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Nsalambi V. Nkongolo * , Darceline Anangi Mokea , Maria Luisa Fernandez-Marcos

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Soil Micronutrients and Aluminum in Agricultural Fields as Affected by Plant Species at Masako Forest Reserve, Kisangani, Democratic Republic of Congo

Nsalambi V. Nkongolo [1,2,3,*], Darceline A. Mokea [4] and Maria Luisa Fernandez-Marcos [5]

[1] School of Science, Environmental and Earth Sciences Section, Navajo Technical University, Crownpoint, NM 87313, USA

[2] Institut Facultaire des Sciences Agronomiques de Yangambi (IFA), BP 1232 Kisangani, Democratic Republic of Congo

[3] Post-Doctoral Program, Institute of Research and Innovation (IRI), Apex Professional University (APU), NH-515, Pasighat Smart City, Arunachel Pradesh-791102, India

[4] Doctoral Program in Agricultural and Forestry Research, University of Santiago de Compostela, 27002 Lugo, Spain

[5] Department of Soil Science and Agricultural Chemistry, Polytechnic School of Engineering, University of Santiago d Compostela, 27002 Lugo, Spain

* Correspondence: nnkongolo@navajotech.edu

Abstract

Plant species can significantly influence soil nutrients. We assessed how soil micronutrients (B, Fe, Cu, Zn, Mn) and Aluminum were affected by plant species in agricultural fields at Masako Forest Reserve. Soil samples were collected in June 2022 and 2023 at three depths: 0–10 cm, 10-20 and 20-30 cm in fields grown to *Costus lucanusianus*, *Manihot esculenta*, *Zea mays*, *Triumfetta cordifolia*, and *Xanthosoma sagittifolium.* A completely randomized design was used with 3 soil depths (SD) x 5 plant species (PS) replicated 4 times. Soil samples were air-dried, sieved 2 mm and sent to Brookside Laboratories (OH, USA) for analyses. Results showed that in 2022, Fe, Mn, Cu and Zn were significantly affected by soil depth ($p<0.05$). Mn, Cu and Zn concentrations were higher in 0-10 cm while Fe dominated in 10-30 cm depth. Only Cu ($p=0.0001$) was affected by plant species. The soil under *Xanthosoma sagittifolium* (0.19 mg/kg) and *Triumfetta cordifolia* (0.47 mg/kg) had significantly the lowest level of Cu. In 2023, however, only Zn was significantly affected by SD ($p=0.0004$) with its highest level (1.22 mg/kg) in 0-10 cm. PS significantly affected Fe, Mn, Cu, Zn and aluminum ($p<0.05$). The soil under *Manihot esculenta* had the highest concentration of Fe (171.42 mg/kg) while Zn (1.03 mg/kg) was significantly higher in the soil under *Zea mays*. The 0-10 cm layer significantly held more micronutrients. Plant species such as *Manihot esculenta* had a noticeable effect on soil micronutrients.

Keywords: micronutrients; agricultural fields; Masako forest; plant species; soil properties

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1. Introduction

Tropical soils, particularly in humid regions, are characteristically highly weathered, acidic, and nutrient-poor due to intense, year-round leaching from heavy rainfall and rapid decomposition of organic matter [1]. These conditions result in a scarcity of essential macro- and micronutrients, such as boron, phosphorus, and potassium, as they are washed out of the soil profile [2]. Consequently, plant selection and management strategies that enhance nutrient retention are critical for successful cultivation [3]. In fact, tropical soils often face inherent micronutrient challenges due to leaching and rapid decomposition, making plant choice critical for nutrient management [4]. Plant species significantly affect soil micronutrients (like Zn, Fe, Mn, Cu) by altering soil chemistry, microbial activity, and organic matter, leading to varied availability, with high-demand crops potentially

