



# Soil nitrogen dynamics affected by coffee (*coffea arabica*) canopy and fertilizer management in coffee-based agroforestry

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**Abstract** Nutrient management in coffee-based agroforestry systems plays a critical role in soil nitrogen (N) cycling, but has not been well documented. The objective of this study was to evaluate the effect of coffee canopy management and fertilization on soil N dynamics. This study used a randomized complete block design ( $2 \times 3 \times 2$ ) with four replications. There were three factors: 1) coffee canopy management (T1: Pruned, T2: Unpruned), 2) fertilizer type (O: Organic, I: Inorganic; M: 50% Organic + 50% Inorganic), and 3) fertilizer dose (D1: low, D2: medium, D3: high). Soil N dynamic indicators (i.e., total N, ammonium ( $\text{NH}_4^+$ ), nitrate ( $\text{NO}_3^-$ ), net  $\text{N-NH}_4^+$ , net  $\text{N-NO}_3^-$ , soil microbial

biomass N) were measured at two soil sampling depths (0–20 cm and 20–40 cm). Results showed that pruning increased soil total N and microbial biomass N (MBN) by 10–56% relative to unpruned coffee trees. In contrast, the unpruned coffee canopy had 15–345% higher  $\text{NH}_4^+$ ,  $\text{NO}_3^-$ , net  $\text{N-NH}_4^+$ , net  $\text{N-NO}_3^-$ , and microbial biomass N concentration than pruned coffee. Mixed fertilizer application increased  $\text{NO}_3^-$  and net  $\text{N-NH}_4^+$  accumulation by 5–15% relative to inorganic and organic fertilizers. In addition, medium to high dose fertilization led to a 19–86% higher net  $\text{N-NO}_3^-$  concentration and microbial biomass N as compared to low dose fertilization. The treatment of no pruning and mixed fertilizer at low to medium doses was the optimal management strategy to maintain soil available N, while pruning combined with organic fertilizer has the potential to improve soil total N and MBN.

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## Introduction

Coffee is a globally important cash crop that has experienced significant production growth over the past decade as a result of increased world coffee consumption (Torga and Spers 2020). FAOSTAT (2021) recorded that the total worldwide harvested area of coffee cultivation reached 11.37 million hectares in 2021, with a total production of 10 million tonnes and an average productivity estimated at as much as 0.79 tonnes/ha. The harvested area and productivity in 2021 increased 10% and 7%, respectively, relative to 2012. Indonesia has the second largest coffee plantation area of all countries, with a total harvested area of 1.25 million hectares. However, coffee productivity in Indonesia, at 0.61 t/ha (Directorate General of Estates 2020), is lower than the average worldwide productivity (Ayele et al. 2021). It is therefore of paramount importance to enhance coffee production in Indonesia. Unfortunately, efforts to increase coffee production in Indonesia has a challenge related to degradation of soil fertility (i.e., low soil nutrient availability especially nitrogen; Sudharta et al. 2022). Therefore, efficacious strategies is crucial to apply for improving coffee productivity (Rowe et al. 2022).

Coffee is cultivated in both monoculture and agroforestry systems (Rigal et al. 2020). Campanha et al. (2004) reported that monoculture systems tended to have higher coffee productivity (2.44 tonnes/ha) as compared to agroforestry systems (515 kg/ha). In Indonesia, coffee plantations are mainly owned and managed by smallholders (about 98% of the total coffee area; Directorate General of Estates 2020). Smallholder coffee agroforestry generally involves different management practices for trees (both the shade trees and the coffee) and soil (fertilization), causing high variation in coffee productivity (Siles et al. 2022). Coffee agroforestry is a land-use system that combines coffee and trees to provide income to local farmers and maintain environmental services such as nutrient cycling. In coffee-based agroforestry systems, coffee canopy management, such as pruning, is used to produce productive branches and increase coffee berry production (Dufour et al. 2019; Karim et al. 2021) and to keep the coffee plant short and easy to harvest. Nevertheless, the consequences of pruning

management on the dynamics of soil nitrogen require further investigation. Management practices above ground can directly or indirectly influence below-ground processes. A comprehensive understanding of the relationship between management systems and the benefits of increased coffee productivity and land sustainability may be achieved through this research.

In addition to coffee canopy management, fertilization is a common soil management practice in coffee agroforestry systems to increase nutrient availability (i.e., N, P, K). Recent studies have suggested that canopy management combined with N fertilizer application is a critical factor for improving the agronomic and economic performance of coffee in both monoculture and agroforestry systems (Rowe et al. 2022; Sudharta et al. 2022). The study, however, only addressed the effects of fertilizers and canopy management on coffee production, C sequestration, and other environmental services. The study of the management effects on soil N dynamics has not been well documented. This is important because N is the main limiting factor in agricultural soils, and its availability is very dynamic in soil systems (Kuypers et al. 2018; Sudharta et al. 2022). Production and management practices to optimize soil N levels are determined by land use systems, soil management, and the soil environment (Allen et al. 2015; Kurniawan et al. 2019). Specifically, soil N dynamics are related to soil organic matter, N availability, and soil microbial biomass (Corre et al. 2010; Allen et al. 2015). Fertilization (i.e., organic and inorganic fertilization) is a factor that strongly determines the N dynamics in the soil. Application of organic fertilizer leads to an increase in available soil N to support plant growth and microbial activities following the mineralization of the added N. Furthermore, the addition of inorganic N fertilizer rapidly releases available N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) increasing N availability for plants. However, an increased concentration of available soil N can stimulate soil microbes leading to the increased rates of soil organic matter decomposition and N immobilization. Therefore, the activity of soil microorganisms can also decrease N availability for plant. High rates of N immobilization by microorganisms lead to positive environmental effects, such as reducing N loss through leaching but can temporarily inhibit N uptake by plants.

Universitas Brawijaya Forest, named UB Forest, is a coffee agroforestry system located in East Java province, Java Island, Indonesia, with low coffee production

due to the high variation in management practices used by farmers. Recent coffee research within UB Forest suggested the importance of managing N fertilization to increase the yield of coffee beans (Sudharta et al. 2022). The type and dose of fertilization may influence the rate of nitrogen (N) release, which in turn affects the density and biomass of soil microorganisms and consequently modifies the dynamics of soil N. This hypothesis is consistent with a previous study conducted in the same location by Rowe et al. (2022), which reported that pruning and fertilization practices not only affect coffee yield but also provide environmental services (i.e., soil carbon and nitrogen dynamics).

The current study was designed to find the optimal management practices in coffee agroforestry systems that can both increase coffee yield and maintain environmental services such as nutrient cycling (i.e., soil respiration, soil microbial biomass, nutrient leaching losses). The aim of the current study was to evaluate the effect of coffee canopy management and fertilization on soil N dynamics and its relationship with coffee bean yield.

## Material and Methods

### Study Site

The study was conducted in the Universitas Brawijaya Forest Research Station (7°49'27.2" S, 112°34'41.0" E, Supplementary Fig. 1), located in Karangploso sub-district, East Java. The Research Station is at an altitude of 1,300 m above sea level (m asl), with an annual rainfall of 2,000 mm year<sup>-1</sup> and an average daily air temperature of 23.61 °C (Indonesian Meteorological Climatological and Geophysical Agency 2023). Coffee agroforestry is established at the station where the main crop is Arabica coffee (*Coffea arabica*, ranging between 8 to 10 years old) shaded by pine (*Pinus merkusii*, 35 years old). Two coffee management approaches are used to support production at the station: pruned coffee management and unpruned coffee management. The pruned biomass was removed from the site. Local coffee agroforestry farmers apply inorganic fertilizer such as Urea, Ammonium Phosphate (ZA), NPK compound fertilizer (i.e.,

Phonska) with the rate 380 kg N/ha/year, 240 kg P/ha/year, and 400 kg K/ha/year. The dose is lower than the recommended fertilizer, as recommended by Indonesia Ministry of Agriculture (2022). Organic fertilizer was added in the form of poultry manure at 25 tons per hectare as a farmer's business as usual.

Coffee agroforestry at the UB Forest is grown on Inceptisols (USDA soil classification), with a Cambic horizon and subgroup Andic Humudepts (Kurniawan et al. 2019). Both coffee management practices have identical soil properties (Supplementary Table 1). The soil has very low available P, acidic pH, high cation exchange capacity, and medium base saturation. The soil texture class is silty loam and bulk density is less than 1 g/cm<sup>3</sup>. Pruned coffee typically has a shorter height than unpruned coffee. The environmental conditions (i.e., soil temperature and air temperature), canopy cover, and coffee production were comparable between pruned and unpruned coffee. However, the change in average air temperature was slightly higher in pruned coffee than in unpruned coffee. In addition, soil organic matter in the pruned and unpruned coffee was categorized as high. Coffee bean productivity in the pruned and unpruned coffee agroforestry is categorized as low, with fresh productivity ranging from 183–194 kg/ha.

