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Impact of Nutritional Management on Available Mineral Nitrogen and Soil Quality Properties in Coffee Agroecosystems

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Abstract: Coffee crop management is guided by an approach of synthetic nitrogen fertilizers application in order to guarantee high production rates; however, this type of management increases soil degradation. A study was conducted in order to evaluate the impact of changing soil nutritional management from Chemical (NPK) to Organic (Farmyard Manure-FYM), and from Chemical (NPK) to Mixed (NPK + FYM) regarding soil quality properties and mineral nitrogen available in coffee agroecosystems; a multi-spatial analysis was carried out considering a unifactorial design; soil samples were taken from depths between 0.10 and 0.20 m in 42 plots; physical and chemical variables were measured (ammonium, nitrates, pH, organic matter, moisture, bulk density and texture). It was found that Chemical Management affects the physical and chemical properties of soil quality (organic matter, humidity, bulk density, and pH), resulting in significant differences ($p < 0.05$) comparing to Mixed and Organic Management. The lowest level of organic matter was found under chemical management, being of 3% and increasing up to 4.41% under mixed management. Mineral nitrogen availability in the form of ammonium, was not affected by nutritional management. A higher concentration of nitrate was found under Mixed Management (105.02 mg NO_3 kg^{-1}), presenting significant differences ($p < 0.05$) against Chemical and Organic. There was no significant difference between Organic and Chemical Management. The study allowed us to determine that, through coffee organic nutritional management, it is possible to keep suitable soil quality conditions in order to reduce soil degradation, and to keep mineral nitrogen available for the development of coffee plants.

Keywords: chemical fertilizer; organic management; soil properties; agroecosystems

1. Introduction

At the global level, coffee production is the main economic-productive activity for approximately 25 million small coffee crop growers [1] and it generates more than 5 million direct and indirect jobs; about 20% of total production costs correspond to the use of synthetic agrochemicals [2]. According to the International Coffee Organization (ICO), coffee consumption has doubled its growth rate in the last 20 years and an upward trend of 2.5% a year is estimated, corresponding to an increase in consumption of 25 million bags in the next 10 years [3]. This coffee consumption's demand is leading to an increasing use of chemical synthesic fertilizers to ensure good yields. However, these fertilizers can produce losses in soil fertility, water sources contamination, increase production costs, and the output of greenhouse gases. Considering that, there is an evidence of the need to develop researches in order to propose strategies aiming at a reduction of the use of synthetic nitrogen fertilizers, thus reducing soil degradation [4].

In Colombia, coffee cultivation involves approximately 563,000 producing families [5], being a fundamental product for the labor market of the agricultural sector. In 2012, coffee was the crop that generated the greatest number of direct and indirect jobs, close to 807,000 and 1.6 million, respectively [6]. Additionally, according to the DANE (National Administrative Department of Statistics), coffee accounted for approximately 10% of the exports from the agricultural sector in 2013 [6]. Thus, coffee cultivation is one of the main production lines in the country, giving Colombia international recognition as one of the main producers and exporters.

In order to guarantee the good performance of coffee crops, the application of synthetic nitrogen fertilizers is estimated to be of about 2000 kg ha^{-1} $year^{-1}$ [7]. The excessive application of these inputs generates an increase in nitrogen volatilization in the form of ammonium (NH_3) [8,9], superficial and underground water contamination by nitrates leaching (NO_3) [10], the increase of greenhouse gases, soil fertility loss [10], dynamic carbon, biodiversity loss, and alteration of soil physicochemical and microbiological quality conditions [11], among other issues.

Also, it has been shown that under conventional management, mineralization rates are elevated by 100%, increasing the risks of mineral nitrogen loss [12]; there are around 30% less species richness and 50% less abundance of organisms in the agroecosystem (birds, soil flora and fauna) [11]; the levels of carbon in the soil can be reduced by 50%, affecting its availability in order for microorganisms to be able to carry out their processes [13]. Also, the soil has a lower organic nitrogen concentration (68%) [14] and contains 15% less microbiological diversity [15]. Similarly, soils under conventional management have a low content of organic matter and a lower percentage of humification [16]. These issues affect soil quality, fertility, and the ecosystem services of food provision and regulation of physicochemical and biological processes.

Soils are a key resource that offer goods and services to humanity. Healthy soil is vital in order to reach sustainable development goals [17]. Hence, [18] the suggested management should be improved to reduce land degradation, and should be shifted to sustainable agricultural production; soil erosion losses decrease soil quality, and as a consequence, it can reduce crop production. It has been shown that management practices adopted under organic farming (such as vegetation cover between trees, chipping after pruning, and spreading the chips on the soil surface) improved the soil quality, supporting access to mineral nitrogen and reducing the use of nitrogen chemical fertilizers. Nutrient recycling and organic matter input [19] also improve of biological conditions, biodiversity abundance, and erosion prevention, among other factors [10].

Therefore, an analysis was carried out in order to evaluate the impact on available mineral nitrogen and soil quality properties produced by the change from chemical to organic and to mixed nutritional management in Colombian coffee agroecosystems, as a strategy to reduce the use of nitrogen chemical fertilizers and soil degradation.

2. Methods

2.1. Study Site

The study analyzes the results of recurrent crop nutritional management changes on available mineral nitrogen and soil quality properties. The study was conducted in the department of Cauca, in the Cajibio village on the Central and Western Cordillera of the mountainous system of the Colombian Andes. The site has an average altitude of 1765 m.s.n.m with temperatures ranging from 12 °C to 24 °C. The farm soils are Andisols, formed on top of pyroclastic materials resulting from a volcanic eruption. The plots sampled were located in Túnel, Venta and Cohetera township (Figure 1).

