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SOIL CONDITIONS AND EFFECT OF FERTILIZATION ON THE EMISSION OF GREENHOUSE GASES IN AN ANDEAN COFFEE GRADIENT

Juan **Burneo-Valdivieso**[1*], Daniel **Capa-Mora**[1], Pablo **Ochoa-Cueva**[1]

[1] Universidad Técnica Particular de Loja. Departamento de Ciencias Biológicas y Agropecuarias. Calle Marcelino Champagnat s/n, Loja, Ecuador. C. P. 1101608.
* Author for correspondence: jiburneo@utpl.edu.ec

ABSTRACT

Coffee (*Coffea arabica* and *C. canephora*) is an important agricultural export product in Ecuador, but yields reported at most coffee farms are low. The main reasons for this are a lack of understanding of soil nutritional status and fertilization management, which implies fertilizer misuse and results in gas emissions into the environment. In this study, the soil nutritional status of coffee plantations was evaluated along an altitudinal gradient of the Ecuadorian Andes as an indicator of soil fertilization plans. A total of 471 farmlands were selected and their pH, soil organic matter, and main macronutrients were determined. The impact of soil fertilization on nitrous oxide emissions was evaluated; for this purpose, an experimental coffee farm was chosen where different doses of mineral and organic soil fertilization were tested, and N_2O emissions were determined. The results showed a negative correlation between soil organic matter, pH, and nitrate concentration with altitude. In all altitudinal strata, the nitrate concentration was higher than that of ammonium. In addition, a strong correlation was observed between soil organic matter and soil nitrate concentration. The amount of potassium decreased as altitude increased, whereas medium and high concentrations of available phosphorus were observed in all altitudinal ranges. However, significant statistical differences were found when comparing low mineral fertilization doses to organic fertilization. The N_2O analyses showed that coffee plantations fertilized with mineral fertilizers emit from 300 to 1142 mg N_2O m^{-2} into the environment. High mineral fertilization resulted in the highest N_2O emissions, with statistically significant differences when compared to low mineral doses and organic fertilization. Therefore, it was concluded that changes in soil nutritional status were observed along the Andean gradient of coffee plantations in southern Ecuador, and that high doses of mineral fertilizer can have a significant impact on N_2O emissions.

Keywords: altitudinal gradient, coffee fertilization, greenhouse gases, nitrous oxide emission, soil fertility, Ecuadorian Andes.

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INTRODUCTION

Coffee, produced basically by the species *Coffea arabica* and *C. canephora*, is an important product of the global economy because of its widespread consumption. Currently, the coffee market is dominated by large producers such as Brazil, Vietnam, and Colombia.

In Ecuador, it is one of the most important agricultural export products, with 4917 Mg of coffee beans exported in 2021 (INEC, 2021). Coffee production is second only to banana production in terms of social, economic, and environmental importance, as more than 4 % of the population directly depend on it for a living. It is also a primary source of foreign exchange for both private producers and the government, and is part of the agroecosystem diversity in Ecuador (Ponce-Vaca *et al*., 2018).

Coffee production in Ecuador has been among the first 20 crops in the last 15 years, with the largest harvested area and production in 23 out of the 24 provinces of the country (INEC, 2021). In 2018, Arabica coffee (*Coffea arabica*) accounted for 68 % of the national production, whereas Robusta coffee (*Coffea canephora*) constituted 32 %. Additionally, 52 % of farmers grow Arabica coffee and 48 % grow Robusta coffee (Venegas-Sánchez *et al*., 2018). However, most Arabica and Robusta coffee plantations have low production yields, with a value of 0.22 Mg ha^{-1} (INEC, 2021).

One possible explanation for low coffee yields is that farmers do not adequately fertilize their crops; furthermore; additionally, there is no structured agronomic management program (including pest management, pruning, and replanting). Other problems reported include the advanced age of plantations, successive stumping, high incidence of coffee leaf rust (*Hemileia vastatrix*) (Martínez-López *et al*., 2021), and a lack of application of appropriate technologies (Capa-Mora *et al*., 2015). This, combined with a labor shortage and a drop in international coffee prices, results in low productivity.

Burneo-Valdivieso *et al.* (2017) reported that a problem of low coffee productivity among some coffee growers in southern Ecuador is their weak administrative structure; many coffee associations do not keep records of their partners' data and do not have adequate crop management information. They have low management input practices, which have a significant negative impact on soil nutrients. In brief, some fields are cultivated for several years without the application of manure or fertilizer, followed by leaving the land fallow when soil nutrients are depleted, causing crop yields to drop dramatically (Benavides-Muñoz *et al*., 2020).

The nutritional status of soil is another indicator of low productivity, which is rarely considered. Its importance is related to quality and productivity, as soil texture, acidity, and pH have a significant influence on some of the cup quality attributes of coffee (Morales-Ramos *et al*., 2020). Because coffee producers do not use diagnostic techniques such as soil testing, there is a lack of knowledge about crop-limiting factors. Proper diagnosis and sustainable fertilizer recommendations cannot be made without recent information on the fertility characteristics of soils. Coffee is a crop grown under a variety of conditions and is widely cultivated in tropical climates, similar to those found in the southern region of Ecuador (Ochoa *et al.,* 2017).

