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SCIENTIFIC ARTICLE

Availability of iron, manganese, copper, and zinc in different land uses and depths of an Oxisol in Alto Paraná, Paraguay

Disponibilidad de hierro, manganeso, cobre y zinc en diferentes usos y profundidades de un Oxisol del Alto Paraná, Paraguay

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RESUMEN

La adecuada disponibilidad de los micronutrientes es fundamental para el desarrollo de los cultivos agrícolas, ya que son esenciales para el crecimiento de la planta, la formación de clorofila y la optimización del aprovechamiento del nitrógeno. El objetivo de este estudio fue determinar la influencia del uso y la profundidad del suelo en los niveles de hierro (Fe), manganeso (Mn), cobre (Cu) y zinc (Zn) en un Oxisol, y analizar la relación de estos micronutrientes con el pH y la materia orgánica (MO). El análisis estadístico se realizó mediante la prueba no paramétrica de Friedman. Los tratamientos consistieron en cuatro usos del suelo (Bosque, Pastura, Agricultura convencional, Agricultura conservacionista) y seis profundidades (0-5, 5-15, 15-30, 30-60, 60-100, 100-150 cm, respectivamente). En el sistema de agricultura se registraron los niveles más bajos de Mn (43,4 mg kg^{-1}), Cu (14,2 mg kg^{-1}) y Zn (2,2 mg kg^{-1}); en contraste la influencia de estiércol en el suelo de pastura favoreció las mayores concentraciones de micronutrientes con valores de Fe: 47,9 mg kg^{-1}, Mn: 47,5 mg kg^{-1}, Cu: 26,9 mg kg^{-1} y Zn 4,5 mg kg^{-1}. En los cuatro usos de suelos los niveles más elevados de Cu se registraron en la capa de 15 a 60 cm. En la capa superficial de 0-5 cm se destacó la mayor concentración de MO en bosque y pastura (6.7% y 4.9%). El análisis estadístico muestra que el suelo de bosque presentó un pH 5,3 más ácido que los demás usos de suelo. No se observó correlación significativa entre los micronutrientes evaluados y las variables pH y materia orgánica del suelo.

Palabras claves: micronutrientes, pH del suelo, materia orgánica, profundidad del suelo, uso del suelo, Oxisol.

ABSTRACT

The adequate availability of micronutrients is fundamental for the development of agricultural crops, as they are essential for plant growth, chlorophyll formation, and optimized nitrogen utilization. The objective of this study was to determine the influence of land use and soil depth on the levels of iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) in an Oxisol, and to analyze the relationship of these micronutrients with pH and organic matter (OM). Statistical analysis was performed using the non-parametric Friedman test. The treatments consisted of four land uses (Forest, Pasture, Conventional Agriculture, Conservation Agriculture) and six depths (0–5, 5–15, 15–30, 30–60, 60–100, and 100–150 cm, respectively). The lowest levels of Mn (43.4 mg kg^{-1}), Cu (14.2 mg kg^{-1}), and Zn (2.2 mg kg^{-1}) were recorded in the agricultural system; in contrast, the influence of manure in the pasture soil favored the highest micronutrient concentrations, with values of Fe: 47.9 mg kg^{-1}, Mn: 47.5 mg kg^{-1}, Cu: 26.9 mg kg^{-1}, and Zn: 4.5 mg kg^{-1}. In all four land uses, the highest Cu levels were recorded in the 15–60 cm layer. The highest concentration of organic matter (OM) was found in the 0–5 cm surface layer in forest and pasture (6.7% and 4.9%, respectively). Statistical analysis shows that the forest soil had a pH 5.3, which was more acidic than the other land uses. No significant correlation was observed between the evaluated micronutrients and the soil pH and organic matter variables.

Key words: micronutrients, soil pH, organic matter, soil depth, land use, Oxisol.

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No conflicts of interest to declare.