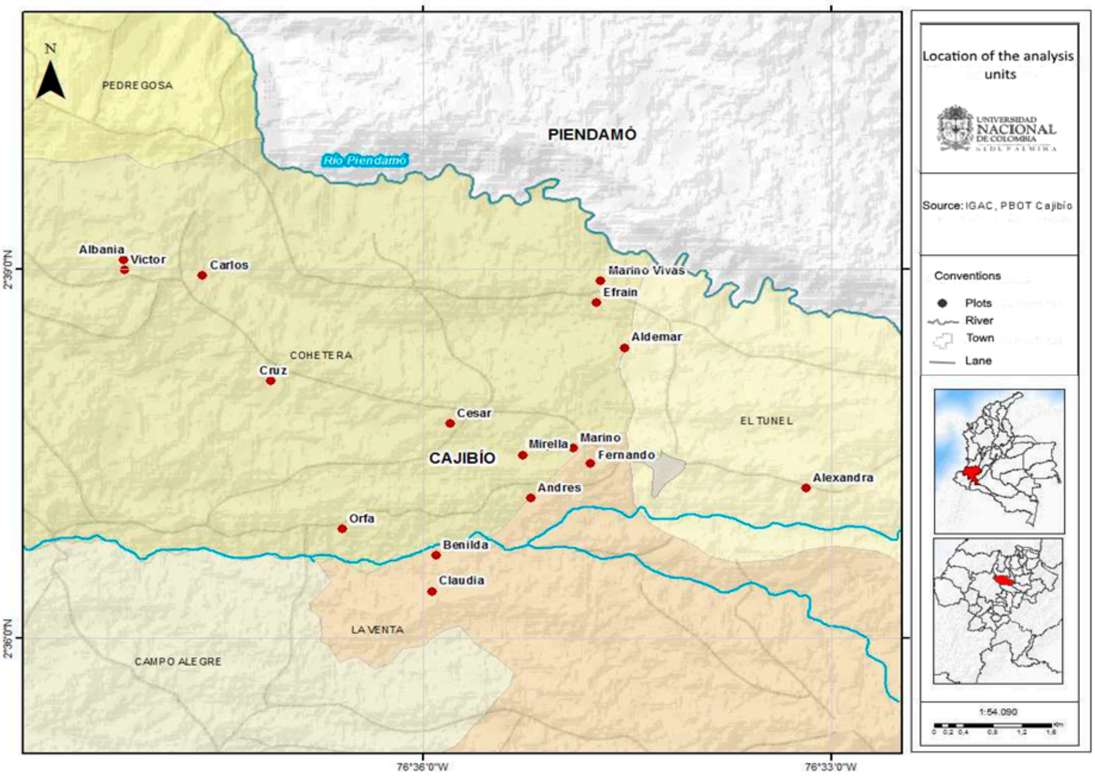

Figure 1. Farms location in the department of Cauca, in the Cajibio village, Colombia.

The three nutritional managements correspond to the use of chemical, organic, and mixed inputs. Initially, all farms have been treated with chemical inputs, but some of them were changed to organic and mixed inputs three years ago (Figure 2). Interviews were carried out to select the farms with the conditions required. In total, eight farms with mixed nutritional management were chosen, along with three farms with organic nutritional management and five farms with chemical nutritional management. In order to get soil samples, 28 plots were selected in mixed farms, six plots in organic farms, and eight plots in chemical farms, corresponding to 42 plots. Chemical management was characterized by the application of chemical inputs (80–100 g NPK per plant). Organic management was characterized by FYM (2–3 kg manure per plant), and mixed management corresponds to the mixed application of NPK and FYM. The total amount of inputs varies according to the plant density and the size of the farm.

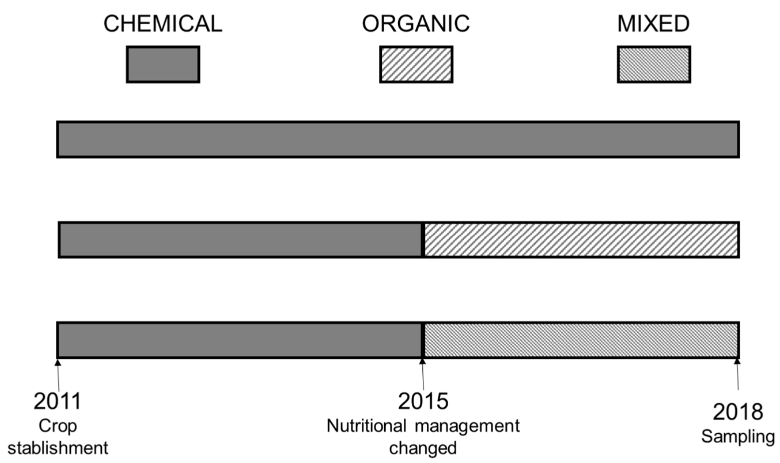

Figure 2. Nutritional management changes (chemical to organic, and chemical to mixed) in coffee agroecosystems.

2.2. Experimental Design to Determine Physical and Chemical Soil Properties

The analysis focused on two sets of variables: (1) soil quality properties and (2) available mineral nitrogen. It was considered a complete randomized design with a unifactorial treatment structure where factor corresponds to a type of nutritional management with three levels (chemical, organic, and mixed). As output variables, soil physicochemical properties (organic matter, nitrates, ammonium, moisture, bulk density, texture, and pH) were selected. For any randomly selected farm, the farm location was georeferenced using a hand GPS.