### Experimental Design and Sampling Method

This study used a randomized complete block design (RCBD) with three factors and four replications. Coffee canopy management (Supplementary Fig. 2a) was the first factor, consisting of pruned coffee (T1) and unpruned coffee (T2). The second factor was the type of fertilizer (i.e., organic fertilizer (O), inorganic fertilizer (I), and a mixture of 50% organic fertilizer and 50% inorganic fertilizer (M)). Three fertilizer doses (low, medium, and high) were used (the name of the organic and inorganic fertilizer, along with the dosage for application, is provided in Supplementary Table 2). Low fertilizer dose is the dose based on nutrient loss from harvested coffee beans (D1 calculated as Equation 1); the medium fertilizer dose is the farmer's dose (D2); the high fertilizer dose is the recommended dose based on Wahyudi et al. (2016) (D3).

$$\text{Fertilizer dose (g/plant)} = \text{nut. Cont. in coffee (g/kg)} \times \text{tot. coffee harvest (kg/plant)} \times \frac{100\%}{\% \text{ nut. In fertilizer}} \quad (1)$$

where: nut.cont.in coffee = nutrient content in coffee bean, tot. coffee harvest = total coffee bean harvested per tree at each plot; % nut. In fertilizer = nutrient content in the fertilizer

The combination of treatments and replications resulted in 72 individual plots, with an area of 4 m<sup>2</sup> in each plot. The amount of fertilizer used for each dose and type of fertilizer is summarized in Supplementary Table 2.

The organic fertilizer used in this research was poultry manure, containing 1.49% N, 2.91% P<sub>2</sub>O<sub>5</sub>, and 2.57% K<sub>2</sub>O (Nugroho et al. 2023). The inorganic fertilizer was a single fertilizer comprising urea (46% N), SP-36 (36% P<sub>2</sub>O<sub>5</sub>), and KCl (60% K<sub>2</sub>O). The mixed fertilizer consisted of 50% organic fertilizer + 50% inorganic fertilizer from each dose (D1, D2, D3). All fertilizer was applied at a depth of 5 cm in a circle around the coffee plant at a distance of 0.5 m from the base of the trunk (Supplementary Fig. 2b).

Soil samples were collected from four points surrounding the base of each coffee plant at a distance of 0.3 m from the trunk (Supplementary Fig. 2b), and then composited into a sample representing each treatment and replication. Soil was collected from two soil depths, 0–20 cm and 20–40 cm, at each location before fertilization and 6 months after fertilization. Each composite sample was split and stored in two different bags (air-dried and fresh). Fresh soil samples were kept at 4 °C to prevent N loss due to volatilization. Dry soil samples were air-dried for one week, then ground and sieved through 2 mm mesh.

### Soil Chemical Analysis

The concentration of total N, ammonium (NH<sub>4</sub><sup>+</sup>), and nitrate (NO<sub>3</sub><sup>-</sup>) in soil was quantified in this study. Soil total N was measured using the method as used by Indonesian Soil Research Institute (2009). Available N was

$$\text{Net N-NH}_4^+ \text{ concentration (mg/kg)} = \text{N-NH}_4^+_{\text{sample}} - \text{N-NH}_4^+_{\text{control}} \quad (3)$$

While the soil net N-NO<sub>3</sub><sup>-</sup> concentration were calculated using Eq. 4.

$$\begin{aligned} \text{Net N-NO}_3^- \text{ concentration (mg/kg)} \\ = \text{N-NO}_3^-_{\text{sample}} - \text{N-NO}_3^-_{\text{control}} \end{aligned} \quad (4)$$

analyzed by extracting ammonium and nitrate from fresh soil using 1 M KCl with a 1:1 ratio of soil to extractant (Kachurina et al. 2000). Then, 2 mL of extraction was used to analyze ammonium using the phenate method, while 5 mL of extraction was used to analyze nitrate using the brucine method (Indonesian Soil Research Institute 2009). A UV-VIS spectrophotometer was used to measure ammonium and nitrate concentration, utilizing wavelengths of 636 and 432 nm, respectively.

### Soil Microbial Biomass N (MBN) Analysis

Soil microbial biomass was analyzed using the chloroform fumigation extraction (CFE) method from Vance et al. (1987) with modification. Ten grams of fresh soil was incubated with chloroform for 24 h in an air-free desiccator. To the incubated soil, 0.5 M K<sub>2</sub>SO<sub>4</sub> was added at a ratio of 4:1 (v/w), then extracted and filtered until a filtrate remained using ash-free filter paper. Estimation of NH<sub>4</sub><sup>+</sup>-N was used to determine MBN (Moore et al. 2000). Soil microbial biomass N was measured in 2 mL of filtrate using the phenate method (Indonesian Soil Research Institute 2009). The microbial biomass concentration was calculated using Eq. 2 as follows:

$$\text{Microbial Biomass (mg/kg soil)} = \frac{s_N}{k_v} \quad (2)$$

where  $s_N$  = (N content on fumigated soil) – (N content on non-fumigated soil), and  $k_v$  = Coefficient factor of microbial biomass N analysis (0.57).

### Calculation of N Dynamics

Soil net N-NH<sub>4</sub><sup>+</sup> and net N-NO<sub>3</sub><sup>-</sup> concentrations were calculated to analyze soil nitrogen pathways (mineralized or immobilized) based on the formula described by Qifli et al. (2014) (Equation 3 and Equation 4). Soil initial condition (before fertilizer application) was used as the control treatment.

where N-NH<sub>4</sub><sup>+</sup> was conversion from NH<sub>4</sub><sup>+</sup> concentration to N concentration, while N-NO<sub>3</sub><sup>-</sup> was conversion from NO<sub>3</sub><sup>-</sup> to N concentration; the N-NH<sub>4</sub><sup>+</sup> and N-NO<sub>3</sub><sup>-</sup> control used the initial measurement before fertilization.

## Coffee bean yield measurement

Coffee bean yield was measured during the period of May to September 2022 and coffee beans were harvested once red color had developed. Harvesting was carried out per coffee tree in each treatment plot by collecting all the red beans. Then, the coffee beans were weighed to obtain the fresh weight of coffee beans per tree. Harvested coffee beans were dried at 105 °C and weighed to obtain the dry weight of the coffee beans. The coffee bean production per tree was then calculated by averaging coffee bean yield from all the coffee tree at each plot.

## Data Analysis

All data were analyzed using R studio. Before performing the analysis of variance, data of each parameter were tested for normality using Shapiro–Wilk’s test. If the data are normally ( $P \geq 0.05$ ), then analysis of variance (ANOVA) for a randomized block factorial design at a 95% confidence level was used to determine the effect of treatment on each tested parameter. When the normality test showed  $P \leq 0.05$ , the data were logarithmically or square root transformed before performing the ANOVA test. Duncan Multiple Range Test (DMRT) was performed to find the difference between treatments. Pearson correlation test and principal component analysis (PCA) were used to determine the relationship between treatments (Crawley 2012).