Ignorance in fertilization plans contributes to another issue related to environmental pollution caused by fertilizer misuse. Fertilization, whether organic or chemical, is an important factor, along with irrigation, since well-managed applications help produce vigorous and healthy plants while also increasing production (Capa-Mora *et al.,* 2015).

However, the widespread use of mineral fertilizers not only contributes to nitrate and phosphate contamination of water and soil, but also has a negative impact on climate change. Chemical fertilizer application accounts for approximately 57 % of the total greenhouse gas emissions from agricultural inputs, mainly from excess nitrogen (N) fertilizer use, and is mostly attributed to N_2O emissions from croplands (Cheng *et al.*, 2011).

For these reasons, the nutritional status of the soil in coffee plantations was evaluated in relation to an altitudinal gradient in the Ecuadorian Andes, characterizing the chemistry of the crop soil and evaluating the impact of soil fertilization on N_2O emissions. This information is key for producers and decision makers to improve the production chain and serves as a reference for other study areas.

MATERIALS AND METHODS

Study area

This study was conducted in the southern region of Ecuador in the provinces of Loja and Zamora Chinchipe, with an approximate area of 21 622 km^2 located between 3° 45′ S and 4° 55 ′S (latitude), 78° 50′ W and 80° 14′ W (longitude) (Figure 1). This is an area where the best coffee in the country is produced, according to contests such as "Golden Cup", and provides favorable conditions for high-quality coffee production (Ochoa *et al.*, 2017).

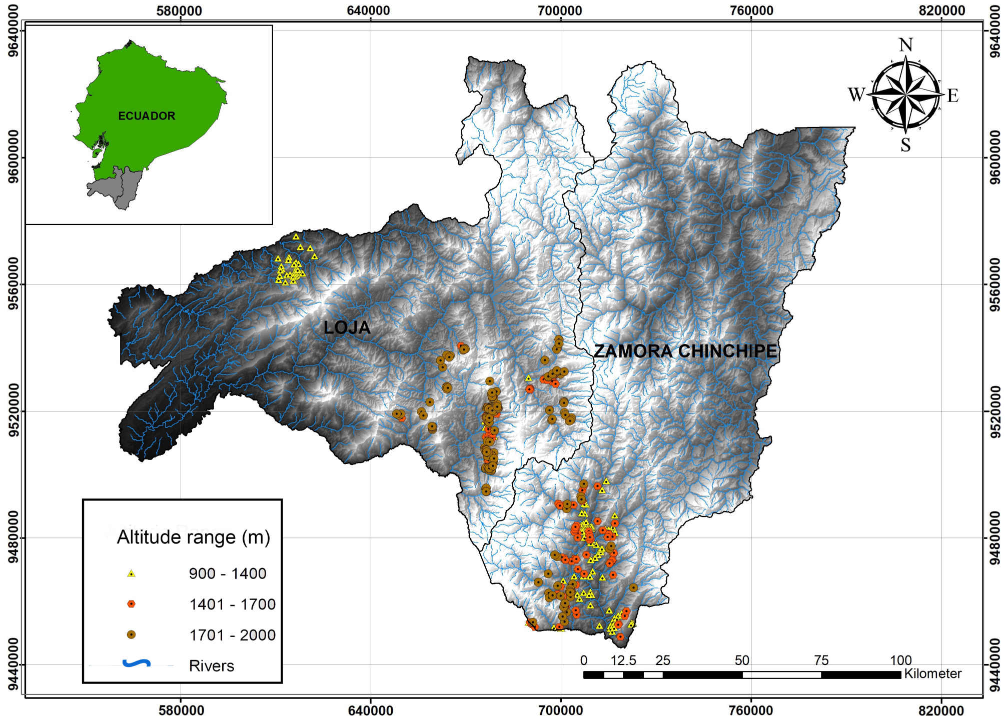

Figure 1. Study area of coffee plantations at various altitudes in southern Ecuador.

Experimental unit and design

To meet the objectives of this study, 471 farms were selected, belonging to five coffee farmer associations with an average farm size between one and three hectares. These associations were: *Productores de Café de Altura del Sudeste de la Provincia de Loja*, *Asociación Agrícola-Artesanal de Productores Orgánicos de la Cuenca del Río Mayo*, *Asociación de Productores Ecológicos Agroartesanales de Café Especial de Loja*, *Asociación Cafeteros Orgánicos de Palanda* and *Asociación de Cafeteros de Altura de Puyango*, all are belonging to the *Federación Regional de Asociaciones de Pequeños Productores de Café Ecológico del Sur Ecuador*.

Three altitudinal ranges were established: the low zone from 900 to 1400 m, the middle zone from 1401 to 1700 m, and the upper zone from 1701 to 2000 m (Figure 1). Loja province has a subtropical-dry climate, with an average annual temperature of 19.4 °C and average annual precipitation of 822 mm. The region is influenced by the Andes mountains, with rains typically falling from December to May, whereas the Zamora Chinchipe province is influenced by tropical easterlies, presenting higher humidity transport from the Amazon Basin (Benavides-Muñoz *et al*., 2020).

Soil sampling and laboratory analysis

Approximately 500 soil samples were collected throughout the study area. Samples were collected to a depth of 0–30 cm using a borer auger. A composite mineral soil sample was obtained from five subsamples at each study site. The soil samples were collected along an altitudinal sequence that crosses several districts in the Loja and Zamora provinces (Figure 1). Geographical coordinates, altitude, and climatic conditions were also recorded for each study site.