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depleting them [5]. Research on the effect of plant species on soil micronutrients in agricultural and related ecosystems highlights that different crops, cover crops, and plant functional groups significantly alter the availability of nutrients like zinc (Zn), iron (Fe), manganese (Mn), and copper (Cu) through root exudates and biomass return. Darch et al [6] investigated the effect of soil type and botanical groups on the micronutrient content of pastures, noting significant interactions between plant species and soil, particularly for forbs. Yin et al [7] examined the role of plant species in shaping soil nutrient availability (including P-solubilization which impacts micronutrients) and the interaction with waste amendments. Ehrenfeld et al [8] reviewed feedback in the plant-soil system, including how different plant species influence nutrient turnover. Sillanpää and Vlek [9] looked at micronutrients and the agroecology of tropical and mediterranean regions. Like in other regions, in the Congo Basin, the selection of plant species in agricultural fields also affects soil micronutrients, largely acting as a driver of depletion or enhancement based on land management [10]. Widespread deficiencies in micronutrients (such as Zinc, S, B, and Copper) are common in the region due to, in part, nutrient mining by crops and low input of fertilizers [11]. The specific agricultural practices, including crop choices and the use of agroforestry, play a crucial role in managing these soil properties [12]. Unfortunately, research on the specific impact of different plant species on soil micronutrients in agricultural fields in the Congo Basin is indeed limited [13], with existing literature often focusing on macronutrients (N, P, K) and soil organic carbon (SOC) due to widespread degradation. The objective of this study was therefore to assess how soil micronutrients (B, Fe, Cu, Zn, Mn) and Al were affected by plant species in agricultural fields at Masako Forest Reserve, Democratic Republic of Congo. These agricultural fields are often established after cutting the forests.

2. Materials and Methods

2.1. Area of Study

This study was conducted from June 2022 to June 2023 at Masako Forest Reserve, Kisangani, Democratic Republic of Congo (DRC). The geographic coordinates of Masako Forest Reserve are 0°36′N and 25°13′E (Figure 1). Masako Forest Reserve contains a tropical evergreen rainforest ecosystem defined by heavy thick vegetation [14]. Masako Forest within the Congo Basin stands out because this location maintains over 10,000 plant species among its endemic flora. The Masako Forest Reserve started under Ministry of Environment administration until the University of Kisangani officially transformed it into its field research station. The change in management has established new opportunities to undertake ecology studies and monitor the environment along with protecting biodiversity and various other essential areas of work. The reserve receives worldwide recognition as a biodiversity hotspot of the DRC since it contains various endemic species found within its flora and fauna [14]. The study was conducted in agricultural fields, one of the four habitats in this reserve. The other being a fallow forest (FW), secondary forest (SF), and a primary forest (PF). Agricultural fields at Masako Forest Reserve are primarily created through slash-and-burn, causing significant deforestation. These fields often feature a mix of staple crops such as cassava, corn (maize), plantain bananas, and groundnuts, and have led to the fragmentation of natural habitats. The conversion of forest to agricultural land is rapid, with reports suggesting high rates of habitat degradation. The area is experiencing climate-related issues, such as increased temperatures and erratic rainfall, which have negatively affected agricultural productivity and reduced the availability of water. Plant species studied are: *Costus lucanusianus*, *Manihot esculenta*, *Zea mays*, *Triumfetta cordifolia*, and *Xanthosoma sagittifolium*.

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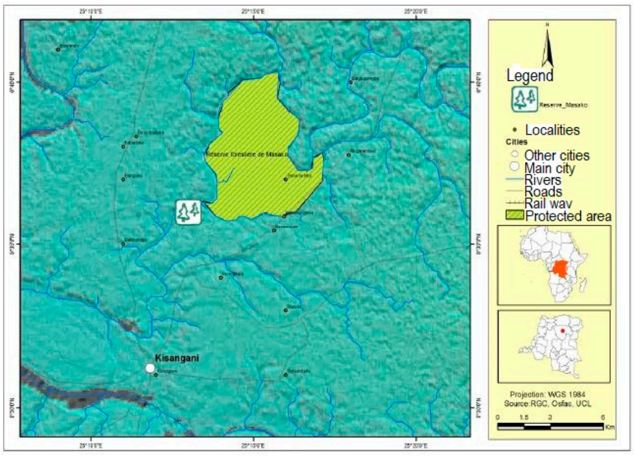

Figure 1. Masako Forest Reserve, source [14].