## Results

### Effect of coffee canopy and fertilization management on total and available soil N

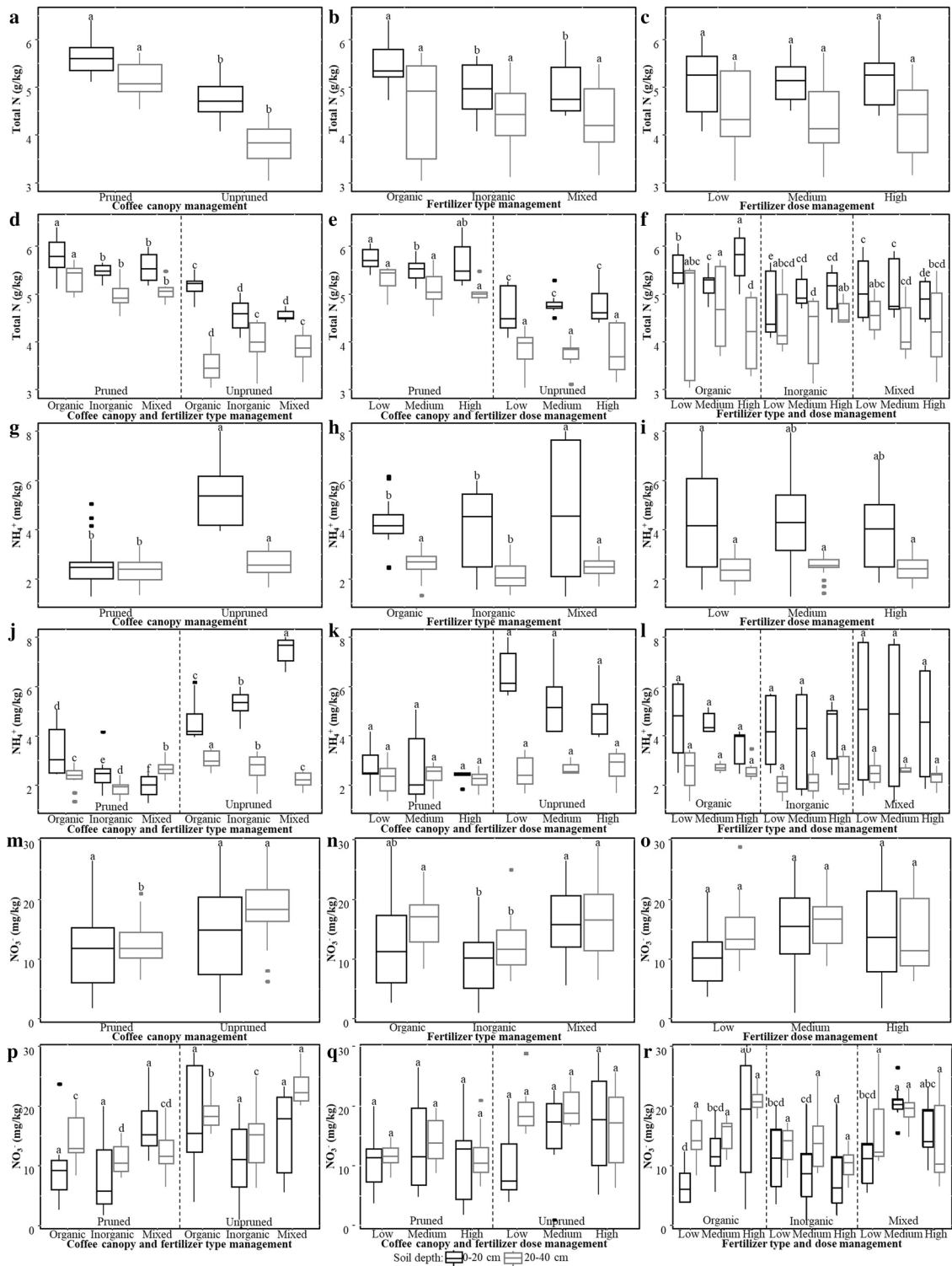
There was a significant effect of coffee canopy management on soil total N at 0–20 cm and 20–40 cm depth of soil (Fig. 1a). Soil total N was 18–35% higher in the pruned coffee as compared to unpruned coffee at all soil depth (Fig. 1a). A significant effect of fertilizer type on soil total N was found only in the topsoil (0–20 cm soil depth), which application of organic fertilizer significantly increased soil total N by 9–10% relative to the other fertilizer types (i.e., inorganic and mixed) after 6 months of application (Fig. 1b.). In addition, application of organic fertilizer combined with

pruned coffee had the highest soil total N than the other combination of fertilizer type and coffee canopy management at 0–20 cm and 20–40 cm of soil depth (Fig. 1d).

Overall, there was no significant effect of fertilizer dose on soil total N (Fig. 1c). However, the combination between fertilizer dose and coffee canopy management or fertilizer type were significantly affected to soil total N (Fig. e and f). The low dose fertilizer combined with pruned coffee canopy had 19–23% higher of soil total N as compared to application of fertilizer with medium to high doses combined with unpruned coffee canopy at 0–20 cm soil depth (Fig. 1e). Furthermore, the interaction of three factors (i.e., fertilizer dose, fertilizer type, and coffee canopy management) was significant ( $P \leq 0.05$ ) in its effect on soil total N both at 0–20 cm and 20–40 cm soil depth (Fig. 2; Supplementary Table 3). Application of organic fertilizer at the highest doses combined with pruning resulted in the highest soil total N ( $6.14 \pm 0.11$  g N/kg) recorded in the study at 0–20 cm soil depth. At the 20–40 cm depth of soil, the highest soil total N was found on the application of organic fertilizer at the low and medium doses combined with pruned coffee ( $5.55 \pm 0.14$  and  $5.49 \pm 0.02$  g N/kg, respectively).

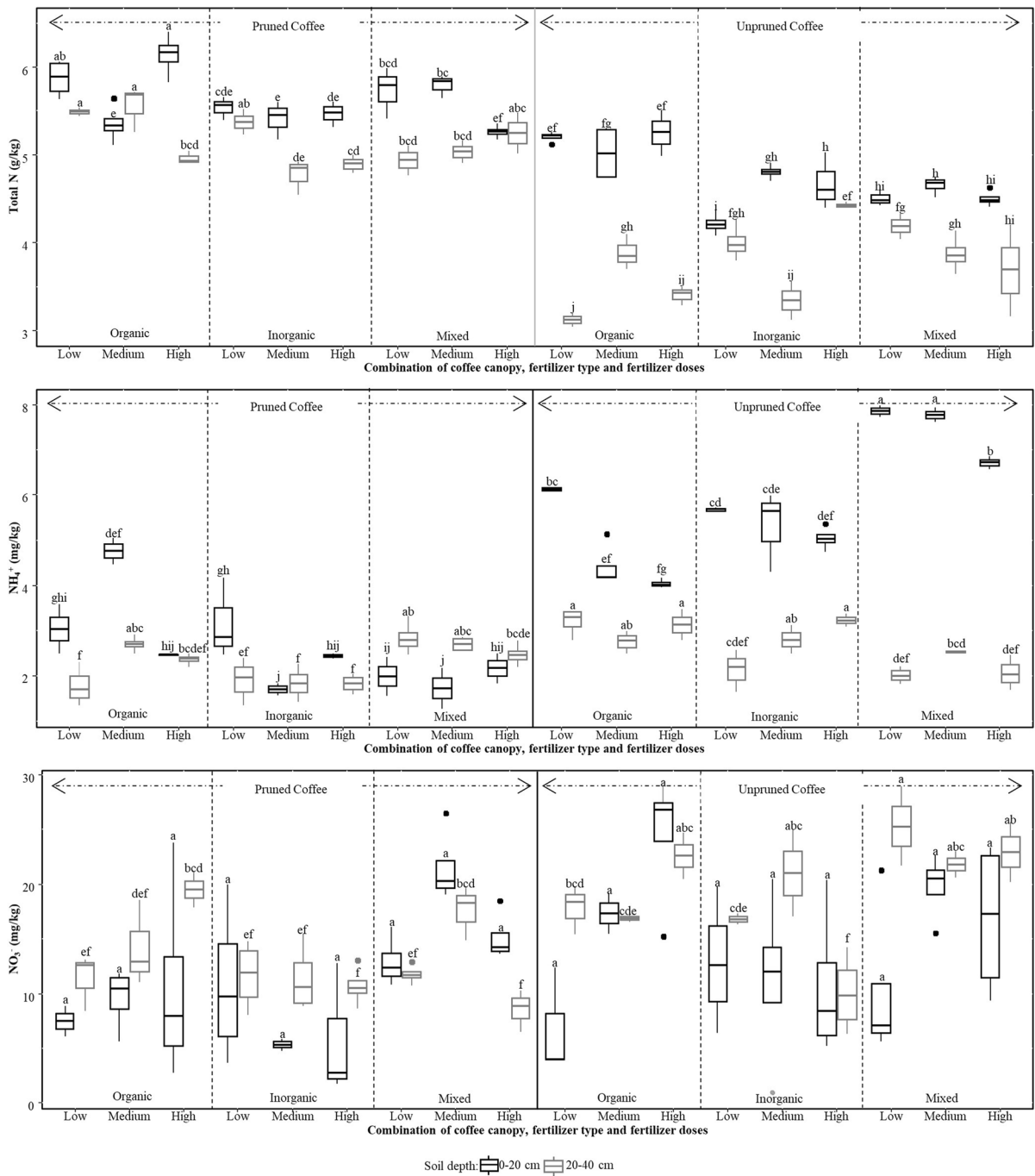
The concentration of soil available N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) exhibited a different pattern and strongly affected by fertilizer management (i.e., types and doses), and the value was greater for the unpruned than the pruned treatment (Fig. 1g and m) at 0–20 cm and 20–40 cm soil depth. The mixed fertilizer treatment (organic and inorganic) increased the  $\text{NH}_4^+$  concentration by 13–15% relative to the other types of fertilizer application (i.e., inorganic and organic fertilizer), and increased the  $\text{NO}_3^-$  concentration by up to 60% higher compared to inorganic fertilizer at 0–20 cm soil depth (Fig. 1h and n). Then, low dose fertilizer application resulted in a 13% higher  $\text{NH}_4^+$ -N concentration at 0–20 cm depth (Fig. 1i and o). The  $\text{NH}_4^+$  concentration was 15–110% higher in the unpruned, in contrast the  $\text{NO}_3^-$  concentration was 47% higher for the pruned treatment at 20–40 cm soil depth.