For the determination of chemical soil properties, the samples were air-dried and sieved through a 2 mm mesh size. The pH was measured potentiometrically in deionized water at a 1:2.5 soil-water ratio. Soil organic matter (SOM) was determined by wet oxidation using the Walkley-Black method (Soil Survey Staff, 2011). The determination of NO_3^- was done using colored complexes with brucine acid. Similarly, the determination of NH_4^+ was based on the formation of blue-colored complexes of indophenol. The Bray and Kurtz protocol was used for determining extractable P by the ammonium fluoride method (Bray and Kurtz, 1945). For the determination of inorganic K, extraction with NH_4^+-Ac solutions was used.

Determination of nitrous oxide (N_2O) emissions

A single experimental farm, located in the province of Loja at an altitude of 2000 m, with a rainfall of 910 mm year^{-1} and an average temperature of 18 °C, was selected. A one-year-old plantation (*Coffea arabica* L. var. Caturra) with a total area of 2500 m^2 was designated, and 12 study plots were established using a randomized block experimental design with three replicates per treatment. Fertilization treatments consisted of low inorganic fertilization with 70, 22, and 31 kg NPK ha^{-1} year^{-1} and 200, 65, and 62 kg NPK ha^{-1} year^{-1}; high inorganic fertilization with 225, 65, and 93 kg NPK

ha^{-1} $year^{-1}$ and 400, 109, and 187 kg NPK ha^{-1} $year^{-1}$; and 3 kg of organic fertilizer $plant^{-1}$ $year^{-1}$. The application rates were based on soil analyses and plant requirements.

Nitrous oxide was measured in coffee plantations to compare the emissions of mineral fertilization (high and low doses) and organic fertilization over a year and a half of crop management. The gas sample was collected using the closed chamber method (Capa-Mora *et al*., 2015), which involved burying a chamber to a depth of 5 cm and tightly sealing it with a lid equipped with a small hole to extract the gas. For each chamber, gas samples were collected every 10 min (1, 11, 21, and 31 min) and immediately transferred into 20 mL pre-evacuated septum-capped glass vials (Vacutainers, Beckton Dickinson, Franklin Lakes, NJ, USA).

The samples were analyzed using a gas chromatograph (Shimadzu GC-14B Duisburg, Germany) equipped with a flame ionization detector (FID), an electron capture detector (ECD), and a Porapak Q 80–100 mesh column for N_2O gas (Loftfield *et al*., 1997). N_2O concentrations were calculated by comparison of integrated peak areas of samples with standard gas (N_2O). The difference in concentrations at the 31st and 1st minute was used to calculate gas fluxes, and N_2O emission rates were calculated by linear interpolation using gas samples from each chamber, with at least three linear points required to validate flux measurements (Koehler *et al*., 2009).

Statistical analysis

Statistical analysis of the experimental data was performed using the Statistical Professional Social Sciences software (SPSS) 24.0 software (SPSS Inc., Chicago, IL, USA). The Kruskal-Wallis test was used on independent samples data ($p < 0.05$). Relationships between different parameters were determined using Spearman's correlation coefficient (r) using a two-tailed test ($p < 0.05$).

RESULTS AND DISCUSSION

Soil nutritional status and its relation to the altitudinal gradient

The results for soil pH in the study area ranged from 4 to 7.5 (Figure 2). Statistical analyses revealed significant differences between the medium altitudinal zone (1401–1700 m) and the high altitudinal zone (1701–2000 m). These two, however, did not show statistically significant differences with the low altitudinal zone (900–1400 m) (Table 1).

The pH values in the study area were negatively correlated with altitude ($r = -0.110$, $p < 0.05$), indicating that at higher altitudes, the pH of soils mostly cultivated with coffee tended to be acidified. A similar relationship with a linear decrease was found by De Bauw *et al*. (2016), with pH values of 7.5 at 1000 m and 4.9 at 2200 m. According to these authors, the increase in soil acidity as a function of altitude can be explained by a variety of factors, including greater acidification of the soil at higher altitudes due to more intense leaching (Tables 1 and 2).

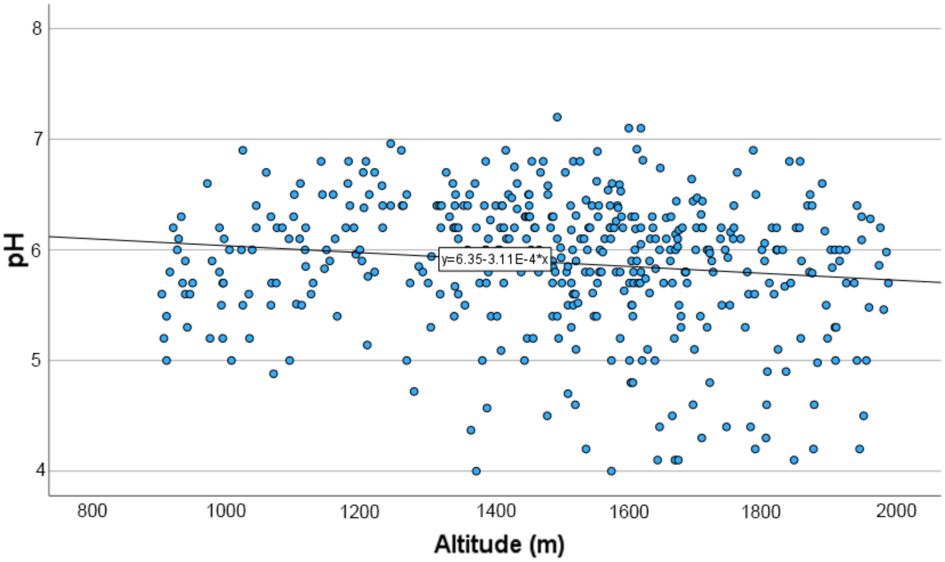

Figure 2. Relationship between soil pH and altitude.