2.2. Measurement of Soil Nutrients

Soil samples were collected at 0–10 cm, 10–20 cm and 20–30 cm depth in each agricultural field. They were air dried, sieved 2 mm then transferred into pre-labeled (30 × 30 cm each) aluminum-foil packets containing approximately 20 g of the soil. The samples were later shipped to Brookside Laboratory (OH, USA) for analysis of soil micronutrients: Copper (Cu), iron (Fe), boron (B), manganese (Mn), zinc (Zn) and aluminum (Al). Other soil nutrients as well as soil chemical properties were also measured to assess the fertility and general nutrient status of the soil, but they are not included in this report.

3. Results and Discussion

3.1. Descriptive Statistics for the Effect of Plant Species on Soil Micronutrients in Agricultural Fields in 2022 and 2023

The effect of plant species on soil micronutrients and Aluminum in agricultural fields in 2022 and 2023 is summarized in Tables 1–5 for *Costus lucanusianus*, *Manihot esculenta*, *Zea mays*, *Triumfetta cordifolia*, and *Xanthosoma sagittifolium*, respectively.

Table 1. Descriptive statistics for the effects of plant species on soil micronutrients and Aluminum in the Agricultural.Fields in 2022 and 2023: 1. Costus lucanusianus.

	---------------2022 ----------------						---------------2023 ----------------					
	---------------Soil micronutrients and Aluminum (mg/kg) ----------------											
Statistics	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**
Mean	0.71	200.33	6.00	0.62	0.26	626.92	0.20	119.17	22.75	0.87	0.78	451.92
SD	0.13	42.85	11.43	0.20	0.42	121.12	0.08	27.20	31.86	0.37	0.39	136.70
C.V.	17.93	21.39	190.43	32.19	160.10	19.32	38.27	22.83	140.06	42.22	49.84	30.25
Min	0.44	128.00	1.00	0.29	0.01	439.00	0.15	83.00	1.00	0.47	0.40	252.00
Med	0.71	193.50	1.00	0.58	0.01	625.50	0.15	114.00	7.00	0.84	0.71	457.00
Max	0.96	284.00	41.00	1.03	1.31	823.00	0.36	181.00	108.00	1.84	1.53	744.00
Skew	-0.12	-0.01	2.67	0.48	1.46	-0.02	1.12	0.73	1.74	1.51	0.70	0.52
Kurtosis	0.68	-0.05	5.76	-0.21	1.08	-1.18	-0.28	0.35	2.26	2.17	-0.73	-0.05

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

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Table 2. Descriptive statistics for the effects of plant species on soil micronutrients and Aluminum in the Agricultural Fields in 2022 and 2023: 2. Manihot esculenta.

	---------------2022 ----------------					---------------2023 ----------------					
	---------------Soil micronutrients and Aluminum (mg/kg) ----------------											
Statistics	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**
Mean	0.74	210.17	6.00	0.72	0.63	607.25	0.25	171.42	5.75	0.89	0.92	607.08
SD	0.09	43.71	6.85	0.29	1.13	103.80	0.21	54.08	5.63	0.45	0.47	169.32
C.V.	11.58	20.80	114.12	40.06	179.72	17.09	82.45	31.55	97.86	51.11	51.62	27.89
Min	0.60	131.00	0.01	0.01	0.01	397.00	0.15	118.00	1.00	0.53	0.40	420.00
Med	0.76	214.50	2.00	0.75	0.01	606.00	0.15	150.50	2.50	0.78	0.80	564.00
Max	0.88	262.00	19.00	1.10	3.68	786.00	0.86	266.00	17.00	2.23	1.73	976.00
Skew	-0.31	-0.44	0.85	-1.09	1.84	-0.35	2.36	0.96	0.96	2.37	0.50	0.92
Kurtosis	-0.81	-0.80	-1.00	1.11	2.42	-0.02	4.52	-0.75	-0.69	4.85	-1.13	-0.14

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

Table 3. Descriptive statistics for the effects of plant species on soil micronutrients and Aluminum in the Agricultural Fields in 2022 and 2023: 3. Zea mays.