The effect of combination between coffee canopy management (i.e., pruned and unpruned coffee) and fertilizer type (i.e., organic, inorganic, mixed) was significant on soil  $\text{NH}_4^+$  concentration (at 0–20 cm and 20–40 cm soil depth) and soil  $\text{NO}_3^-$  concentration



**Fig. 1** The effect of coffee canopy management, types, and doses of fertilizer as well as combination among two factors on soil total N (a–f), NH<sub>4</sub><sup>+</sup> (g–l), and NO<sub>3</sub><sup>-</sup> (m–r) at 0–20 cm and

20–40 cm soil depth. Different letters indicate significantly different according to DMRT test



**Fig. 2** The effect of combination coffee canopy management, fertilizer types, and fertilizer doses on soil total N, NH<sub>4</sub><sup>+</sup>, and NO<sub>3</sub><sup>-</sup> at 0–20 cm and 20–40 cm soil depth. Different letters indicate significantly different according to DMRT test

(at 20–40 cm soil depth), whilst combination between type and dose of fertilizer gave significant effect on soil NO<sub>3</sub><sup>-</sup> concentration at 0–20 cm and 20–40 cm

depth of soil (Fig. 1j, p, r). In the unpruned coffee, application of mixed fertilizer (organic and inorganic) increased 41–280% and 23–108% of soil available

$\text{NH}_4^+$  (at 0–20 cm) and  $\text{NO}_3^-$  (at 20–40 cm; Fig. 1j and p). Then, application of organic and mixed fertilizer with medium to high dose increased 48–143% and 32–103% of soil  $\text{NO}_3^-$  concentration (Fig. 1r).

The interactive effect combination of three factors (i.e., pruning, fertilization types, and fertilizer doses) was significant for both  $\text{NH}_4^+$ -N and  $\text{NO}_3^-$  concentrations (Fig. 2 and Supplementary Table 3), specifically in the deeper soil layer (20–40 cm). The combination of low to medium doses of mixed fertilization with unpruned coffee resulted in the highest  $\text{NH}_4^+$ -N concentration, on average 162% higher than the other treatments. Different from the upper soil layer, there were significant differences between the various combinations of canopy management, types, and doses of fertilizer on  $\text{NO}_3^-$ -N concentration for the deeper soil layer. The concentration of  $\text{NH}_4^+$  further down the soil profile (20–40 cm soil depth) showed a different pattern compared to the upper layer where the  $\text{NH}_4^+$  concentration increased after the application of organic fertilizer (especially with low and high doses) on unpruned coffee (Supplementary Table 3). Soil available N (especially the soil  $\text{NH}_4^+$  concentration) was related to soil total N.  $\text{NH}_4^+$  concentration had a negative correlation with soil total N at 0–20 cm and 20–40 cm depth of soil (Pearson's correlation test,  $r = -0.74$  and  $-0.44$ ,  $P$  value  $\leq 0.01$  and  $0.07$ , respectively). This study revealed that the highest  $\text{NO}_3^-$  concentration at 20–40 cm depth was recorded for the combination of low doses of mixed fertilizer on unpruned coffee. Thus, our study suggests that low and medium doses of mixed fertilization combined with an unpruned plant management strategy leads to high availability of both  $\text{NH}_4^+$  and  $\text{NO}_3^-$  in coffee agroforestry systems.

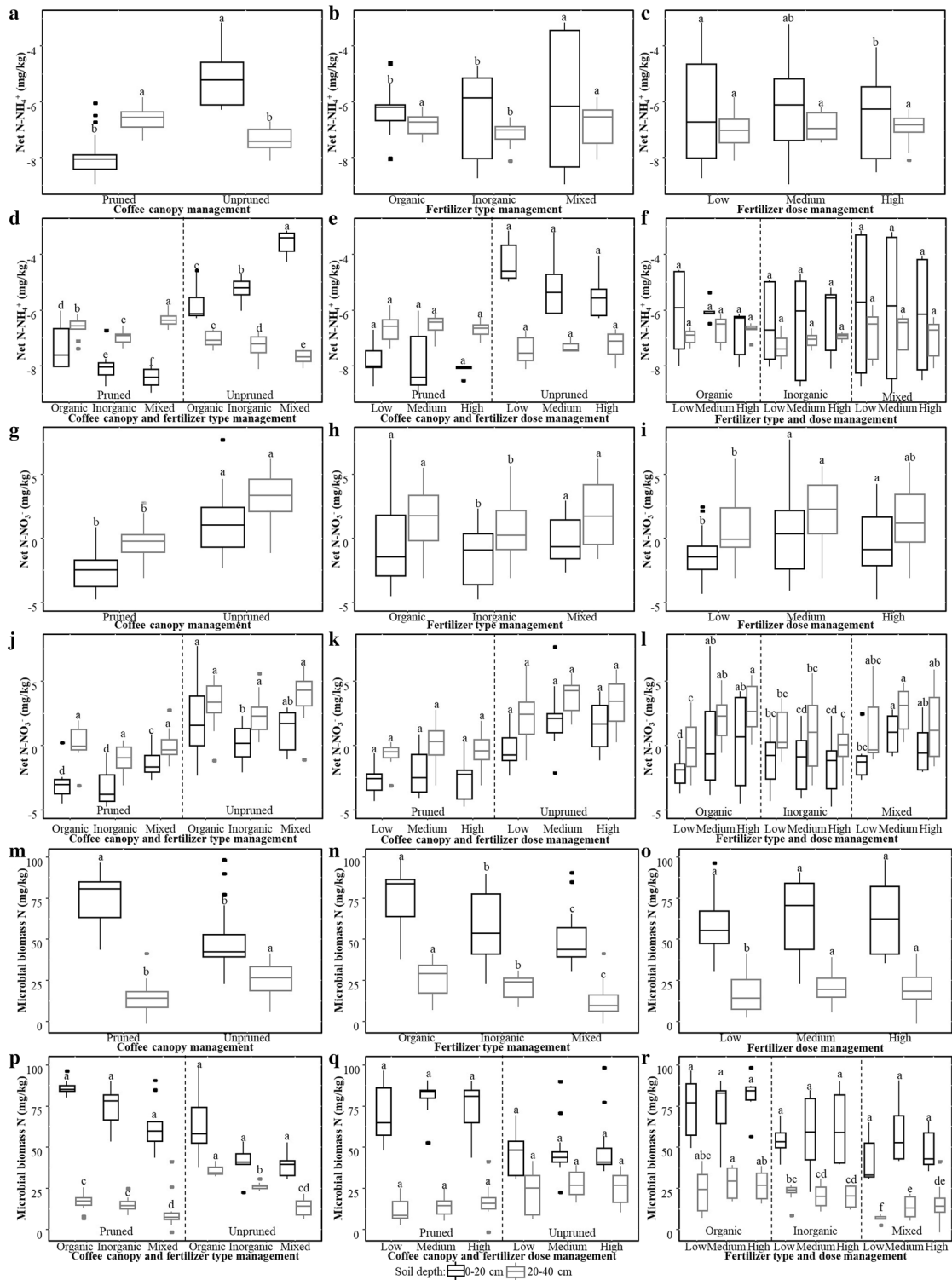
#### Effect of coffee canopy and fertilization management on soil N dynamic and soil microbial biomass N

Better understanding of soil N dynamic can be facilitated through calculating net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$  concentration. The data from the current study shows net negative  $\text{N-NH}_4^+$  concentration from all management systems (i.e., coffee canopy, types, and doses of fertilizer). A negative value for net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$  records a reduction in soil available N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentration) after six months fertilization relative to the initial condition as control, whereas a positive value records an increase

in the availability of N (Figs. 3 and 4). The pruned coffee canopy had 56% lower net  $\text{N-NH}_4^+$  at 0–20 cm soil depth and 11% higher net  $\text{N-NH}_4^+$  at 20–40 cm soil depth relative to the unpruned coffee canopy (Fig. 3a). The application of mixed fertilizer resulted in a 3–8% reduction of net  $\text{N-NH}_4^+$  when compared to inorganic fertilizer application for both studied soil depths (Fig. 3b). Net  $\text{N-NH}_4^+$  at 0–20 cm depth was 1% and 5% higher for the low dose of fertilizer application compared to the high and medium doses, while net  $\text{N-NH}_4^+$  at the deeper layer was comparable among the different fertilizer doses (Fig. 3c). In addition, combination between coffee canopy management and type of fertilizer gave significant effect on net  $\text{N-NH}_4^+$  at both soil depth (Fig. 3d), with the highest net  $\text{N-NH}_4^+$  was found in the combination of mixed fertilizer with unpruned coffee (at 0–20 cm depth) and in the combination of mixed fertilizer with pruned coffee (at 20–40 cm depth).