Table 1. Average soil parameters in relation to altitudinal ranges.

Altitude (m)	pH	SOM (%)	Nitrate	Ammonium	Phosphorus	Potassium
			(mg kg^{-1})			
900–1400 (Low)	5.9±0.5ab	2.87±1.1b	34.26±20.2b	15.88±11.3a	46.49±26.8b	161.8±159.3b
1401–1700 (Medium)	6.0±0.56b	2.50±1.0a	34.26±26.4b	20.84±18.3b	37.98±27.5b	155.8±176.4b
1701–2000 (High)	5.7±0.66a	2.33±0.7a	27.22±22.3a	14.33±13.9a	34.80±30.8a	118.0±153.6a

Mean values per column with different letters indicate significant differences among altitudes ($p < 0.05$). The standard error is shown next to each mean value. SOM: soil organic matter.

Table 2. Soil analysis interpretation in relation to altitudinal ranges.

Altitude (m)	pH	SOM*	Nitrate	Ammonium	Phosphorus	Potassium
900–1400 (Low)	slightly acid	low	high	high	high	medium
1401–1700 (Medium)	slightly acid	low	high	high	medium	medium
1701–2000 (High)	slightly acid	low	high	high	medium	low

*SOM: soil organic matter.

Pastor-Mogollón and Martínez (2009) reported similar results in an altitudinal gradient in the Venezuelan Andes, where a decrease in soil pH was observed with altitude, with the highest pH value (6.6) found at 720 m and the lowest value (4.7) found at 1400 m. According to these authors, the low pH values are related to the highest values of precipitation, which are registered in the mountainous region of the Andes in the highest places (Arteaga-Marín *et al*., 2022), which washes the changeable bases of soil (Jiménez *et al*., 2007). These studies support our findings in the altitudinal range of 1701–2000 m, where the lowest values of acidity and exchangeable bases, such as potassium, were found. López-Báez *et al*. (2016) found similar trends in the pH behavior with altitude, high precipitation, orographic conditions, and the mineralogical characteristics of geological materials.

The geological substrates of the study area in southern Ecuador are composed of a) Tertiary age sedimentary rocks to the east, b) Quaternary age volcano-sedimentary rocks located northeast, and c) rocks of intrusive magmatic origin (granites and granodiorites) located throughout the provinces that have intruded into the Paleozoic, Cretaceous, and Tertiary rocks. In addition, Wilcke *et al*. (2003) argued that the soils of these areas have Oxisol characteristics, with metamorphic and crystalline rocks as the most outstanding parent materials, which is typical of the final stage of ferralitization (the processes associated with strong weathering that led to the formation of Oxisols or Ferrosols). As a result, these soils are acidic.

Soil acidity may be caused by the accumulation of organic matter on the soil surface because of minimal tillage. However, our results revealed the opposite, namely, a higher degree of soil acidity as a function of the decrease in organic matter in the higher areas, which could be explained by the use of nitrogen fertilizer as well as the inclusion of certain tree species that increase soil acidity (Tully *et al*., 2013). A local study on mineral and organic fertilization for coffee cultivation (Capa-Mora *et al*., 2015) reported that any nitrogen contribution (mineral or organic) contributes to soil acidification.

SOM average concentrations in the study area ranged between 2.3 and 2.9 %, with the lowest value (2.3 %) located in the high altitudinal zone (1701–2000 m) and the highest value (2.9 %) in the low altitudinal zone. These results showed significant difference among the low altitudinal zone *versus* the middle and upper zones. However, there were no significant differences between the last two altitudinal zones (Figure 3). A negative correlation with the height ($r = -0.219$, $p < 0.05$) was revealed, indicating that the higher altitude of coffee plantations, less organic matter accumulates. Additionally, this may be due to the needs and characteristics of the crop, which develops in optimal altitude ranges between 1200 and 1600 m.

In the soils of the Ecuadorian highlands, SOM values below 3 % are considered low for all altitudinal ranges (Table 2). Generally, SOM is expected to increase with elevation (De Bauw *et al*., 2016); however, this trend was not observed in our results, as SOM concentration decreased as altitude increased. This contradiction implies that other factors, not included in this study, such as farmers' management of the cultivation