	---------------2022 ----------------					---------------2023 ----------------					
	---------------Soil micronutrients and Aluminum (mg/kg) ----------------											
Statistics	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**
Mean	0.69	218.58	7.34	0.68	0.56	806.17	0.34	147.42	4.92	0.72	0.65	609.25
SD	0.16	83.33	11.26	0.25	0.95	433.95	0.25	12.51	3.60	0.43	0.25	263.14
C.V.	23.62	38.12	153.49	36.36	168.59	53.83	74.99	8.48	73.31	60.49	38.17	43.19
Min	0.42	88.00	0.01	0.40	0.01	424.00	0.15	126.00	2.00	0.29	0.40	306.00
Med	0.66	201.00	1.50	0.72	0.01	668.50	0.15	148.00	3.50	0.57	0.63	582.50
Max	0.93	382.00	38.00	1.14	2.81	2027.00	0.83	168.00	13.00	1.50	1.13	1343.0
Skew	0.07	0.37	1.86	0.41	1.52	2.03	0.79	-0.20	1.17	0.75	0.69	1.81
Kurtosis	-0.85	-0.40	2.60	-0.96	0.94	3.37	-0.93	-0.79	0.14	-0.94	-0.56	3.26

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

Table 4. Descriptive statistics for the effects of plant species on soil micronutrients and Aluminum in the Agricultural Fields in 2022 and 2023: 4. Triumfetta cordifolia.

	---------------2022 ----------------					---------------2023 ----------------					
	---------------Soil micronutrients and Aluminum (mg/kg) ----------------											
Statistics	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**
Mean	0.72	228.83	3.25	0.47	0.28	595.83	0.24	138.42	2.00	0.55	0.86	550.33
SD	0.09	33.70	3.70	0.10	0.51	117.00	0.19	50.23	1.21	0.10	0.37	252.51
C.V.	11.75	14.73	113.66	20.62	182.50	19.64	77.55	36.29	60.30	18.63	42.56	45.88
Min	0.51	173.00	0.01	0.26	0.01	350.00	0.15	88.00	1.00	0.37	0.40	309.00
Med	0.74	245.50	2.00	0.47	0.01	639.50	0.15	125.50	1.50	0.54	0.91	451.50
Max	0.85	266.00	13.00	0.65	1.50	730.00	0.70	241.00	4.00	0.71	1.35	1046.0
Skew	-1.13	-0.49	1.74	-0.38	1.47	-0.84	1.70	1.06	0.65	-0.05	-0.13	1.07
Kurtosis	1.60	-1.40	2.05	0.56	0.64	-0.48	1.24	-0.11	-1.13	-0.67	-1.52	-0.30

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

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Table 5. Descriptive statistics for the effects of plant species on soil micronutrients and Aluminum in the Agricultural Fields in 2022 and 2023: 5. Xanthosoma sagittifolium.

	---------------2022 ----------------						---------------2023 ----------------					
	---------------Soil micronutrients and Aluminum (mg/kg) ----------------											
Statistics	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**	**B**	**Fe**	**Mn**	**Cu**	**Zn**	**Al**
Mean	0.83	243.25	2.42	0.19	0.12	730.17	0.17	122.08	5.25	1.40	1.03	879.33
SD	0.31	53.40	2.64	0.16	0.20	212.76	0.04	20.66	4.05	0.94	0.96	383.87
C.V.	37.31	21.95	109.20	85.37	166.03	29.14	25.14	16.92	77.11	66.90	92.43	43.65
Min	0.46	149.00	0.01	0.01	0.01	506.00	0.15	85.00	1.00	0.30	0.40	483.00
Med	0.74	236.50	2.00	0.26	0.01	691.00	0.15	123.00	4.50	1.42	0.50	709.00
Max	1.37	345.00	10.00	0.36	0.48	1315.00	0.25	163.00	12.00	2.94	3.00	1660.0
Skew	0.60	0.31	2.03	-0.22	1.18	1.80	1.17	0.22	0.50	0.19	1.14	1.22
Kurtosis	-0.92	-0.27	3.93	-1.81	-0.58	2.88	-0.63	-0.07	-1.21	-1.47	-0.38	0.12