2.3. Soil Samples and Laboratory Analysis

The soil samples were obtained using a composite method [20] in 42 plots. In each plot, two composite samples of fifteen samples each were obtained. The samples were collected at depths of 10 to 20 centimeters, using a shovel in a zig-zig pattern in each plot. They were taken to the agrochemical laboratory at Cauca University for analyzing nitrate, ammonium, organic carbon, pH, bulk density, texture, and moisture. The texture was measured by the Bouyoucos method using American Society for Testing and Materials (ASTM) HYDR Fisher Brand D2487-06. The bulk density was determined by the cylinder method [21]. The pH (H_2O) was determined potentiometrically by method 9045D [22]. Soil organic carbon was measured by oxidation with chromic acid (Walkley and Black method). Nitrates and ammonium were determined by UV spectrophotometry (Universidad del Cauca, Popayan, Colombia). The soil moisture content was determined gravimetrically, linking water mass and soil solids mass D2216-05.

2.4. Statistics Analysis of Soil Properties

An outlier analysis was applied. A descriptive analysis was applied (range, average, standard deviation) to describe the data set. All data were tested firstly for normality with the Shapiro–Wilk test and Levene's test for equality of variances. Thereafter, Kruskal–Wallis and Mann–Whitney tests were used to investigate the differences between the nutritional managements used in plots, considering that the data did not show a normal distribution. All analyses were performed in SPSS version 25 (IBM, Bogotá, Colombia).

3. Results

Nutritional management did not affect the soil ammonium concentration (NH_4). The highest value (0.59 mg NH_4 kg^{-1} soil) was found under Organic Management (OM) and the lowest value (0.43 mg NH_4 kg^{-1} soil) was found under Chemical Management (CM) (Table 1). There were no significant differences ($p < 0.005$) between nutritional managements. Additionally, the ammonium concentration was more homogeneous in OM than in Mixed Management (MM) and CM (Figure 3).

Table 1. Mean of soil parameters to compare nutritional management.

Soil Parameters	Units	Nutritional Management		
		Organic	Chemical	Mixed
NO_3	mg kg^{-1} soil	68.77 (20.52) ^{a}	70.65 (36.81) ^{a}	105.02 (63.46) ^{b}
NH_4	mg kg^{-1} soil	0.59 (0.30) ^{a}	0.43 (0.11) ^{a}	0.46 (0.18) ^{a}
OM	%	4.23 (1.07) ^{a}	3.00 (1.33) ^{b}	4.41 (0.89) ^{a}
H	%	17.99 (1.08) ^{a}	15.32 (3.65) ^{b}	17.94 (2.17) ^{a}
pH		5.01 (0.16) ^{a}	5.16 (0.19) ^{b}	4.92 (0.27) ^{a}
Bulk density	g cm^{-3}	0.89 (0.080) ^{a}	0.95 (0.16) ^{a}	0.92 (0.079) ^{a}
Sand	%	72.96 (6.67) ^{a}	70.88 (9.13) ^{a}	71.70 (6.24) ^{a}
Clay	%	5.21 (4.78) ^{a}	10.87 (9.93) ^{a}	7.24 (3.36) ^{a}
Silt	%	21.83 (3.79) ^{a}	18.25 (9.91) ^{b}	21.05 (7.03) ^{a}

A different letter indicates a statistically significant difference between nutritional managements ($p < 0.05$). OM, Organic Management; H, Moisture.

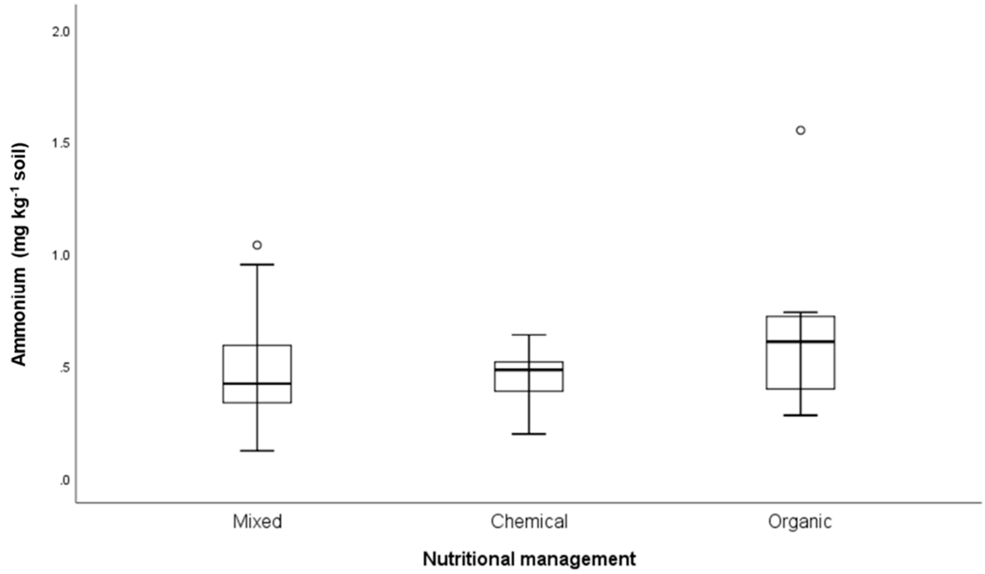

Figure 3. Ammonium content for the different nutritional managements. Circles correspond to extreme values.