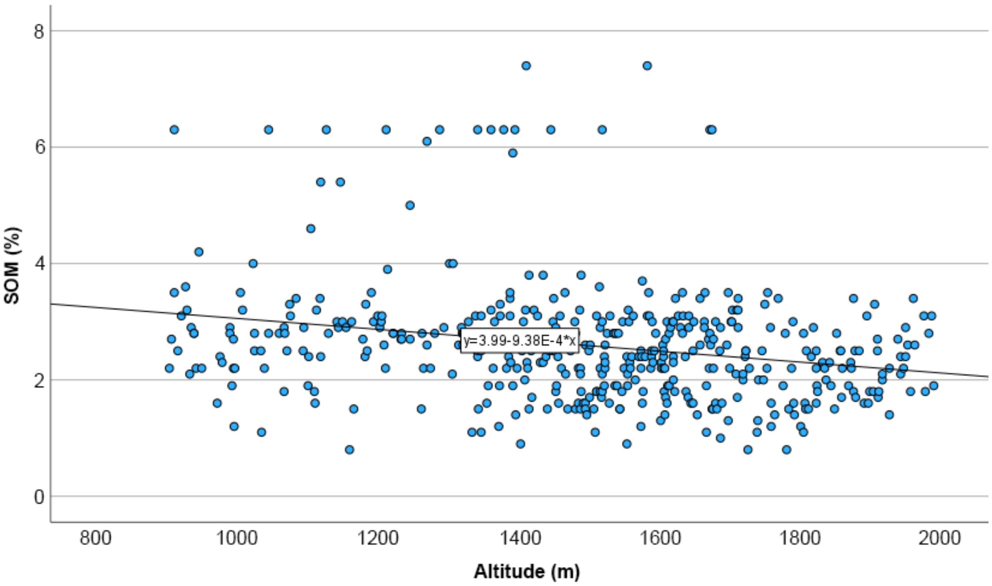

Figure 3. Relationship between soil organic matter SOM concentration (%) and altitude.

system, type of vegetation, soil erosion, and topography, among others (Arteaga-Marín *et al*., 2022), have an impact on SOM reserves.

SOM and sediment accumulation are often favored by topography (López-Báez *et al*., 2016; Arteaga-Marín *et al*., 2022), where SOM is transported to the lowest point in the landscape through runoff processes. This type of erosion may have long-lasting secondary effects on plant growth and litterfall input (Quichimbo *et al*., 2017). If erosion reduces productivity by limiting replenishment, the amount of SOM may decrease in the long term (Bahr *et al*., 2013).

Erosion studies in our area show a high to moderate susceptibility, mainly due to climatic and topographic factors (Arteaga-Marín *et al*., 2022). This could explain why, in this study, a lower SOM concentration was found in high areas than in low areas, possibly due to the high soil erosion risk in the area. The influence of the land relief is determinant in both the SOM quantity and quality, because the characteristics of the soil change with altitude in many cases. Also, precipitation, temperature, and the vegetation type influence the microbial biomass and the microbiological activity in soil (Quichimbo *et al*., 2017), which is directly related to the SOM concentration. According to Vélez-Mora *et al*. (2022), areas with intensive agricultural activity have the lowest SOM levels. This could explain the tendency of SOM to decrease, depending on the height found in our study. However, the average SOM concentration in the study area is within the appropriate ranges for this crop (> 2 %) (Ochoa *et al*., 2017).

Alternatively, our results indicate that that as the height of the study area increased, the nitrate concentration of the soil decreased (r = -0.20, $p < 0.05$). However, no significant difference was observed between the low and medium altitudinal zones, but both showed a significant difference with the higher zone (Figure 4A). Furthermore,