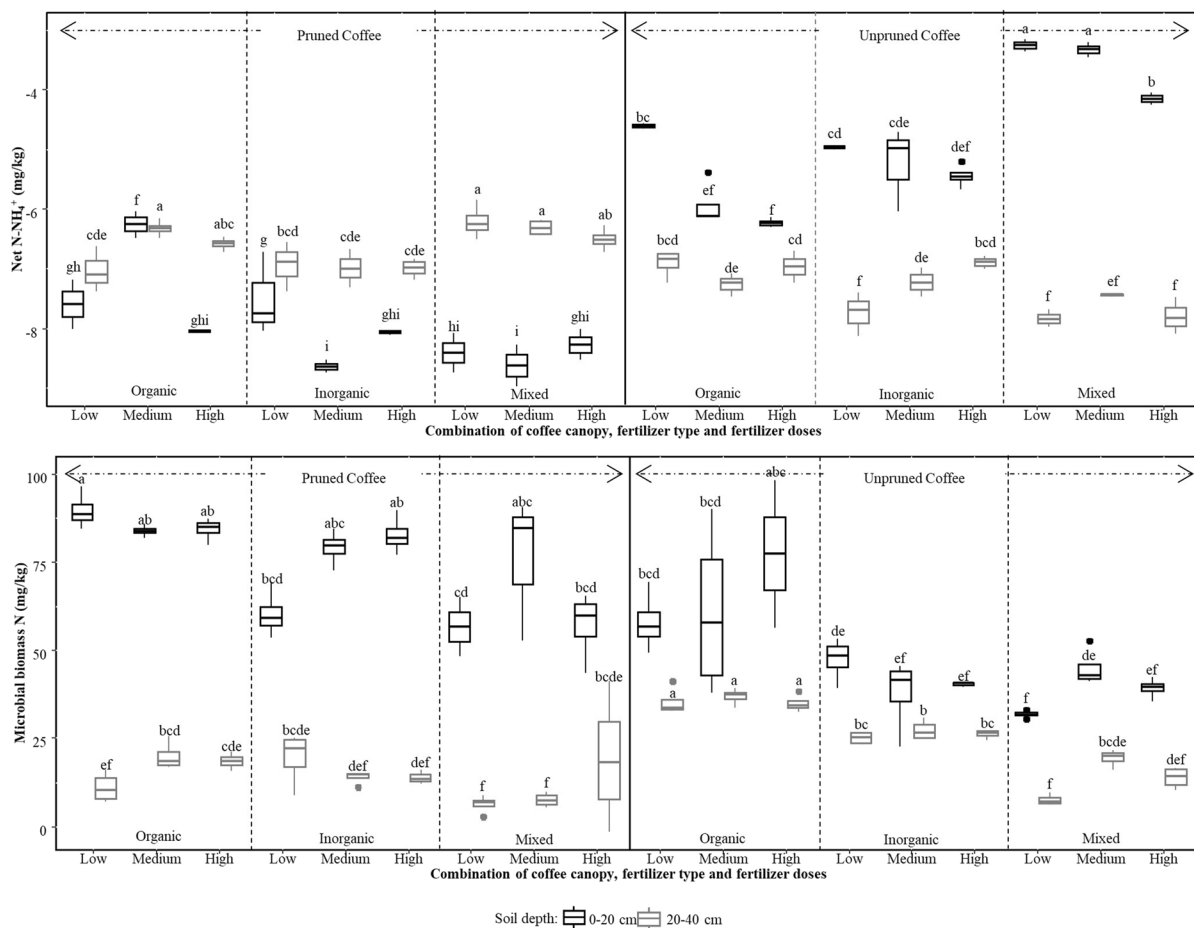
Soil net  $\text{N-NO}_3^-$  across the top 40 cm soil depth showed significant differences between treatments, with a positive value recorded for the unpruned coffee and a negative value for the pruned coffee (Fig. 3g). Mixed fertilizer application increased net  $\text{N-NO}_3^-$  by factors of 2.2 to 20.6 as compared to inorganic fertilization at 40 cm depth of soil (Fig. 3h). However, net  $\text{N-NO}_3^-$  at 0–20 cm soil depth was 1.6 to 6.0 times lower for the low fertilizer dose as compared to the medium and the high fertilizer doses. The low dose of fertilizer application was associated with a 1.7 times lower value for net  $\text{N-NO}_3^-$  at 20–40 cm compared to the medium dose of fertilizer application (Fig. 3i). The effect of combination of coffee canopy management and fertilizer type was significantly affected to net  $\text{N-NO}_3^-$  at the top 20 cm soil depth, whilst combination of type and dose of fertilizer had significant effect on net  $\text{N-NO}_3^-$  at 0–20 cm and 20–40 cm depth of soil (Fig. j and l).

The combination of the three factors in this study (i.e., coffee canopy management, types, and doses of fertilizer) had a significant effect on net  $\text{N-NH}_4^+$  (Fig. 4, Supplementary Table 3). The highest net  $\text{N-NH}_4^+$  was found for the application of low to medium doses of mixed fertilizer to unpruned coffee, especially at soil depths of 0–20 cm. At 20–40 cm, the highest net  $\text{N-NH}_4^+$  was associated with the application of low to medium doses of mixed fertilizer and the medium dose of organic fertilizer on pruned coffee. Differences in soil net  $\text{N-NO}_3^-$  were



**Fig. 3** The effect of coffee canopy management, types and doses of fertilizer as well as combination among two factors on net N-NH<sub>4</sub><sup>+</sup> (a-f) and net N-NO<sub>3</sub><sup>-</sup> (g-l) and microbial biomass

N (m-r) at 0–20 cm and 20–40 cm soil depth. Different letters indicate significantly different according to DMRT test



**Fig. 4** The effect of combination coffee canopy management, fertilizer types, and fertilizer doses on net  $\text{N-NH}_4^+$  and microbial biomass N at 0–20 cm and 20–40 cm soil depth. Different letters indicate significantly different according to DMRT test

associated with different fertilizer types and doses combined with coffee canopy management, especially at 0–20 cm depth of soil. The highest soil net  $\text{N-NO}_3^-$  was associated with the application of organic fertilizer on pruned coffee plants and the application of mixed fertilizer, mainly the medium dose. At 20–40 cm soil depth, changes in soil net nitrate-N were a function of the different fertilizer types and doses. The highest soil net  $\text{N-NO}_3^-$  was associated with the application of mixed fertilizer in medium doses and organic fertilizer in high doses.

Similar to soil total N, soil microbial biomass N (MBN) was strongly affected ( $P < 0.01$ ) by coffee canopy and fertilization (types and doses) management at 20–40 cm soil depth. However, at 0–20 cm soil depth, MBN was strongly affected only by the

type of fertilizer and canopy management. Microbial biomass N at 0–20 cm soil depth increased by up to 56% for pruned relative to unpruned coffee management. In contrast, at 20–40 cm soil depth, MBN for the pruned plants was 75% lower than for the unpruned coffee (Fig. 3m). Application of organic fertilizer increased soil MBN by 30–52% relative to the inorganic and mixed fertilizer application at 0–20 cm depth of soil. Microbial biomass N at 20–40 cm soil depth increased by 25–112% after organic fertilizer application compared to the inorganic and mixed fertilizer application (Fig. 3n). A significant effect of fertilizer dose was found on soil MBN at 20–40 cm soil depths where the medium to high fertilizer application increased MBN by 20% relative to the low fertilizer dose application (Fig. 3o).

Combination of fertilizer type with coffee canopy management or fertilizer dose gave significant effect on soil MBN at 20–40 cm depth of soil (Fig. 3 p and r). Then, the interaction of three factors (i.e., coffee canopy, types and doses of fertilizer) had a significant effect ( $P \leq 0.05$ ) on soil MBN at both 0–20 cm and 20–40 cm soil depth. The application of a low dose of organic fertilizer and pruning resulted in 88–181% higher soil MBN compared to all doses and types of fertilizer on unpruned coffee trees, especially at 0–20 cm soil depth (Fig. 4, Supplementary Table 3). Furthermore, the combination of pruning and a low dose of organic fertilizer increased soil MBN to levels that were 49–58% higher than for all combinations of pruning with inorganic and mixed fertilizer at the low doses. In contrast, at the 20–40 cm soil depth, the absence of pruning combined with organic fertilizer (at all different doses) led to soil MBN that was 75–488% greater than for pruned coffee trees combined with all types and doses of fertilizer application. Pearson's correlation test revealed a strong positive relationship between soil MBN and total soil N, especially at 0–20 cm soil depth ( $r=0.73$ ,  $P$  value  $\leq 0.01$ ).

In the top layer (0–20 cm soil depth), the increase in soil MBN resulted in an increase of soil total N ( $R^2=0.66$ ;  $P$  value  $\leq 0.05$ ; Fig. 5a, 0–20 cm row). However, the increase in soil MBN was also associated with decreasing soil available N (especially  $\text{NH}_4^+$ ), net  $\text{N-NH}_4^+$ , and net  $\text{N-NO}_3^-$  ( $r=-0.66$ ;  $R^2=0.29 - 0.52$ ;  $P$  value  $\leq 0.05$ ; Fig. 6b-d, 0–20 cm row). The influence of soil MBN on the soil N pool deeper in the soil profile (20–40 cm soil depth) showed a different pattern as compared to the top layer. The increase in soil MBN deeper in the soil was associated with a trend towards decreased soil total N ( $r=0.57$ ;  $R^2=0.37$ ,  $P$  value  $\leq 0.05$ , Fig. 5a, 20–40 cm row) that was associated with increasing soil available N (especially  $\text{NH}_4^+$ ) and net  $\text{N-NO}_3^-$  ( $R^2=0.33$  and  $0.21$ ;  $P$  value  $\leq 0.05$ ; Fig. 5b and d, 20–40 cm row) at 20–40 cm. Our study shows no significant effect of soil MBN on net  $\text{N-NH}_4^+$  at 20–40 cm soil depth (Fig. 5c, 20–40 cm).