Available nitrate (NO_3) was modified by the changes in nutritional management. MM soil had the highest nitrate concentration (105.02 mg NO_3 kg^{-1} soil), while OM had the lowest value (68.77 mg NO_3 kg^{-1} soil) (Table 1). Significant differences ($p < 0.005$) were found when comparing MM to OM and CM; however, that was not the case between OM and CM (Table 1). Furthermore, soil nitrate concentration had the highest variability under MM and the highest homogeneity under OM (Figure 4).

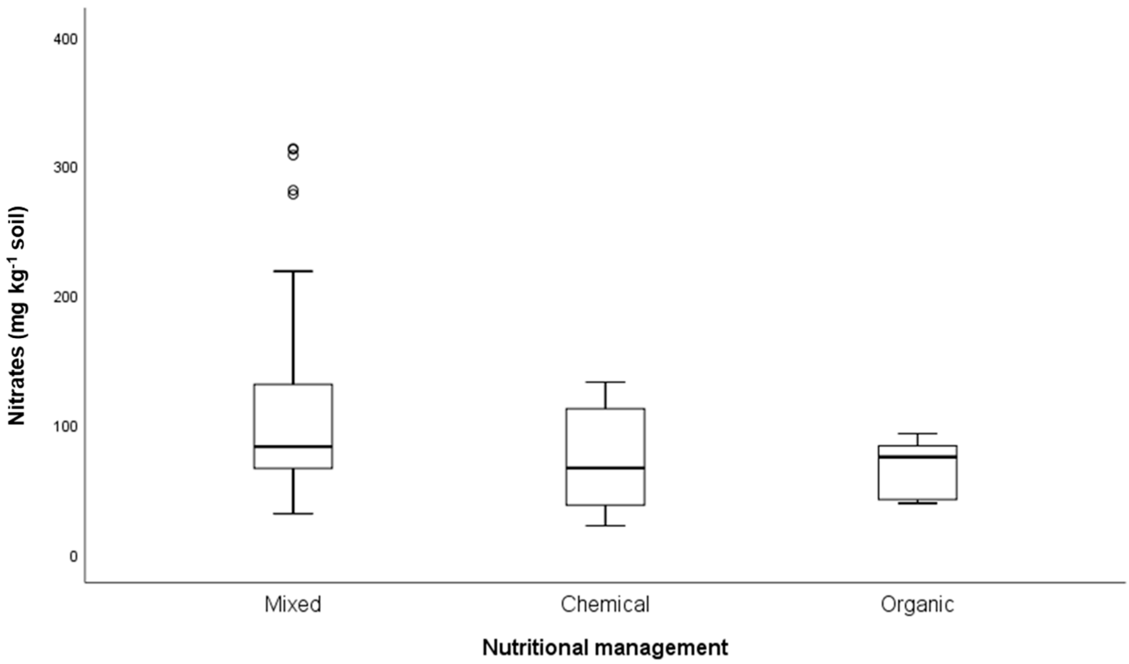

Figure 4. Nitrate content for the different nutritional managements. Circles correspond to extreme values.

Moisture percentage was improved by OM and MM. Lower moisture percentage was found under CM (15.32%) (Table 1) than in MM and OM; it also had the highest data variability (Figure 5).

OM had higher moisture percentage (17.99%) (Table 1) and data homogeneity (Figure 5) than MM and CM. Moisture percentage in soils under CM differed significantly ($p < 0.005$) from MM and OM.

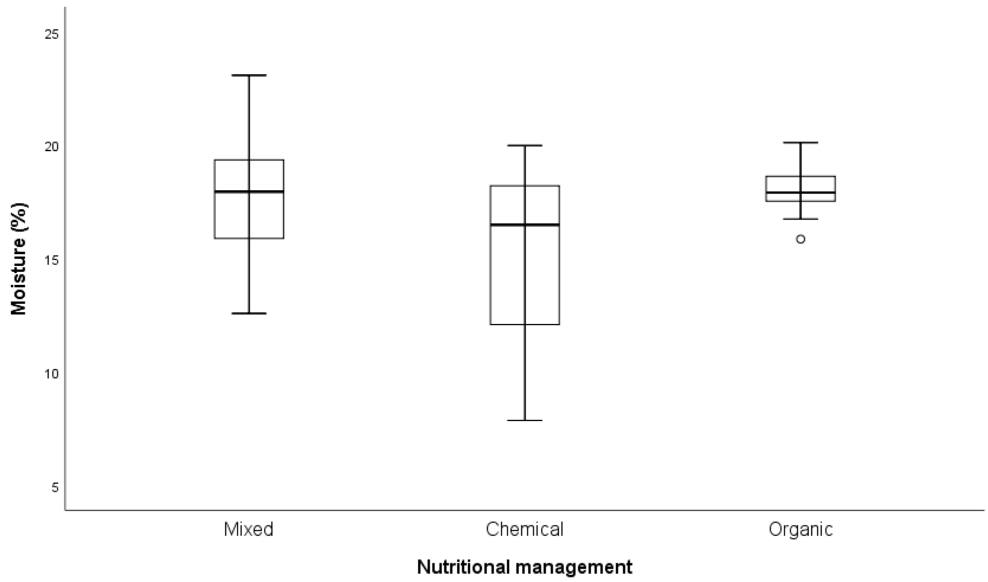

Figure 5. Moisture content for the different nutritional managements. Circles correspond to extreme values.