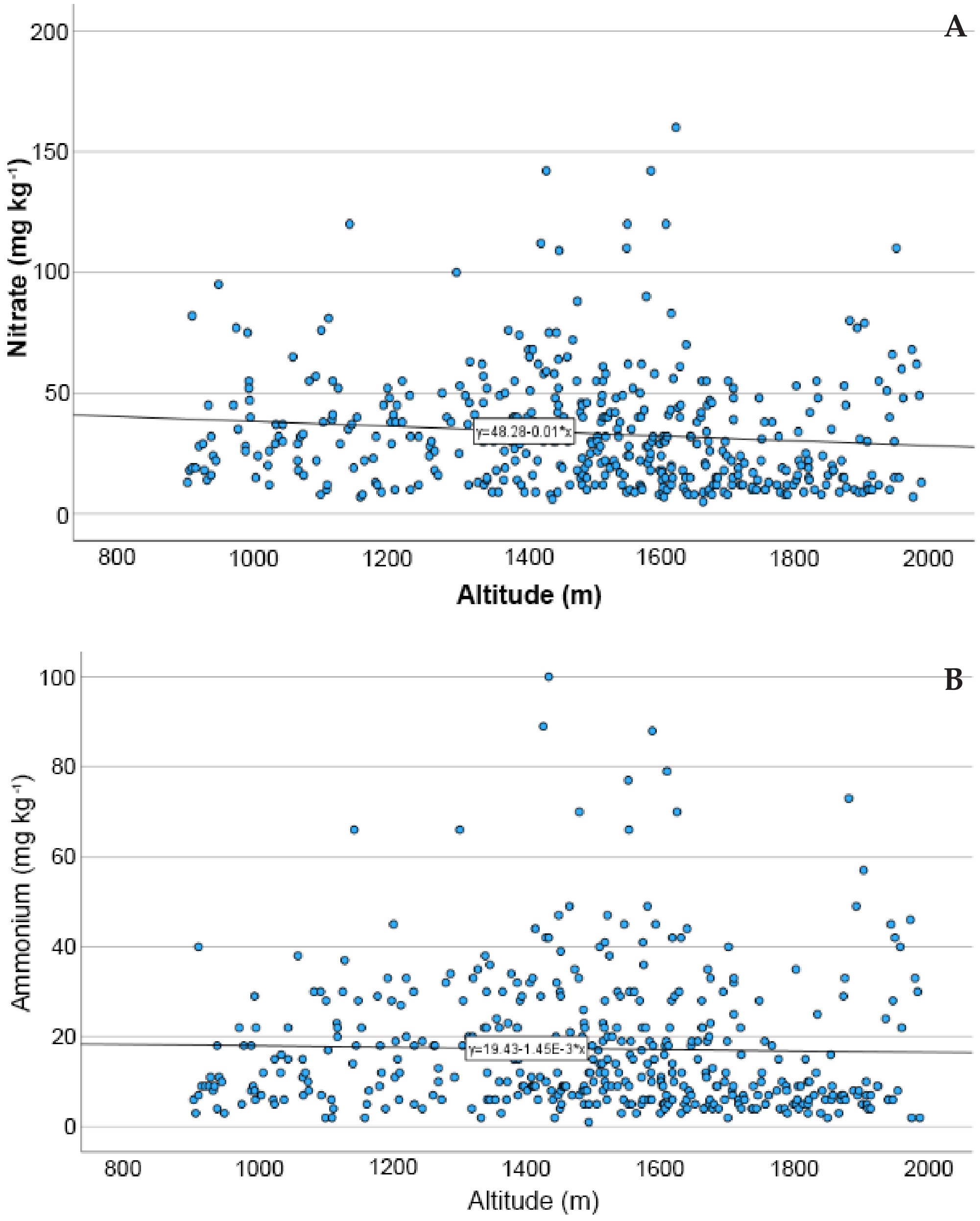

Figure 4. Inorganic forms of nitrogen in relation to altitude. A: nitrate concentration; B: ammonium concentration.

ammonium concentration showed a similar statistical relationship, with statistical differences in the low and high areas in relation to the soil in the medium zone, which contained the highest levels of ammonium (20.84 mg kg^{-1}) (Figure 4B).

Nitrogen forms available to plants, such as nitrate (N-NO_3^-) and ammonium (N- NH_4^+), vary depending on environmental factors such as temperature and humidity. Nitrate concentrations between 20 and 30 mg kg^{-1} are considered high, while ammoniacal nitrogen concentrations above 10 mg kg^{-1} are considered high (Table 2). Plant and animal waste degradation in the soil is a biological process in which carbon is recycled to the atmosphere as carbon dioxide, nitrogen is transformed into a usable form by plants as ammonium and nitrate, and other associated elements such as phosphorus, sulfur and several microelements are also transformed (Bahr *et al*., 2013). This supports our findings as higher altitudes showed less SOM and lower nitrate, ammonium, phosphorus, and potassium concentrations.

In all the altitudinal zones studied, the nitrate concentration was higher than that of ammonium. Also, a strong correlation was observed between SOM and soil nitrate concentration. According to Valarezo-Torres *et al.* (2021), in areas with higher SOM, the addition of organic waste is accompanied by an increase in the microbial population, which requires nitrogen to allow the growth of the microbial biomass. Because plants require nitrogen for growth and the microbial flora reduces its levels, particularly of ammonium, nitrogen availability for nitrifying organisms and plants is reduced.

While Zebarth *et al*. (2015) observed that lowering the soil pH limits soil nitrification and thus soil inorganic N will remain primarily in the NH_4^+ form, this may explain why in the upper zone (1701–2000 m), where the lowest pH values were present (5.7), a decrease in nitrate was also observed. Meanwhile, the average pH values in the middle zone (1401–1700 m) were 6, with an increase in nitrate concentration. However, it must be emphasized that in all the studied areas, the nitrate values were always higher than those of ammonium. By decreasing the SOM mineralization rates, less inorganic nitrogen is released, resulting in lower ammonium concentrations. This aspect is reflected in our results, since lower values of SOM and ammonium were found in higher areas.

Phosphorus availability was also related to altitudinal range. Results showed that the low SOM concentrations may also influence the low concentrations of other macronutrients at higher altitudes such as phosphorus (P) and potassium (K), since the majority of these nutrients are found in the organic layer of the soil. Therefore, in the lower zone (900–1400 m), where the highest SOM values were found (2.87 %), the highest P and K values were also obtained.

Available phosphorus analysis indicates that values between 20 and 40 mg kg^{-1} are considered medium, whereas values above 40 mg kg^{-1} are considered high. In the middle and high zones studied, medium phosphorus concentrations were observed, whereas in the low zone, high phosphorus values were registered (Tables 1 and 2). Statistical differences were observed between the lower zone and the other two altitudinal zones, also indicating a negative correlation ($r = -0.16$, $p < 0.05$), with lower phosphorus concentration available at higher heights (Figure 5).