Effect of coffee canopy management and fertilization on coffee bean yield

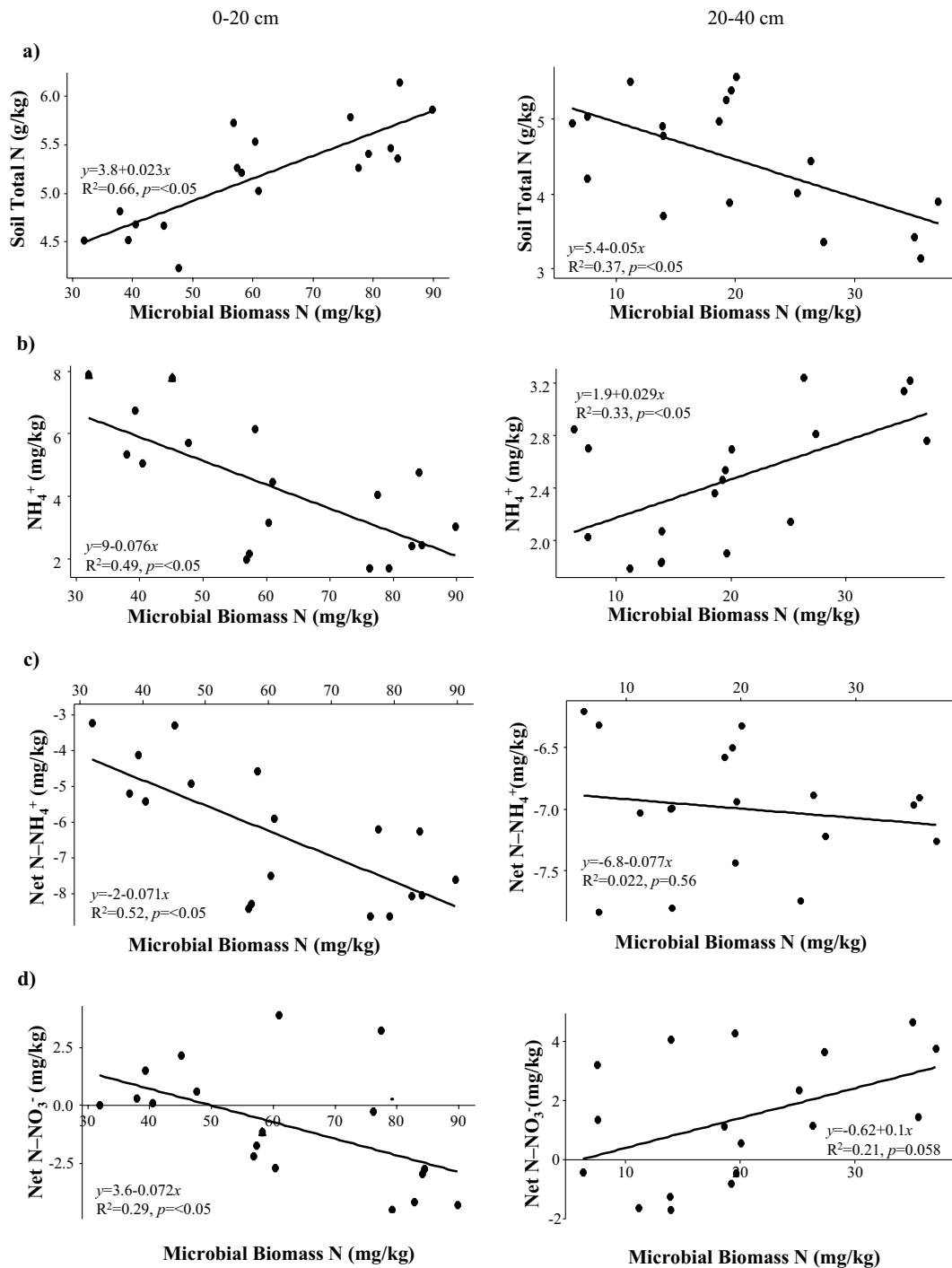
Fertilizer type significantly affected the fresh and dry weight of coffee beans per tree (Fig. 6a). The

application of mixed fertilizer increased the fresh weight of coffee beans by 41–68% and the dry weight of coffee beans by 51–78.5% compared to organic and inorganic fertilizers as single fertilizers (Fig. 6b). In addition, the dose of fertilizer also significantly affected coffee productivity, especially the fresh weight of coffee bean. The plot with medium dose of fertilizer had 56% higher fresh weight of coffee beans per tree than those in the plot with low dose of fertilizer application (Fig. 6c). Among combination two factors (i.e., coffee canopy management and fertilizer type, coffee canopy management and fertilizer dose, type and dose of fertilizer), combination between type and dose of fertilizer gave significant effect on fresh and dry weight of coffee bean yield (Fig. 6d-f). Application of mixed fertilizer with medium dose had the highest coffee bean yield both fresh and dry coffee bean. Furthermore, the interaction of three factors (i.e., coffee canopy, fertilizer types and doses) had a significant effect ( $P \leq 0.05$ ) on coffee bean yield per tree (i.e., fresh and dry weight). The application of a medium dose of mixed fertilizer and no pruning resulted in an average 2.5 times higher fresh weight of coffee bean yield compared to all doses and types of fertilizer on pruned coffee trees (Fig. 6g, Supplementary Table 3). Furthermore, application of mixed fertilizer at the low dose to pruned coffee trees recorded an average 3.2 times higher dry weight yield than other fertilizer type and dose combinations in the pruned coffee trees. Application of mixed fertilizer at low dose to pruned coffee trees increased the average dry weight yield by a factor of 3.7 relative to the application of other fertilizer type and dose combinations in the unpruned coffee, with the exception of the mixed fertilizer at the medium dose (Fig. 6g, Supplementary Table 3).

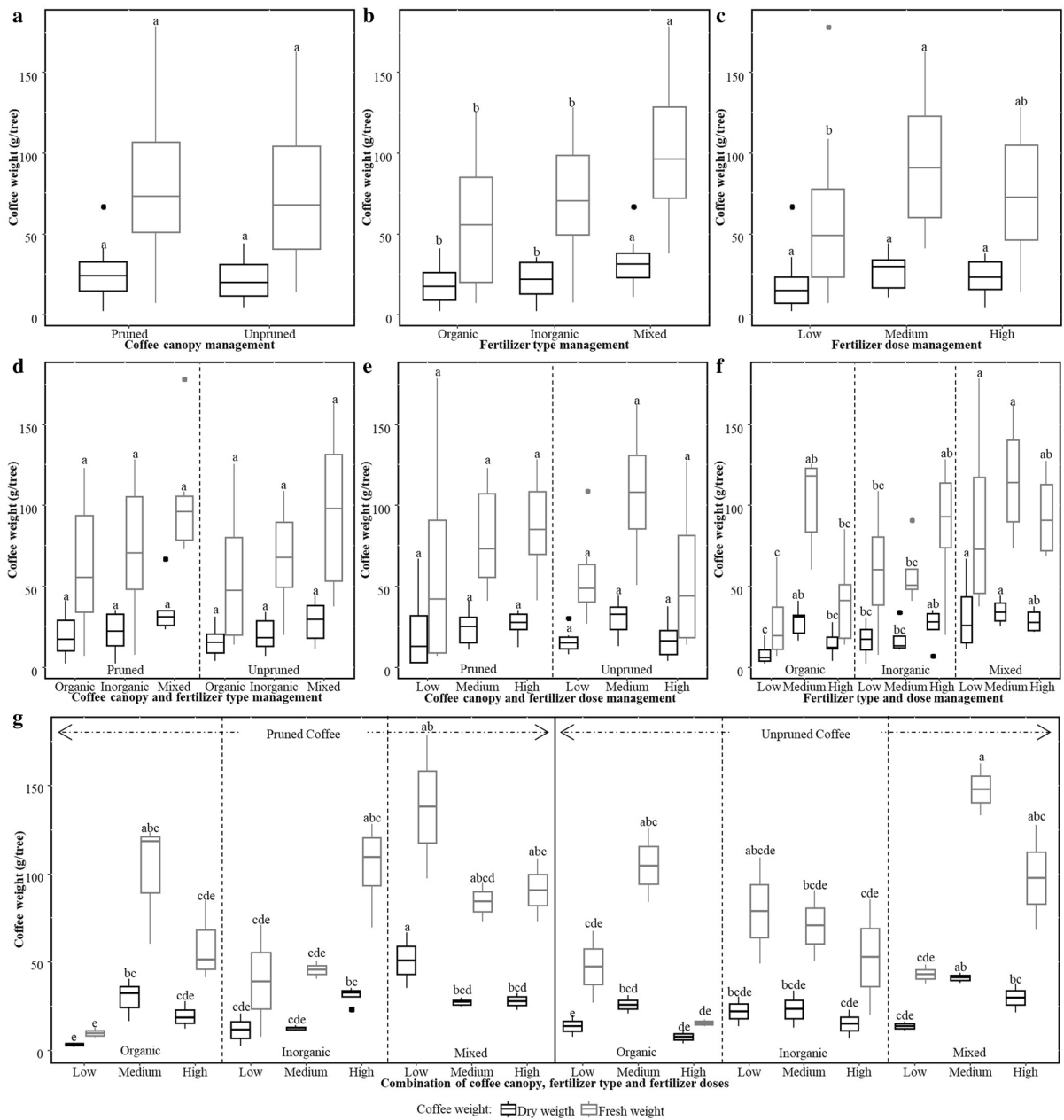
## Discussion

The effect of coffee canopy management and fertilization on soil N dynamic

The volcanic soil that supports coffee agroforestry within the UB Forest has high soil organic C and total N, but low pH, soil available P, and soil available N (Supplementary Table 1). Pruning the coffee canopy resulted in higher soil total N (i.e., 0–20 cm and 20–40 cm), soil MBN (i.e., 0–20 cm) and net  $\text{N-NH}_4^+$