Author Contributions:
M.P.A. designed and carried out the experiment, collected the data, and performed the statistical analysis, in addition to managing the funding. A.E.R., J.R.A., D.R.M. and D.A.F.F. supervised the development of the study and prepared the initial draft of the article. E.M.M.C. designed the figures and tables of the research, performed the statistical analysis, and corrected the citations and bibliographic references.

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INTRODUCTION

Soil is a non-renewable natural resource that sustains plant nutrition, agricultural production, and, consequently, the constantly growing global food security (Rodríguez, Martín, Pérez, and García, 2025). It constitutes the fundamental basis for plant development, as it provides physical support, water, and essential nutrients. The Food and Agriculture Organization of the United Nations (FAO, 2025) defines soil as the natural medium for plant growth, whose composition and dynamics largely determine agricultural productivity.

Adequate nutrient availability is an indispensable requirement for the success of any agricultural system. Among these, the micronutrients iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) perform essential functions in various physiological and biochemical processes, such as chlorophyll synthesis, photosynthesis, and nitrogen assimilation. Their deficiency, even at low concentrations, can significantly affect plant growth, crop yield, and agricultural production quality (Macías, 2022).

Micronutrient levels and availability vary considerably depending on soil type and use, and are influenced by factors such as parent material, erosion, leaching, pH, and agricultural management practices (Villasanti, Román, and Pantoja, 2013). According to Roca, Pazos, and Bech (2007), the main causes of micronutrient deficiency are: i) low concentration of the element in the soil, ii) the presence of chemical forms unavailable to plants, and iii) antagonistic interactions between different elements. Likewise, Arroyo, Sanzano, Rojas Quinteros, and Navarro (2022) note that understanding the dynamics, requirements, and functions of these nutrients is essential for achieving more efficient, profitable, and sustainable agricultural production systems.

Limited micronutrient availability can reduce crop yield and quality, directly affecting the profitability of production systems and the well-being of producers. In this context, and considering the scarce information available on the status of micronutrients in the soils of the Minga Guazú district, the present study aimed to compare the availability of iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) among different soil uses and depths in an Oxisol of Alto Paraná, Paraguay. Additionally, the relationship between these micronutrients, soil pH, and organic matter content was analyzed.

MATERIALS AND METHODS

Study area, treatments, and soil collection

The study area was located in the district of Minga Guazú, Alto Paraná department. The region's climate is humid subtropical, with an average annual temperature of 22.5 °C. The soil corresponds to the taxonomic subgroup Rhodic Kandiudox, characterized by clayey texture, good aeration, deep profile, good permeability, predominantly dark red color, and geologically derived from basaltic parent material (López Gorostiaga & Lesme Brun, 2024).

This research was classified as a descriptive comparative study. Sample collection was carried out using simple stratified random sampling, considering micronutrient levels, pH, and soil organic matter across the different soil uses and depths.

The independent variables were soil use, with four categories (forest, conventional agriculture, no-till/direct seeding, and pasture), and profile depth, with six levels (0–5, 5–15, 15–30, 30–60, 60–100, and 100–150 cm). Both factors constituted the comparison categories of the study.

Laboratory analyses

Soil pH was determined in water (pH H_2O) at a soil:water ratio of 1:2.5, using a pH meter. Organic matter was determined using the Walkley-Black method, for which potassium dichromate ($K_2Cr_2O_7$) and concentrated sulfuric acid (H_2SO_4) were used, with subsequent titration using ferrous sulfate ($FeSO_4$) according to Lana, Fey, Fradoloso, Richart & Fontaniva (2010). The micronutrients Fe, Mn, Zn, and Cu were determined using the Mehlich-1 extracting solution and reading by atomic absorption spectrophotometer (Silva, 2009).

Data analysis

The data were evaluated using normality tests. Since they did not meet the assumption of normality, comparisons between treatments were performed using Friedman's non-parametric test at a 5% significance level. In addition, linear regression analysis was performed to evaluate the relationships between micronutrients and soil organic matter content and pH.