After nitrogen, phosphorus (P) is usually the most limiting nutrient for crop production. It is a macronutrient with a low soil supply rate and noticeably low retention or bioavailability (Howell *et al*., 2016). Because of root exudates, soil P solubility can affect some plants (Campos-Janegitz *et al.,* 2017). Different plant species, and even cultivars

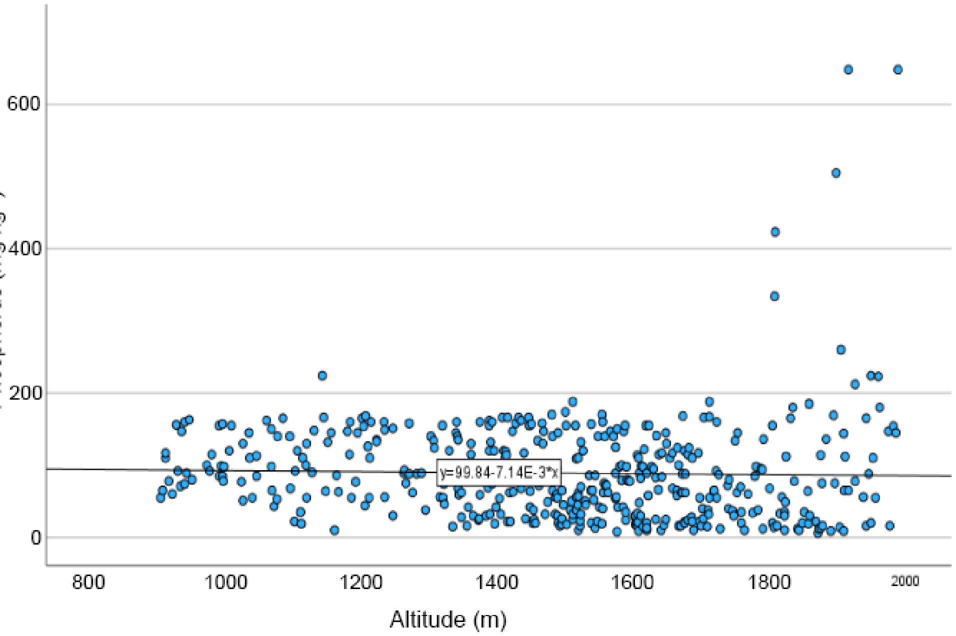

Figure 5. Relationship between phosphorus (P) concentration in soil and altitude.

of the same species, may exhibit growth variability due to phosphorus concentration (Akhtar *et al.*, 2016). Therefore, phosphorus is added in much greater quantities than the crop can remove. Soil heating can also increase phosphorus availability by partially oxidizing organic phosphorus in the soil. Slash and burn farming practices significantly increase phosphorus stocks (Hamer *et al.*, 2013). This could explain the higher phosphorus concentration in lower areas, where fire incidence is lower.

The findings of this study revealed statistically significant differences in potassium levels. This nutrient decreases with increasing altitude, with a negative correlation of r = -0.34 ($p < 0.05$) (Figure 6). Soluble potassium values below 150 mg kg^{-1} are considered low, as would be the case in the high zone with 118.0 mg kg^{-1}, while the middle (155.8 mg kg^{-1}) and low (161.8 mg kg^{-1}) zones were in the medium potassium concentration (Table 2). According to Howell *et al*. (2016), intensive cropping, runoff, leaching, and soil erosion lead to soil potassium deficiency, resulting in stunted growth and limited physiological activities of the plant.

The average K reserves in soil are generally large, but the most of its are not available to plants. Olaniyan *et al*. (2022) stated that physical, chemical, mineralogical, and biological factors, particularly soil microbiota, influence the release of potassium from soil minerals through cation exchange and dissolution processes. In this sense, soil pH and acidity play a key role in K release from clay minerals, which is related to the findings in this study as low potassium values were found in soils in lower zones with higher soil acidity.

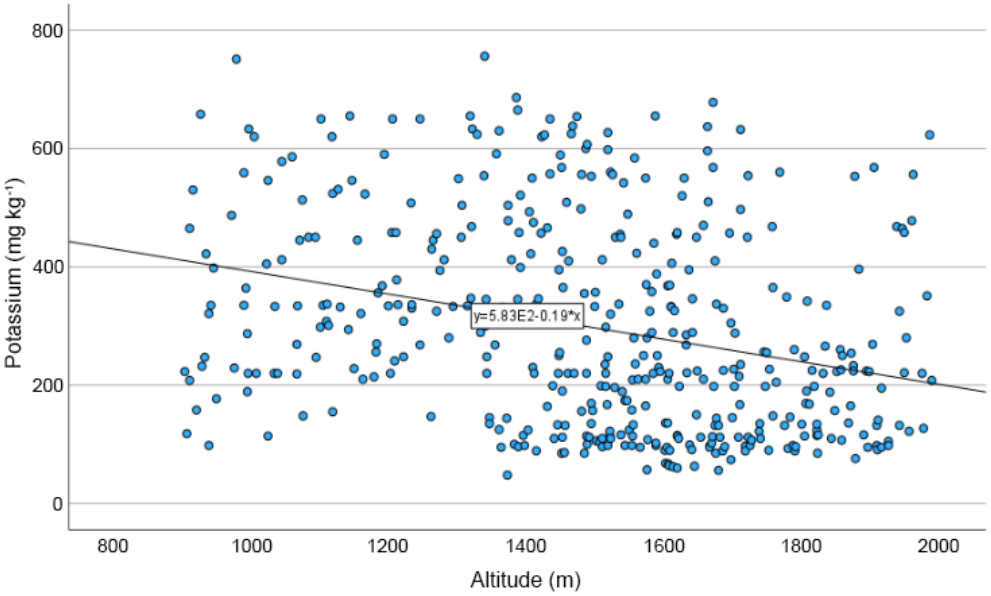

Figure 6. Relationship between potassium (K) concentration in soil and altitude.