**Fig. 5** The effect of soil microbial biomass N on soil total N (a),  $\text{NH}_4^+$  concentration (b), net N- $\text{NH}_4^+$  (c), and net N- $\text{NO}_3^-$  (d) concentration at two different soil depths



**Fig. 6** The effect of coffee canopy management, types and doses of fertilizer (a, b, c) as well as their combination (d-g) on fresh weight and dry weight of coffee bean yield per tree

(i.e., 20–40 cm depth) relative to the unpruned canopy. Soil total N is dominantly in the form of organic matter (Brady and Weil 2008). Thus, the higher concentration of soil total N and soil MBN associated with pruning was possibly related to the return of the pruning to the soil which increased soil organic N in the form of soil organic matter (Supplementary

Table 1). Kim and Isaac (2022) showed that soil N in agroforestry systems is derived from decomposition and mineralization of soil organic matter, input of N from fertilization (i.e., organic and inorganic) and fixation of N<sub>2</sub>. However, the rate of soil organic matter decomposition and mineralization is determined by the quantity and quality of the organic matter input

(i.e., C:N ratio, lignin, and polyphenols) (Gachengo et al. 2004; Kusumawati and Prayogo 2019). In addition, the positive correlation between soil total N and soil MBN at 0–20 cm depth (Fig. 5a) indicates that N is sequestered by soil microorganisms. Liu et al. (2019) showed that the application of pruning material (PM) in the form of compost significantly increased microbial activities, total C, and total N, which was consistent with our result. A previous study at the same site reported that coffee canopy and fertilization strongly influenced the population of free-living N bacteria (Nugroho et al. 2023), which is in line with our findings (i.e., soil microbial biomass N). Furthermore, the higher amount of soil available N (i.e.,  $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) and soil N dynamics (i.e., net N- $\text{NH}_4^+$  and net N- $\text{NO}_3^-$ ) in the unpruned coffee plot than in the pruned coffee plot may relate to lower immobilization due to lower soil total N and MBN (Fig. 6b-d). Soil N dynamics are related to mineralization and immobilization, important soil processes that are influenced by microorganisms and the environment. The high negative value of net N- $\text{NH}_4^+$  and net N- $\text{NO}_3^-$  concentration recorded in the study six months after fertilization indicates a low concentration of available N in the soil, possibly due to a dominance of the immobilization process rather than mineralization. The soil MBN plays an important role in regulating the soil N pool. Thus, the coffee agroforestry system with coffee canopy pruning potentially maintains soil N sustainability by increasing soil N storage in the form of organic N.

Fertilizer type and application rate are the second factor affecting soil N (total and available N) and soil MBN in the coffee agroforestry system. Inorganic fertilizer application is less effective than organic and mixed fertilizer in changing soil total N, soil available N, N dynamics, and MBN. This is expected due to the rapid release of N from inorganic fertilizer, which may increase potential N losses through plant uptake, leaching losses, or volatilization. Organic fertilizer increased soil total N and MBN due to the addition of soil organic matter as an energy source for soil microorganism and soil organic N. Zhang et al. (2016) reported a positive relationship between microbial biomass and organic matter application due to the provision of an external energy source that is more readily available to microbes. In addition, the addition of mixed fertilizer (organic and inorganic) possibly improved the soil N mineralization process,

as indicated by the high  $\text{NH}_4^+$  and  $\text{NO}_3^-$  concentrations, as well as net N- $\text{NH}_4^+$  and net N- $\text{NO}_3^-$ . This may be due to the hydrolysis of the inorganic fertilizer and the subsequent release of more N than just the organic fertilizer. Some of this N will be adsorbed by soil microorganisms as a source of energy for decomposing organic fertilizer (as a fraction in the mixed fertilizer) and another part of N could potentially be available for plant uptake. The higher ammonium concentration associated with the application of mixed fertilizer may be due to the binding of  $\text{NH}_4^+$  by organic acid from organic fertilizer decomposition. Yang et al. (2020) reported that organic fertilizer helps to keep N in the soil because it is bound by the released organic acids. Therefore, mixed fertilizer can be a good solution to maintain N availability in coffee agroforestry systems.

Differences in fertilizer dose affected several soil N parameters, including  $\text{NH}_4^+$  concentration, net N- $\text{NH}_4^+$ , net N- $\text{NO}_3^-$ , and microbial biomass N. The low fertilizer dose application had a higher  $\text{NH}_4^+$  concentration and net N- $\text{NH}_4^+$  accumulation as compared to the other fertilizer doses, whereas medium and high fertilization resulted in higher net N- $\text{NO}_3^-$  and soil microbial biomass N as compared to the low fertilizer dose application. This result indicates that increased N addition by increasing the dose of fertilizer application will increase both N release which is potentially increase N losses and N immobilization by soil microorganism. We also assumed that the un-significant differences in soil total N and  $\text{NO}_3^-$  concentration among fertilizer dose application probably due to the effect of N uptake by plant and N losses from the soil systems. The increases dose of fertilizer is expected to provide a large amount of N release which may cause a rapid conversion of  $\text{NH}_4^+$  to  $\text{NO}_3^-$  and lead to soil N saturation, resulted in decrease soil  $\text{NH}_4^+$  and N- $\text{NH}_4^+$  concentration, a low nutrient used by plant and a high N leaching losses and emissions. Wang et al. (2023) reported the increase in gross  $\text{NH}_4^+$  immobilization rates was affected by enhancing nitrogen supply and MBN due to fertilizer added, which is consistent with our findings. Li et al. (2007) also shown that N use efficiency increased up to 3 times higher with decreases in N fertilizer applied. Another result by Cannavo et al. (2013) reported that N uptake by coffee trees was almost 20% of N applied from fertilizer and 60% of N applied was still in the soil system which

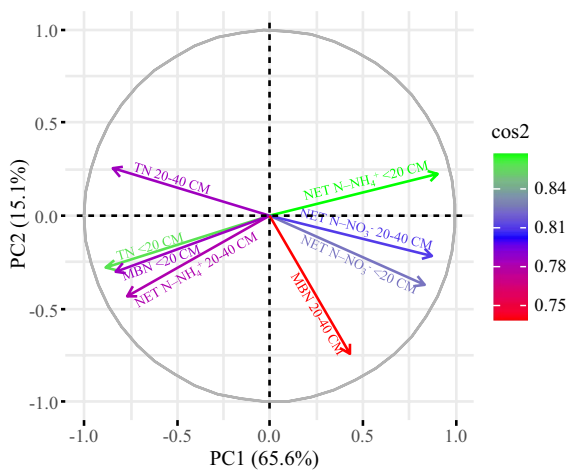
is potentially losses through leaching in the form of  $\text{NO}_3^-$ .

Overall, coffee agroforestry management (i.e., coffee canopy management and fertilization) affected the concentration of soil total N, available N and soil microbial biomass (Fig. 5). Principle Component Analysis (PCA) results showed that PC1 explained 65.6% of the total variance, while PC2 explained 15.1% of the total variance (Fig. 7). Coffee agroforestry management positively affected soil N dynamics such as net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$  concentration (e.g., 0–20 cm depth), as well as net  $\text{N-NO}_3^-$  and soil microbial biomass N (e.g., 20–40 cm depth), which was shown in the PC1. In addition, the positive effect of coffee canopy management and fertilization) was also found for soil total N at 20–40 cm soil depth (shown in the PC2). The PCA analysis summarized that soil total N and N dynamics (net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$ ) at 0–20 cm depth were the parameters strongly influenced by coffee canopy management and fertilization. In addition, the study highlighted that the use of an unpruned coffee canopy approach, combined with mixed fertilizer at low to medium dose, was the optimal combination to provide  $\text{NH}_4^+$  and  $\text{NO}_3^-$  to the coffee agroforestry system. However, if a farmer were to prune the coffee canopy, this management could be combined with organic fertilizer application to maintain soil N (i.e., soil total N and soil microbial biomass N). This was due to release N stored in coffee leaf and organic fertilizer into soil in