RESULTS AND DISCUSSION

Relationship between iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) in different soil uses

Figure 1 presents the results of the Friedman test analysis for the micronutrients, of which Fe, Cu, and Zn content showed significant differences across the different soil uses, while Mn did not show statistically significant differences.

The lowest Fe content was observed in the conventional system, which differed statistically from the other uses. Values in forest and no-till were similar, while the highest content was recorded in soil under pasture.

The increase in Fe in pasture soil can be attributed to the constant incorporation of animal manure, which constitutes an important source of this micronutrient. Salazar et al. (2007) reported Fe concentrations of 3332 mg kg^{-1} in bovine manure, values similar to those obtained by Barbazán et al. (2011). In these systems, the continuous deposition of organic residues generates a natural pedogenetic process that enriches the surface soil in Fe. Similar results were observed by Lobo et al. (2012), who reported greater micronutrient availability in soils under pasture, particularly with Brachiaria decumbens.

Regarding soil use, the lowest Cu values were recorded in the forest and conventional agriculture systems, with no significant differences between them. In contrast, no-till soils showed higher Cu levels, differing statistically from forest and the conventional system. The highest Cu content was observed in pasture soil, being significantly higher than the other uses.

The increase in Cu in no-till and pasture systems may be associated with soil management and the type of vegetation cover. According to Lavado, Porcelli, and Álvarez (1999), management practices, such as tillage type, can modify the vertical distribution of micronutrients. Lobo et al. (2012) also highlighted that soil use and management directly influence Cu content and distribution in the profile.

The higher Cu content in pasture soils could be due to the nature of the predominant vegetation, which favors micronutrient accumulation in the root system and in the organic matter contributed. Casanova and Lobo (2011) noted that botanical composition affects variation in micronutrient content, while Mosqueda and González (2015) indicated that Cu is one of the most abundant elements in forage species, especially in dicotyledons, which is consistent with the results observed.

Soil under pasture recorded the highest Zn values, differing significantly from the other uses. No-till also showed higher levels than forest, while the conventional system had the lowest Zn concentrations, differing statistically from forest.

The increase in Zn in pasture and no-till soils can be attributed to the greater contribution of organic matter and the presence of vegetation with high nutrient recycling capacity. Casanova and Lobo (2011) indicated that variation in micronutrient content under different vegetation covers is associated with differences in organic residue inputs and differential nutrient extraction by plant species. In contrast, conventional soil management tends to reduce Zn levels due to organic matter loss and increased surface erosion. According to Derpsch (2025), conventional soil preparation, by leaving the surface exposed, favors structural degradation and micronutrient loss.

Relationship between iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) with soil depth

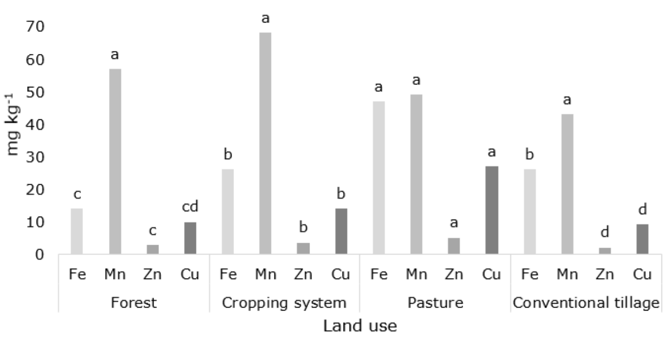
Figure 2 presents the results of the Friedman test analysis for the micronutrients, of which Mn, Cu, and Zn content showed significant differences with soil depth, while Fe did not show statistically significant differences.

The highest Mn concentrations were recorded in the surface layer (0–5 cm), decreasing progressively with depth. Differences were significant between most of the layers analyzed, with the exception of the 60–100 and 100–150 cm depths, where no statistical differences were detected. This vertical distribution suggests an effect of organic matter (OM), whose higher concentration in the surface layers contributes to Mn retention through organometallic complexes.