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

3.1.1. *Costus lucanusianus*

The effects of *Costus lucanusianus* on soil micronutrients and aluminum in 2022 and 2023 is showed in Table 1. *Costus lucanusianus* is a common herbaceous plant in tropical agricultural systems, particularly in humid tropical regions such as Masako Forest Reserve [15]. Table 1 reveals that in 2022, the soil under *Costus lucanusianus* had boron (B) with the highest concentration (0.71 mg/kg) as compared to other micronutrients. Boron had also a relatively low coefficient of variation (CV = 17.93%). This suggests a consistent availability of boron in the soil under this plant, possibly due to the plant's influence on litter quality and pH stabilization. Iron (Fe) was also prominent with a mean of 200.33 mg/kg and moderate variability (CV = 21.39%). The skewness near zero (–0.01) indicates a symmetrical distribution of iron values, suggesting a balanced Fe cycle possibly maintained by microbial activity in the rhizosphere or regular organic inputs from root decomposition [16]. Manganese (Mn) showed notable variability, with a mean of 6.00 mg/kg and an exceptionally high CV of 190.43%. The skewness of 2.67 and kurtosis of 5.76 reveal a strong right-tailed distribution, indicating that while most values were low, a few sampling points exhibited unusually high Mn concentrations. This could reflect micro-environmental conditions that enhance Mn solubility, such as acidic pH or localized waterlogging [17]. Moreover, the extreme skewness and kurtosis in Mn indicate hotspots of accumulation or leaching, which may reflect plant-specific interactions with the soil microbial community or past land management interventions [17]. Copper (Cu) presented a moderate average concentration (0.62 mg/kg) with a CV of 32.19%, suggesting that while variation existed, Cu levels were relatively stable. The positive skew (0.48) points to slightly elevated values in a subset of samples, possibly due to natural mineral content. Zinc had a low average concentration (0.26 mg/kg) but a very high CV of 160.10%, indicating substantial spatial variability. The data for Zn were strongly positively skewed (1.46), showing that Zn availability is limited in most sites but spikes in certain areas—likely due to uneven to prior cropping practices [18]. Aluminum had the highest mean value (626.92 mg/kg) among all elements measured, with moderate variability (CV = 19.32%). The near-zero skewness (–0.02) indicates a symmetric distribution, but the high levels of Al suggest potential risks for aluminum toxicity, especially since the pH is low in these soils [19]. **In 2023** (Table 1), the concentrations of B, Fe and Al decreased while those of Mn, Cu and Zn. increased in soils occupied by *Costus lucanusianus*. The coefficients of variability (CV) increased for B, Cu and Al, were similar in both years for Fe and lowered for Mn and Zn. B recorded a mean of 0.20 mg/kg, with a C.V. of 38.27%, and a right-skewed distribution (Skewness = 1.12), indicating that most sites had lower B concentrations, while a few had notably higher values (maximum = 0.36 mg/kg). Boron's relatively mobile nature in acidic soils and its dependence on organic matter levels may explain this variability [20]. In agricultural fields where soil moisture, tillage, and crop residue management fluctuate, such inconsistencies in boron availability are expected [21]. Manganese (Mn) stood out with a mean concentration of 22.75 mg/kg, making it the most enriched micronutrient in the soil under *C.*