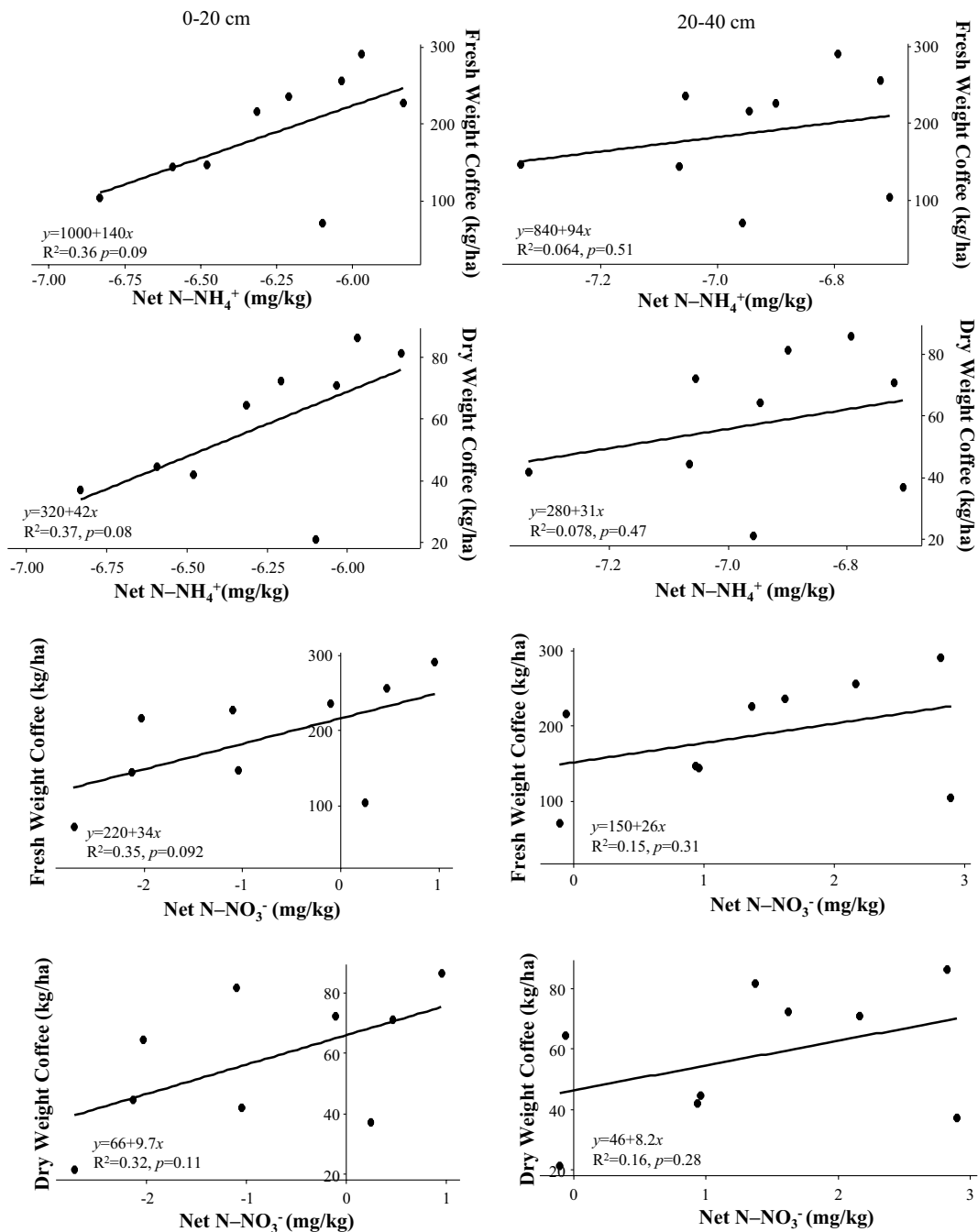
the long-term period through mineralization process (Guimarães et al. 2013; Muñoz et al. 2016); nutrient release from mineralization can be used to replace nutrient loss through harvest export (Karim et al. 2021). The previous research by Tully and Lawrence (2012) reported that N released from coffee leaf (e.g. Arabica coffee) decomposition was 34% in 4 weeks and 94% in 52 weeks, probably due to the high lignin content of coffee leaf (44% of lignin; Petit-Aldana et al. 2019). Further evaluation of the effect of fertilization (i.e., organic fertilizer) and coffee leaf from litter and/or pruning should therefore be conducted in the long-term period (52 to 104 weeks).

### Outlook for manipulating soil N dynamics for coffee productivity

Soil N is a key factor affecting coffee productivity in agroforestry systems. The study investigated the correlation between soil N and coffee bean yield per tree. The Pearson correlation test was unable to detect a significant correlation between soil N parameter (i.e., total N, available N, net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$ ) and coffee bean yield per tree in all combination of coffee canopy management and fertilization (i.e., type and dose of fertilizer). Therefore, the correlation test between soil N parameters and coffee productivity was performed using the average of coffee canopy management (i.e., pruned and unpruned) at each fertilizer type and dose of fertilization. We excluded the effect of coffee canopy management to evaluate whether soil N parameters after application of different types and doses of fertilizer had a significant impact on coffee bean yield per tree. Our results showed that an increase in net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$  is associated with an increase in coffee bean yield (i.e., fresh and dry coffee bean weight), especially at 0–20 cm soil depth (Fig. 8). The increase in net  $\text{N-NH}_4^+$  and net  $\text{N-NO}_3^-$  concentration recorded in this study is associated with an increase the available N in the soil, and this would be expected to increase N uptake by the plant, resulting in increased coffee productivity. However, the previous research by Sudharta et al. (2022) reported the negative correlation between soil available N and coffee bean yield, possibly due to uptake of the available N by the coffee tree. Therefore, at the similar time measurement soil available N had an inversion relationship with coffee bean yield as the nutrient has been uptake by plant



**Fig. 7** Principal component analysis of soil N dynamic after the application of different types and doses of fertilizer combined with coffee canopy management



**Fig. 8** The relationship between soil N dynamics and coffee productivity for the UB coffee agroforestry system

and/or lost from soil systems (Sudharta et al. 2022). Our finding shows that applying proper dose of fertilizer was not only affected yield, but also soil nitrogen availability. Tateno and Takeda (2010) reported positive correlation between nitrogen uptake and N

mineralization, indicate that soil available N concentration enhance N plant uptake resulted in increase plant yield.

The coffee bean yield in our plots was lower than the average yield of coffee under optimal growth

condition outside the system condition of the current study: for this study the average yield was less than 1 kg per tree as compared to a yield of more than 2.5 kg per tree per year reported by Nigam and Singh (2014). This result indicates that the effect of coffee canopy and fertilization management on coffee yield would be undetectable in the short-term due to the complexity of factors affecting coffee yield. The fresh and dry weight coffee bean yield in our research (9.91 – 147.9 g/tree and 3.25 – 51.3 g/tree, respectively) was comparable with the research of Siahaan et al. (2020) who reported that the fresh and dry weight of coffee fruit by combining shade trees, pruning, and fertilizer in Arabica coffee was around 57.4 – 83.4 g/tree and 17.9 – 39.1 g/tree, respectively. While, Karim et al. (2021) reported that combination of Lamtoro shade, pruning (shade, *wiwilan*, unproductive branches, and maintenance), and organic fertilizer (with a dose 7.5 kg/tree) resulted in a green bean yield 1.66 ton/ha. In addition, Rowe et al. (2022) stated that coffee bean yield in the agroforestry system within the UB Forest could be increased up to 1.8 kg/tree by implementing high management of coffee plot (i.e. pruning at 2 years, removing non-productive stem regularly, managing shade intensity by trimming/thinning, applying fertilizer once a year, and controlling weed around the coffee plant frequently). Optimal management to increase coffee bean yield while maintaining environmental sustainability is a critical measure in the UB Forest Research Station which aims to model land management that will achieve sustainable levels of production with minimal impact on the environment.

## Conclusions

Coffee canopy management and fertilizer types were the two factors affecting soil N dynamics and soil microbial biomass N for coffee trees under agroforestry management. Coffee canopy pruning increased soil total N and soil MBN relative to the unpruned coffee canopy. Application of organic fertilizer (especially to the pruned coffee canopy) increased soil total N and soil microbial biomass N. The positive correlation between soil total N and soil microbial biomass N explained that a large amount of N in the soil is in the form of organic N. However, the study was unable to detect a significant effect of soil N dynamics on

coffee bean production. A management system that leaves the coffee canopy unpruned combined with mixed fertilizer at low to medium doses was shown to be the optimal combination to provide soil available N ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) for coffee agroforestry while pruning can be combined with organic fertilizer to improve soil total N and MBN.

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**Author contributions** SK: Designed the research, analyzed the data, wrote the main manuscript, manuscript revision RMYAPN: field and laboratory measurement, analyzed the data, manuscript revision RMYAPN, RU, IN, GAN, CP, CWNA: wrote the manuscript, manuscript revision

**Data Availability** No datasets were generated or analysed during the current study.

## Declarations

**Competing interests** The authors declare no competing interests.

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