In relation to pH, the highest value was observed in CM (5.16) and the lowest value in MM (4.92) (Table 1). It was found that pH in MM differed significantly ($p < 0.005$) (Table 1) from OM and MM. Also, greater variability was observed under MM (Figure 6).

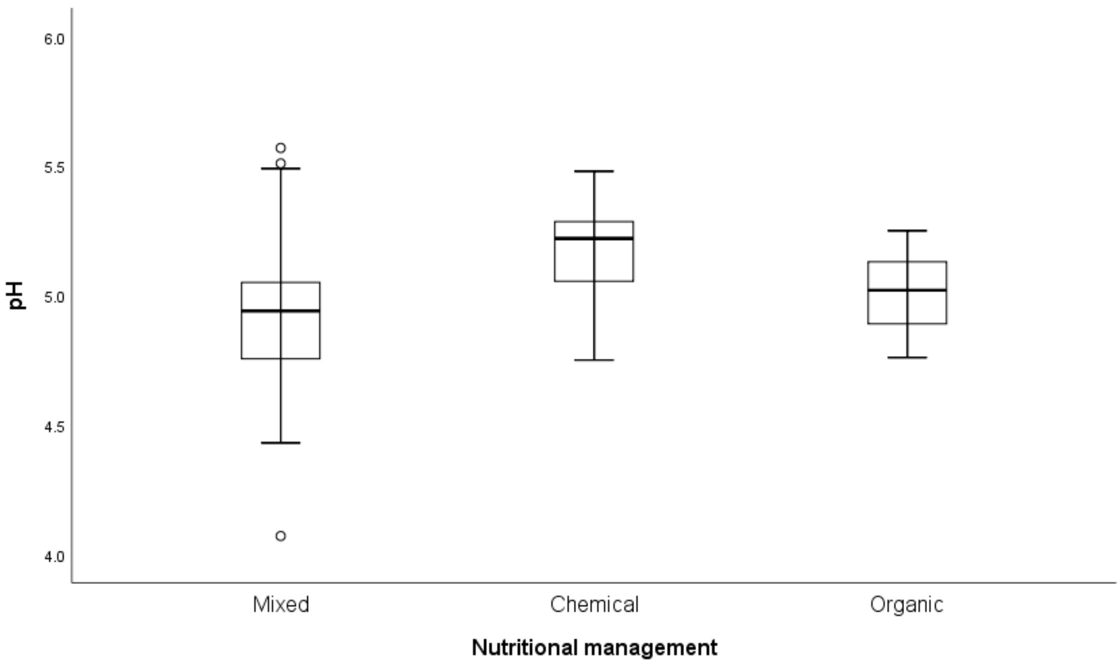

Figure 6. pH for the different nutritional managements. Circles correspond to extreme values.

The organic matter varied among nutritional managements. It was higher in MM, followed by OM and CM and was significantly lower ($p < 0.005$) in CM (3%) than in OM (4.23%) and MM (4.41%) (Table 1). There were no significant differences between OM and MM. The highest data variability was observed in CM (Figure 7).

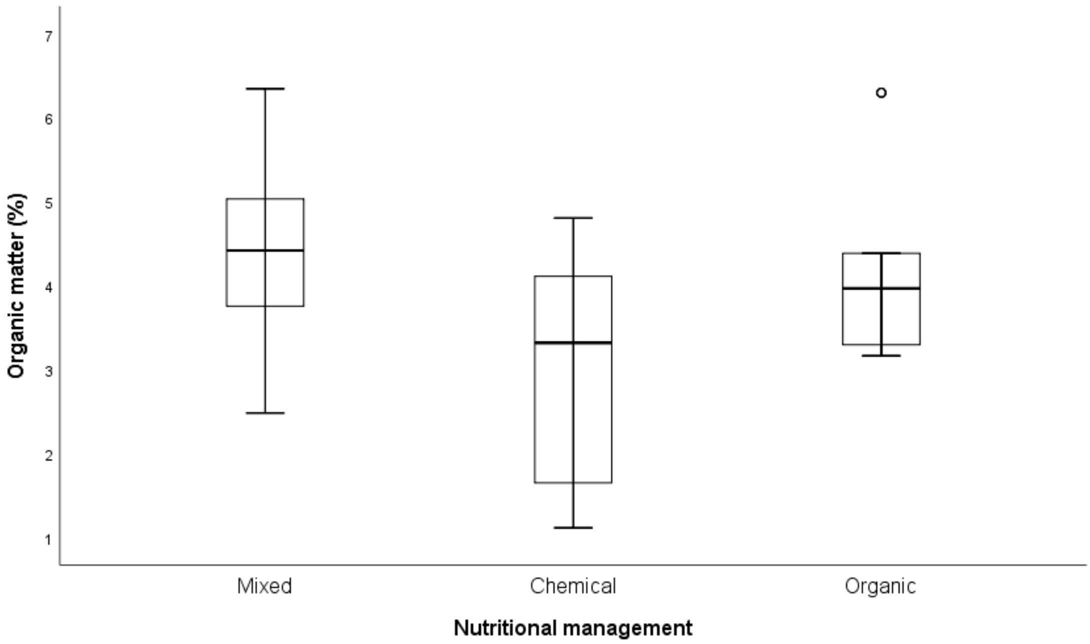

Figure 7. Organic matter content for the different nutritional managements. Circles correspond to extreme values.

Bulk density was higher in CM (0.95 g cm^{-3}), followed by MM (0.92 g cm^{-3}) and OM (0.89 g cm^{-3}) (Table 1); The highest data variability was found in CM (Figure 8). There were no significant differences between nutritional managements.