These results are consistent with those reported by Santiago, Quintero, and Delgado (2008) and Lobo et al. (2012), who observed a decreasing trend in Mn with profile depth. This decrease is mainly associated with the reduction in OM content and the increase in pH in the deeper layers, which decreases Mn solubility. In agreement with this, the present study showed higher pH values with depth (Table 1), reinforcing the influence of this parameter on micronutrient availability.

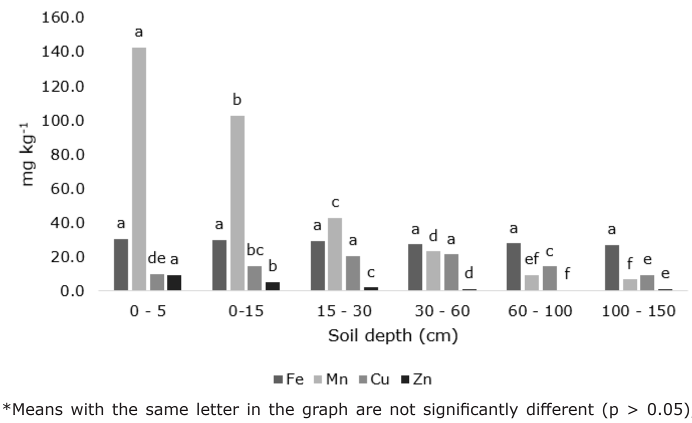
Regarding the vertical distribution (Figure 2), the lowest Cu content was recorded at depths of 0–5 and 100–150 cm, with no significant differences between them. The highest concentrations were observed between 15–60 cm, differing statistically from the other layers. This behavior can be explained by the intermediate mobility of Cu in the soil profile. Roca (2007) reported that Cu tends to move relatively easily throughout the profile, reaching maximum levels at approximately 100 cm depth, which is consistent with findings by Ratto and Fatta (1990) and by Lobo et al. (2012), who found increases in Cu with depth in tropical soils.

Regarding Zn in the vertical distribution (Figure 2), the highest contents were concentrated in the surface layer (0–5 cm), decreasing gradually with depth. Differences



*Means with the same letter in the graph are not significantly different (p > 0.05), according to Friedman's test.

Figure 1. Content of Fe, Mn, Cu, and Zn in the different soil uses. FIA-UNE. 2026.



*Means with the same letter in the graph are not significantly different (p > 0.05), according to Friedman's test.

Figure 2. Content of iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn) at different soil depths. FIA-UNE. 2026.

were statistically significant among all layers evaluated. This behavior is consistent with the findings of Santiago et al. (2008) and Domańiska (2009), who reported a decrease in Zn with soil depth. Aruani and Sánchez (2003), Lobo et al. (2012), and Roca (2007) also noted that Zn is a micronutrient with low mobility in the profile, which explains its greater accumulation in the surface horizons.

The Zn distribution observed in this study is related to organic matter content (Table 1), as this favors the surface retention of the element through the formation of stable organic complexes.

Relationship between organic matter (OM) and different soil uses and depths

Table 1 presents the organic matter (OM) and pH contents under the different soil uses and depths. The Friedman test results revealed significant differences between the uses and between the depths analyzed.

Forest soil showed the highest OM values, followed by pasture and no-till, and finally conventional management, which showed the lowest values. No-till and conventional uses differed significantly from forest, while pasture showed no significant differences from forest. These results regarding pasture soil are consistent with those reported by Sá et al. (2014) and Derpsch (2025), who noted that management systems with permanent vegetation cover tend to increase organic carbon accumulation and improve soil structural stability.

The high OM concentration in pasture is mainly due to the continuous contribution of root residues and organic exudates, as well as the absence of mechanical disturbance, which reduces organic matter oxidation. In contrast, conventional management, through plowing and frequent soil disturbance, accelerates mineralization and carbon loss. This pattern has been described by Domańiska (2009) and Lobo et al. (2012), who observed significant reductions in OM levels in soils subjected to intensive tillage.