Fertilizer application recommendation

Based on a comprehensive analysis of soil fertility in coffee cultivation at various altitudes, inorganic fertilization was proposed (Table 3). This fertilization program is intended for crop plots.

Table 3. Recommendations for coffee fertilization of soil macronutrients (N-P-K) in relation to altitude.

Altitude (m)	N g per plant	P_2O_5 g per plant	K_2O g per plant
900–1400 (Low)	120	60	200
1401–1700 (Medium)	120	100	200
1701–2000 (High)	120	100	280

While organic fertilization of this crop based on age of coffee would be 3 kg plant^{-1}. depending on the age of the plantation, older age, greater development, and greater need for organic fertilizer to meet nutritional needs.

Impact of soil fertilization on N_2O emission.

Significant statistical differences were found in the experimental farm chosen to evaluate the impact of soil fertilization on N_2O emissions when compared to low mineral fertilization doses and organic fertilization. Furthermore, there was no statistically significant difference between the low mineral dose and organic fertilization.

According to N_2O analyses, coffee plantations fertilized with mineral fertilizers emit between 300 and 1142 mg N_2O m^{-2} emissions to the environment, while coffee plantations fertilized with organic matter reported fluxes of less than 300 mg N_2O m^{-2}, regardless of the type and amount of organic matter used (Figure 7). In addition, Noponen *et al.* (2012) found that organic fertilization contributes less N_2O emissions to the environment. These authors indicated that nitrogen-based fertilization could contribute up to 50 % of N_2O emissions, which is corroborated here, since coffee farmers mostly use urea as a nitrogen source to fertilize their coffee plantations, often without considering a previous soil analysis, affecting the environmental sustainability of these ecosystems and contributing to the emission of greenhouse gases and climate change. Similarly, Martinson *et al*. (2013) reported that the addition of nitrogen increases N_2O emissions.

Verchot *et al*. (2006) reported that high nitrogen fertilization in coffee crops can emit up to 7 kg N_2O ha^{-1} y^{-1}. If we scale our N_2O emission data to the scale of one hectare, the results for coffee plantations with high doses of mineral fertilization would reach 11 kg ha^{-1} y^{-1} of N_2O emission, demonstrating that the more fertilizer used, the more gas emissions are produced. Farmers in our study's vicinity, on the other hand, use high doses of nitrogen fertilizers such as urea because, according to them, these high doses result in higher yields in their coffee plots. However, according to Tully *et al*. (2013),

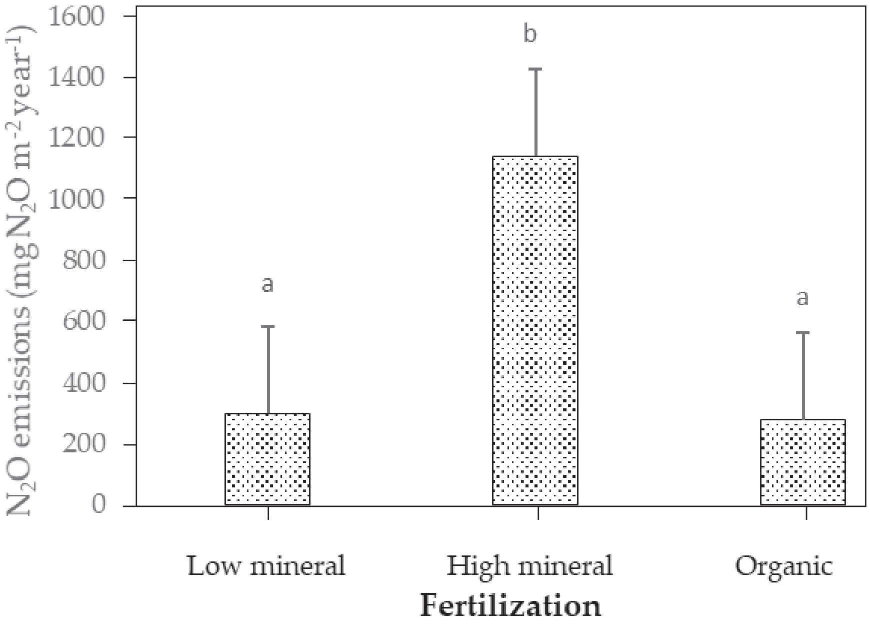

Figure 7. N_2O emissions in coffee plantations of mineral fertilization (high and low doses), and organic fertilization.

the way and amount of how much N is applied can have a differential impact on the higher leaching of mineral fertilizers and, as observed in our results, result in higher N_2O emissions to the environment.

CONCLUSIONS

Changes in the nutritional status of the soil were observed along an Andean gradient in coffee plantations in southern Ecuador. This is due to the high susceptibility of these soils to erosion, primarily due to their steep slopes, which promote nutrient accumulation in lowlands. A high rate of mineral fertilization rapidly improves coffee crop productivity; however, the environmental impact is greater because of high N_2O emissions. When organic fertilization is used, nutrient assimilation is slower, but N_2O emissions to the environment are reduced. Therefore, organic fertilization would be more environmentally sustainable.

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