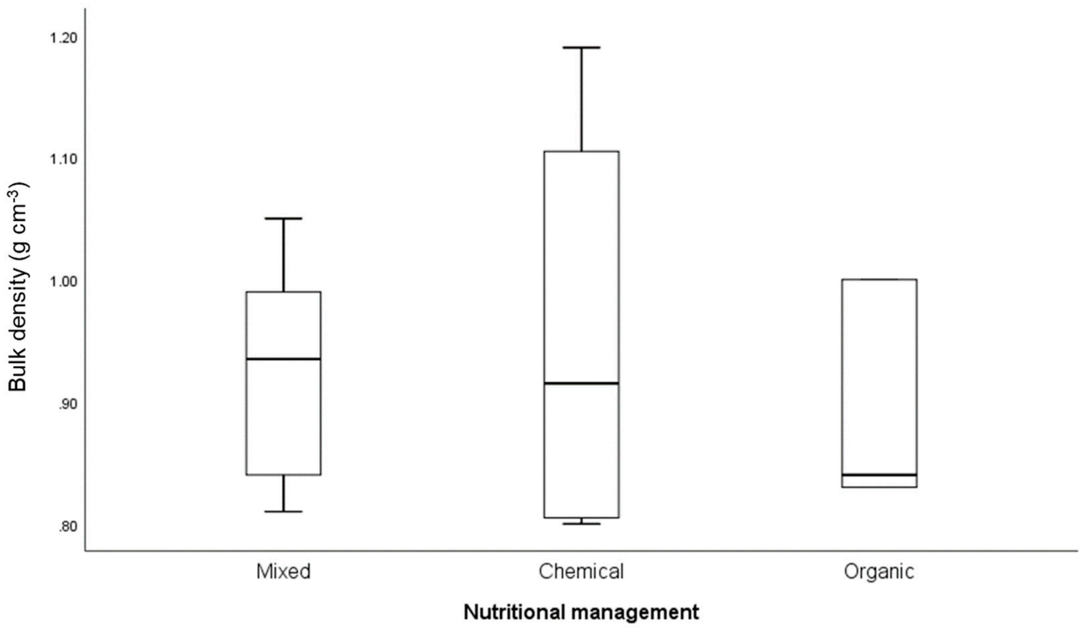

Figure 8. Bulk density for the different nutritional managements.

Texture was affected by nutritional managements. Sand percentage was higher in OM (72.96%), followed by MM (71.70%) and CM (70.88%) (Table 1). The highest data variability was found in CM (Figure 9); there were no significant differences between nutritional managements. Clay percentage was higher in CM (10.87%), followed by MM (7.24%) and OM (5.21%) (Table 1); no significant differences were found between nutritional managements; the highest data variability was found in CM (Figure 10).

Finally, silt percentage was higher and significantly different ($p < 0.005$) in OM (21.83%) compared to MM (21.05%) and CM (18.25%) (Table 1). The highest data variability was found in CM (Figure 11).

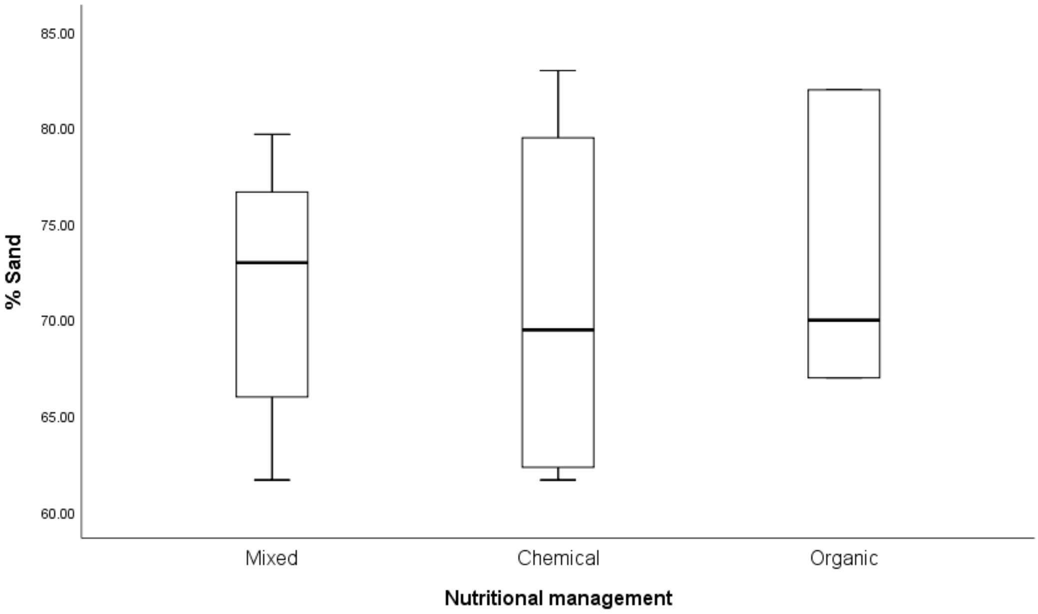

Figure 9. Sand content for the different nutritional managements.