Regarding the vertical distribution (Table 1), the highest organic matter contents were recorded in the surface layer (0–5 cm), decreasing progressively with depth. This behavior is consistent with reports by Lobo et al. (2012) and Derpsch (2025), who note that systems with permanent cover and minimal soil disturbance favor organic matter accumulation in the surface horizons.

The higher micronutrient concentration observed in the surface layers could be associated with the higher organic matter content. Although no statistically significant correlation was found between these two variables in the present study, this behavior is consistent with what was described by Stevenson (1994), who indicated that humic substances possess functional groups capable of forming complexes with metallic cations, favoring their retention in the soil and reducing their mobility toward deeper horizons.

Therefore, the results obtained show a close relationship between organic matter conservation and micronutrient availability, confirming that sustainable management practices—such as no-till farming and permanent cover—are determinant factors for maintaining chemical fertility in Oxisols.

In the comparison between the different soil uses, pH was highest in pasture areas, followed by conventional agriculture and no-till, while forest showed the lowest values. These results are consistent with those reported by Caires et al. (2015), Zhalnina et al. (2018), and Fariña P. R. V. et al. (2025), who observed that pasture and no-till systems tend to maintain more stable chemical conditions due to nutrient recycling by roots and the decomposition of organic residues.

The lower pH recorded in forest soil can be attributed to the continuous production of organic acids during litter decomposition and to the intense nutrient recycling characteristic of forest ecosystems. In contrast, agricultural systems managed with conservation practices favor greater soil chemical stability by maintaining vegetation cover and continuously contributing organic residues.

Regarding the vertical distribution of pH (Table 1), a general trend of increase with depth was observed. This behavior is associated with the lower contribution of organic residues in the deeper horizons and the redistribution of exchangeable bases in the soil profile. Similar results were described by Souza et al. (2019) in Oxisols of southern Brazil, where pH values increased gradually from the surface down to 100 cm depth.

Although a trend toward lower concentrations of Fe, Mn, Cu, and Zn was observed as pH increased, the statistical analysis did not show a significant correlation

Table 1. pH and OM levels of soils with different uses and at different depths. FIA-UNE. 2026.

	Soil use types					
	Forest	**No-till**	**Pasture**		**Conventional system**	
OM (%)	2,5 a	1,5 bc	2,2 ab		1,4 c	
pH	5,3 c	5,5 b	5,7 a		5,6 ab	
	Depths (cm)					
	0 - 5	***5-15***	***15 - 30***	***30 - 60***	***60 - 100***	***100 - 150***
OM (%)	4,4 a	2,5 b	1,6 c	1,3 d	0,9 e	0,7 f
pH	5,3 c	5,6 a	5,6 a	5,6 a	5,5 b	5,5 b

*Means with the same letter in the graph are not significantly different (p > 0.05), according to Friedman's test.

between these variables. Nevertheless, this behavior is consistent with what was described by Lindsay (1979) and Alloway (2008), who note that the availability of these micronutrients tends to decrease as pH increases, due to the formation of less soluble compounds.

Overall, the results indicate that soil management influences both pH and the availability of the evaluated micronutrients. The adoption of conservation practices, such as no-till farming and the maintenance of vegetation cover, contributes to preserving the soil's chemical properties and favors greater nutrient stability in Oxisols.

CONCLUSIONS

The contents of Fe, Mn, Cu, and Zn were, in general, higher in soils under pasture and no-till than in conventional agriculture.

Forest showed higher values than conventional agriculture for most micronutrients, except Fe. These differences could be influenced by inherent soil characteristics, such as higher organic matter content and clayey texture.

The highest concentrations of Mn, Cu, and Zn were recorded in the first 30 cm of the profile, while Fe predominated in the deeper layers (30–150 cm).

No statistically significant correlation was observed between the evaluated micronutrients and the soil pH and organic matter variables. Forest soil had the most acidic pH (5.3) among the uses evaluated. Although organic matter recorded higher concentrations in the surface horizons and in the forest and pasture systems, this variable did not show a statistically significant relationship with the availability of iron (Fe), manganese (Mn), copper (Cu), and zinc (Zn).

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