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lucanusianus as it increased by more than 300% in comparison to 2022. However, Mn also showed extremely high variability, with a coefficient of variation of 140.06%, although a decrease in comparison to 2022. It also had a strong right-skewed distribution (skewness = 1.74). This suggests a broad range of Mn values among plots. The elevated kurtosis (2.26) indicates a leptokurtic distribution, pointing to the presence of a few highly enriched Mn sites amidst mostly lower concentrations. These results align with the redox-sensitive nature of manganese, which tends to accumulate in fluctuating wet-dry tropical field conditions, especially where organic matter decomposes quickly [22]. Iron (Fe) had a mean concentration of 119.17 mg/kg, a little less than in 2022. Its variability was relatively low (C.V. = 22.83%) and similar to 2022. As in 2022, this indicates a fairly even distribution with a few slightly higher values. The median value of 114.00 mg/kg reinforces the stability of Fe under this species, likely maintained by consistent organic input from crop residues and limited soil disturbance [16]. Copper (Cu) and Zinc (Zn) showed moderate mean concentrations of 0.87 mg/kg and 0.78 mg/kg, respectively. Both nutrients exhibited substantial variability (C.V. = 42.22% for Cu and 49.84% for Zn), as well as positively skewed distributions, suggesting occasional nutrient-rich patches potentially due to microsite organic matter accumulation. Notably, Cu skewness (1.51) and kurtosis (2.17) indicate that several plots had high Cu concentrations (up to 1.84 mg/kg), although most remained near the median (0.84 mg/kg). Zinc displayed a slightly lower skew (0.70), but still revealed a similar enrichment pattern, with values ranging from 0.40 to 1.53 mg/kg. Although sharply less than in 2022, aluminum (Al) followed as the second most abundant micronutrient, with a mean of 451.92 mg/kg, and a moderate level of variability (C.V. = 30.25%). The distribution was slightly positively skewed (Skewness = 0.52), indicating that while most sites had moderately high Al, a few had elevated values (up to 744.00 mg/kg). This is typical of acidic, weathered tropical soils where aluminum becomes more soluble and mobile [19]. The stability in Al distribution suggests that its presence is less impacted by immediate cultivation practices and more governed by underlying soil chemistry [19]. In summary, the soils under *Costus lucanusianus* in agricultural fields were marked by high manganese and aluminum concentrations, moderate iron presence, and substantial spatial variability in copper, zinc, and boron. The distribution patterns, especially for Mn and Cu, indicate potential nutrient hotspots influenced by cultivation intensity and moisture variability. Compared to forested land uses, the agricultural fields showed evidence of both nutrient enrichment in specific microsites and overall heterogeneity, reflecting the complex interplay between plant uptake, fertilization history, and soil disturbance in cultivated landscapes. The broad variability in Mn and Zn, coupled with elevated levels of Al, highlights potential challenges in nutrient management in agricultural fields at Masako Forest Reserve [21]. In fact, it has been reported that high Al concentration interferes with root growth and nutrient uptake, especially in acid-prone tropical soils. Several studies have reported the toxic effects of Al and the tolerance mechanisms of plants [23–26]. However, a few studies have also reported beneficial effects of Al on plant growth [27,28].

3.1.2. *Manihot esculenta* (2022)