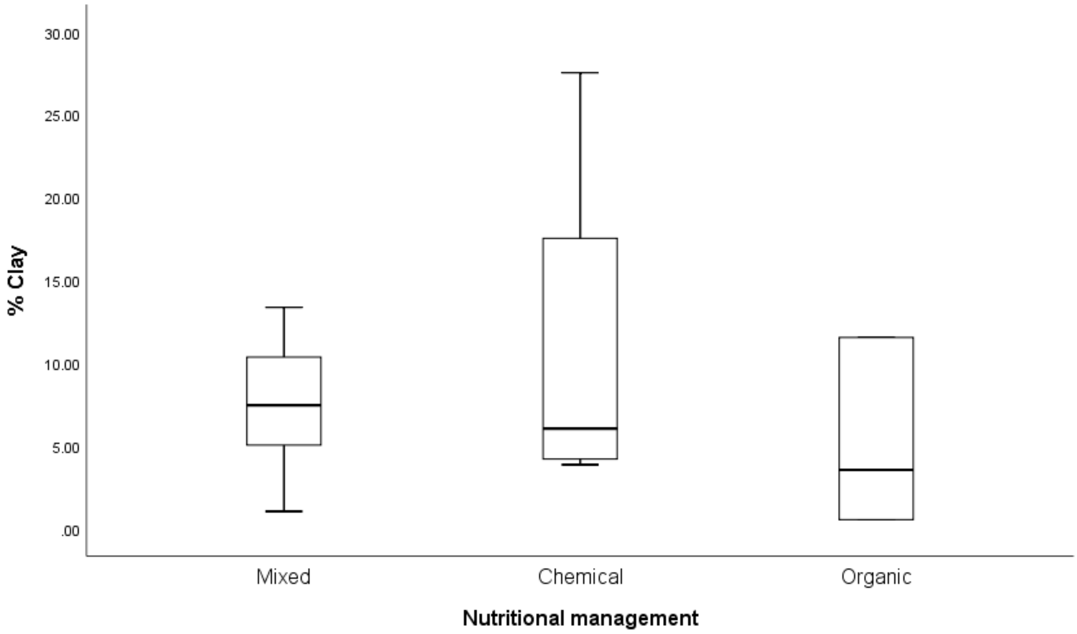

Figure 10. Clay content for the different nutritional managements.

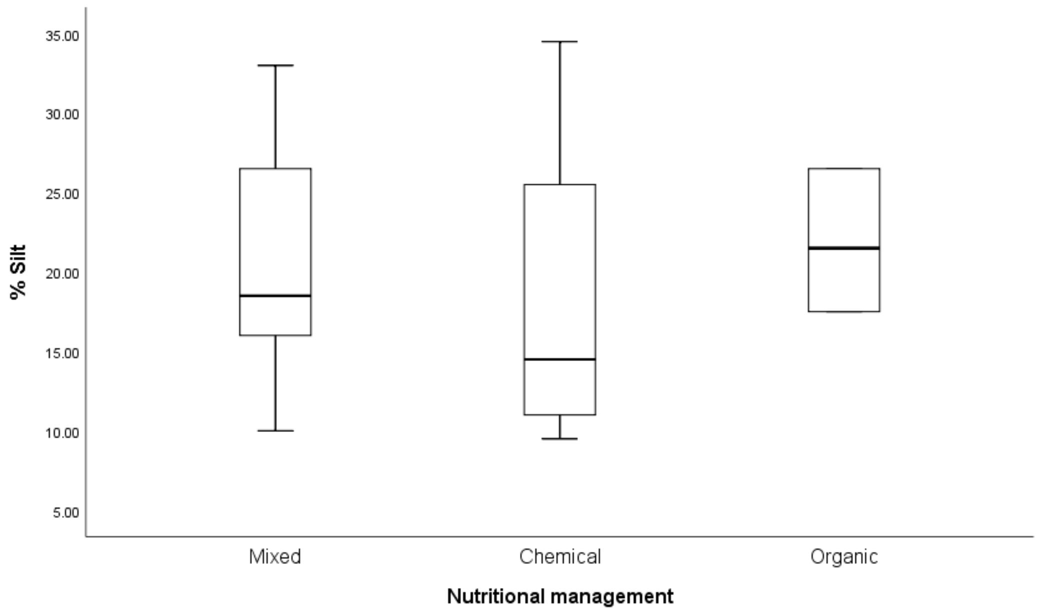

Figure 11. Silt content for the different nutritional managements.

4. Discussion

4.1. Nutritional Management Effects on Available Mineral Nitrogen

There was no significant difference between OM and CM regarding nitrate concentration (NO_3), showing that the amount of organic matter contributes to the availability of mineral elements (NO_3 and NH_4) in the soil; the input of organic matter has approximately 5%–8% of organic nitrogen (N), therefore, its addition provides the organic nitrogen required by microorganisms in order to carry out processes considered in the nitrogen cycle, assimilating the N required for its growth and releasing the remaining N, which will be absorbed by plants in their available forms (NO_3 and NH_4) or by the soil organic matter [23]. In addition, NO_3 availability was similar in OM and CM (68.77 and 70.65 mg NO_3 kg^{-1} soil, respectively), which suggests that these soils are capable of storing excess NO_3 absorption that has been reported in tropical Andisols [24,25], which is the predominant soil order in this region [26].

On the other hand, MM had the highest value of NO_3, showing significant differences to OM and CM. The results obtained may be due to the fact that, under CM, only NPK and other mineral elements essential for the growth of the plants are applied, but the requirements to strengthen physical and chemical processes that allow guaranteeing the sustainability of the soil resources are not considered. In this way, under a long period of CM, microorganisms will not have the input of organic material as an energy source; therefore, this input will be obtained from the soil humus, generating a reduction in the soil organic matter content. These findings were consistent with [27], which revealed that residual nitrate-N (NO_3-N) contents at 0 to 40 cm and 120 to 200 cm in the NPK + 22.5 t ha^{-1} swine manure (NPKM) and NPK + 33.7 t ha^{-1} swine manure (NPKM+) were 4–16 and 2–9 times higher than those in the NPK.

