati and Prayogo 2019). The types of litter found at the research site were coffee and pine litter. It has been reported that the lignin content in pine litter was high compared to litter from other plants (Devianti and Tjahjaningrum (2017); Kusumawati and Prayogo (2019). Litter that has high quality can increase or accelerate the decomposition process of the litter so that it can cause nutrients to be quickly available and released (Kusumawati and Prayogo 2019; Garcia et al. 2021).

The results of the correlation analysis showed that total soil nitrogen at a depth of 0-0.2 m had a positive and strongest relationship with coffee bean yield (R^2 = 0.47). The total soil nitrogen in all types of management was in the medium category with a mean of 0.42 % (0-0.2 m soil depth) (Figure 5A) and 0.43 % (20-40 m soil depth) (Figure 5B). This is consistent with the findings of Agustina et al. (2020) in which total soil nitrogen ranging from 0.21 % to 0.50% belongs to the medium category. In addition, the results of total soil nitrogen in this study were relatively lower than the critical levels (0.3-0.6 %) for optimal coffee production as recommended by The Coffee Research Foundation (CRF) (Mwenda et al. 2022). This is in line with Nzeyimana et al. (2019) which reported that increasing total soil nitrogen was able to increase coffee production. Higher levels of total soil nitrogen were found at the PFM plot, which was a research plot with fertilization management. Agroforestry systems still need fertilizer to increase the nutrient content in the soil (Sida et al. 2020). Several studies have shown that soil organic matter content can increase the nitrification process so that the soil nitrogen content in the soil would increase (Supriadi et al. 2016; Sosa et al. 2019; Zhang et al. 2022). Nitrogen is an essential nutrient that plants need in large amounts. Coffee plants need nitrogen for vegetative growth, such as leaves, stems and roots (Netsere and Takala 2021). Nitrogen is also very important in relation to the formation of chlorophyll in plant leaves (Arena et al. 2020). Nitrogen element functions to increase plant growth, indicated by nourishing leaf growth with greener leaf colors (Putri et al. 2021). Plants that have a high chlorophyll content are expected to be efficient in utilizing solar energy to carry out the photosynthesis process (Janeeshma et al. 2022), and will also increase plant biomass and crop seed yields (Putri et al. 2021). Coffee plants lacking nitrogen will experience a decrease in coffee bean production by up to 60% (Jimenez et al. 2017). Plants that have a high chlorophyll content are expected to be efficient in utilizing solar energy to carry out the photosynthesis process (Janeeshma et al. 2022), and will also have an effect on increasing plant biomass and crop seed yields (Putri et al. 2021). Coffee plants that lack nitrogen will experience a decrease in coffee bean production by up to 60% (Jimenez et al. 2017).

The results showed that the available soil nitrogen in the rainy season was lower than that in the dry season (Figures 7A and 7B). This occurred in all research plots. Nitrogen is generally absorbed by plants in the form of ammonium (NH_4^+) and nitrate (NO_3^-). Furthermore, the relationship between available soil nitrogen and coffee bean yield showed an inverse relationship (Figures 8A and 8B). The production of coffee beans will increase, followed by a decrease in the available soil nitrogen in the soil. The decrease in the available soil nitrogen of the soil indicated that plants could utilize ammonium (NH_4^+) and nitrate (NO_3^-) in the soil. We assume that the available soil nitrogen at the study site during the dry season was higher, presumably due to the role of understorey vegetation and the density of plants which could suppress the evaporation of nitrogen into the air. An increase in the content of available soil nitrogen during the dry season was found in all research plots. Available soil nitrogen in the rainy session may be lost due to leaching by rainfall to the soil surface, resulting in low levels of available soil nitrogen. Nitrogen is an element that has mobile properties, so it is easily leachable and volatile so plants are susceptible to deficiency of this element (Nuraeni et al. 2019). Nitrogen is also one of the most susceptible macronutrients to loss thought, ammonia volatilization (NH_3), nitrous oxide (N_2O) emissions, nitrate leaching (NO_3), etc. (Mahmud et al. 2021). According to Xu et al. (2018) and Liu et al. (2021), the levels of available soil nitrogen in the soil are strongly influenced by soil moisture, water content and aeration which can be a limiting factor on the rate of mineralization, nitrification and denitrification so that the amount of pore space filled with water is a factor that plays a direct role in the transformation of nitrogen in the soil, especially those related to with the activity of nitrogenous bacteria. Rainfall can directly change soil moisture. Rainfall can also encourage the growth of vegetation which will increase the absorption of nitrogen in the soil and can increase the contribution of litter to the soil surface. Adam et al. (2022) added that a significant increase in temperature could increase the rate of mineralization of organic matter, so it also has an impact on increasing available soil nitrogen in the soil. The presence of nitrogen in the soil is influenced by climate, topography, type of soil parent material and plants that live on it (Zhong et al. 2019). This makes the presence of available soil nitrogen in the soil less stable or always changing. The presence of nitrogen in the soil can also be influenced by the nature of the soil, the type of plant and the stages of plant growth. The high and low soil nitrogen is influenced by the amount of input and loss in the nitrogen cycle. Khalif (2018) show that the agroforestry system can support the best quality of soil fertility compared with the dry land agriculture system which is characterized by high levels of available soil nitrogen in the soil. The agroforestry system has a relatively dense land cover which can minimize loss of nitrogen due to leaching and evaporation, and can withstand the energy of rainwater which can inhibit the rate of eluviation of clay particles that play a role in nutrient uptake.

The coffee bean yield at the PFM plot showed the highest yield, followed by the SPM, PM and NM plots. The high yields at the PFM plot were influenced by the application of fertilizer and the use of the pruning residues as mulch by farmers. Such management increased soil fertility at the PFM plot. This is supported by the results of the measurement of the three parameters of the production limiting factors, where the PFM plot showed good results. So that the management carried out at the PFM plot was able to increase coffee bean production. The same case was reported by Boas et al. (2017), that the combination of fertilization and organic mulch gave a positive response to coffee bean yield and increased soil fertility, when compared to without fertilization. On the other hand, the high coffee production at the SPM plot was influenced by light intensity regulation. The SPM plot shade trees spacing compared to other plots. This condition affected the amount of light entering the land which is related to the need for coffee plants as C3 plants. The stomata opening of coffee plants which belong to the C3 photosynthesis type, is sensitive to high light intensity. Coffee beans appear on primary, secondary and tertiary branches so pruning coffee branches is not only to increase productive branches but also to increase bean yield. Pruning can make a redistribution of photosynthetic results in the form of photosynthate which leads to the number of coffee beans which will affect higher production (Dufour et al. 2019). This is in line with the research results of Siahaan et al. (2019), Musa et al. (2020), Rowe et al. (2022) that pruning coffee branches and setting the level of shade in the cultivation of coffee plants in an agroforestry system can increase the production and quality of coffee beans.

Although the correlation results were not statistically significant, the presence of soil organic matter was sufficient for plants to support their growth. Nonetheless, the total soil nitrogen at the study site was the strongest factor that affected coffee bean production. Research plots that carried out fertilization management gave better results in total soil nitrogen content. Also, available soil nitrogen at the study site was influenced by climate (rainy season and dry season) and had a good response to coffee bean production even though it showed negative regression results.

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