In addition, the application of nitrogen chemical fertilizers in high dosage and unfavorable periods, under inadequate levels of physicochemical and biological soil conditions, as evidenced by the values of organic matter, moisture and pH obtained in CM, generates a negative impact on the ecosystem, causing an increase in the water sources contamination levels, due to leaching and infiltration processes, and increased atmospheric pollution (nitrous oxide, ammonia) derived from denitrification and volatilization processes. Also, when carrying out MM, it is ensured that the soil has a constant organic material input in order to maintain adequate levels of physicochemical and biological characteristics. However, when applying the same amounts of nitrogen chemical fertilizers as in CM, high amounts of mineral elements (NO_3 and NH_4) could be added, guaranteeing nitrogen availability for plants but generating an excess that can lead to the same pollution problems mentioned in CM and incurring in high levels of indirect energy consumption derived from the use of chemical synthetic fertilizers. Similarly, additional expenses would occur, derived from the nitrogen chemical fertilizers and the costs associated with the preparation and application of manure. As such, under mixed management, it is necessary to evaluate the amount of nitrogen brought by the two sources (organic and chemical) in order to reduce the management costs and the negative impacts generated on the environment.

4.2. Impact of Nutritional Management in Soil Quality Properties

Under MM and OM, there is an input of organic matter that could increase the decomposition and mineralization processes, thus increasing humus, assuring the regulation of physical, chemical, and biological dynamics, as well as the soil quality and fertility, as indicated by moisture, pH, and organic matter values, which, in the case of the two managements did not show significant differences, as opposed to CM which had lower values of soil quality properties [27]. The lower value of soil moisture under CM is probably due to the fact that there is no organic matter input of any kind, while the input of organic matter strengthens soil structure, decreases leaching, runoff, and evapotranspiration rate, thus increasing water availability [28].

The pH is one of the greatest limiting factors for coffee production. OM increased organic carbon percentage by 29% and reduced the pH from 5.16 to 5.01. These findings were consistent with [28], which found a lower pH and higher soil organic carbon in OM as compared to CM in coffee farming. In the same way, these findings were consistent with [29], which found a positive effect of OM in the increase of SOC content by 53%, in soil depths of 17–18 cm, over 21 years. The lower value of pH in MM may be attributed to the use of chemical fertilizers and the input of organic matter, considering that the chemical fertilizers contain ammonia compounds (ammonium sulfate, ammonium nitrate, etc.) which, in the soil, release hydronium ions (H^+) that increase the soil acidification levels. Also, the mineralization of the organic matter added could release organic acids that can increase the soil pH [30,31]. This process can be increased under MM or OM, as a result of a greater input of organic matter, which can induce higher rates of mineralization, humification, and assimilation processes that lead to a greater metabolism of microorganisms, consequently increasing the elements that reduce the soil pH [32].

The addition of organic carbon to the soil can improve many aspects of its functioning, such as fertility, structure, water retention, infiltration capacity and nutrient regulation [33]. Fertilization with NPK + FYM has shown organic matter increases to a lesser extent than the input of NPK alone, because this mixed addition increases the sources of soil organic matter formation and, at the same time, reduces its consumption; this was consistent with [34], which reported the increase of SOC storage in soils under a mixed nutritional management (NPK + FYM). Additionally, the results showed that three years of OM significantly increased organic matter from 3% to 4.23% in relation to CM, indicating that FYM application can promote soil aggregation and recovery; this was consistent with [35], which showed an increase of aggregate associated C and N concentrations under OM. Therefore, maintaining and improving carbon storage in the soil is a strategy to avoid further land degradation [17].

Moreover, bulk density was lower for OM, followed by MM. When organic inputs are applied to the soil, they improve the soil porosity and water retention, which can increase bio-pores, aeration, and soil aggregation [36,37]; this was consistent with [38,39], which show that bulk density can be reduced with the application of organic inputs.

5. Conclusions

The current study shows that through the change from chemical to organic and mixed nutritional management, it is possible to have the same mineral nitrogen levels (ammonium and nitrates) than with NPK application only. Therefore, long-term manure application is beneficial for soil nitrates retention, being an adequate strategy to reduce the use of nitrogen chemical fertilizers, reducing the pollution generated by them. Also, it improves the soil quality properties (moisture, organic matter, bulk density, and pH); thus, it will improve physical, chemical, and biological processes that enable the regulation of functions and the ecosystem services which stimulate agroecosystems sustainability. Similarly, the change from chemical to mixed nutritional management generates an increase on the nitrates concentration and the improvement of the soil quality properties (moisture, organic matter, bulk density, and pH), making this a strategy to support the mineral requirements and soil quality properties, but it is necessary to consider an optimal plan to reduce the consumption of nitrogen chemical fertilizers and to avoid the problems associated with their use. The study suggests that, in order to get the environmental benefits of organic production, farmers ought to be encouraged to practice coffee organic production or mixed nutritional management under an optimal plan.

Author Contributions: The authors contributed significantly to the discussion and the outcome of the manuscript. J.F.C.O. wrote the paper; M.-C.O. reviewed and edited the paper and J.R.S. supervised the entire process and validated the quality of the manuscript.

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