Table 2 presents the descriptive statistics for the effects of *Manihot esculenta* (Cassava) cultivation on soil micronutrients and aluminum in in 2022 and 2023. *Manihot esculenta*, a staple crop widely cultivated in the tropics, particularly within smallholder agricultural systems like those at Masako Forest Reserve. Except for boron (B) which had a nearly 3 times concentration decreases in 2023 and compared to 2022, all other micronutrients and Al had similar levels in both years. In 2023 particularly, B was the most variable micronutrient under *Manihot esculenta*, recording a mean of 0.25 mg/kg and with exceptionally high C.V. of 82.45%. The distribution was heavily right-skewed (Skewness = 2.36) with leptokurtic features (Kurtosis = 4.52), suggesting a large concentration of low-B plots with only a few having substantial boron enrichment (maximum = 0.86 mg/kg). These patterns are consistent with boron’s susceptibility to leaching in tropical soils, particularly in agricultural contexts where erosion and water flow are more intense due to vegetation clearance [21]. The mean concentrations for Iron (Fe) mean were higher in 2022 as compared to 2023, but similar for their maximum values. In 2022, Fe averaged 210.17 mg/kg with a moderate variability (CV = 20.80%), implying a consistent availability of this micronutrient likely maintained by organic matter decomposition and mineral weathering in cultivated soils [16]. Manganese showed a mean of 6.00 mg/kg in 2022 and 2023, but with high variability (CV), suggesting heterogeneous distribution potentially influenced by micro-environmental factors like root density or soil moisture gradients [22]. In 2022, Copper had a mean value of 0.72 mg/kg with a CV of 40.06%, indicating moderate variation that may reflect differential organic matter decomposition rates or fertilizer inputs across plots [29]. Zinc, while averaging 0.63 mg/kg, showed very high variability (CV = 179.72%), hinting at uneven spatial distribution that could affect plant uptake efficiency and potentially necessitate localized soil amendments [18]. As for the distribution patterns and environmental implications, the high skewness values for Zn (1.84) and Mn (0.85) suggest that extreme values—either due to localized nutrient enrichment or depletion—may be present [18]. This uneven distribution can influence crop nutrient uptake and may signal areas of nutrient imbalance or stress [22]. In 2022 as well 2023, Al recorded the highest mean concentration at 607.08 mg/kg, reflecting the strongly acidic and weathered nature of these tropical agricultural soils. Although Al levels were elevated, they remained relatively stable compared to other nutrients, with a coefficient of variation of 17.09 and 27.89% in 2022 and 2023, respectively. The distribution exhibited mild right skewness in 2023 (0.92), indicating that while most plots had Al levels clustered around the mean, some experienced higher concentrations (maximum = 976.00 mg/kg). This reflects the influence of both parent material and leaching processes on Al retention, which tends to be high in older tropical soils regardless of land use [19]. Manihot esculenta appears to influence soil micronutrient dynamics in a way that supports relatively stable boron and iron availability but exhibits spatial variability for manganese, copper, and zinc. This highlights the need for targeted soil management strategies in agricultural fields where cassava is dominant, to enhance nutrient uniformity and avoid localized deficiencies or toxicities. In summary, the soil under *Manihot esculenta* was marked by high concentrations of aluminum and iron, strongly variable levels of manganese, copper, and boron, and moderately enriched zinc, with clear indications of spatial heterogeneity. Compared to *Costus lucanusianus*, *M. esculenta* showed higher means for most micronutrients, including Fe, Cu, Zn, and Al, suggesting that cassava cultivation is associated with greater nutrient retention or possibly reflects residual inputs from past agricultural activities. These trends underline the importance of crop type in influencing micronutrient distribution, especially in intensively managed tropical soils.

3.1.3. *Zea mays* (2022)

Table 3 presents the descriptive statistics for the effects of *Zea mays* (maize) on soil micronutrient concentrations and Al in agricultural fields in 2022 and 2023. Boron (B), Fe, Mn and Al all decreased while Cu and Zn slightly increased in 2023 as compared to 2022. Similar results were also observed in soil under Manihot esculenta. Furthermore, the results reveal that in 2022, boron exhibited a relatively high average concentration of 0.69 mg/kg with a low coefficient of variation of 23.62%, suggesting that it was fairly evenly distributed across the sampled locations. This stable distribution may reflect an influence of maize root exudates and residues in contributing to soil boron levels. Iron followed with a mean value of 218.58 mg/kg, accompanied by a moderate CV of 38.12%, indicating notable but manageable variability across the field. Manganese, on the other hand, displayed a more variable pattern with a mean of 7.34 mg/kg and a high CV of 153.49%. This variability implies uneven distribution, likely caused by microsite conditions such as differences in organic matter content or redox conditions, which are known to affect Mn mobility and availability [22]. Copper showed a mean of 0.68 mg/kg and a CV of 36.36%, representing moderate variability. Zinc had a mean concentration of 0.56 mg/kg but was characterized by a very high variability (CV = 168.59%), pointing to an inconsistent distribution that may lead to localized deficiencies, particularly in areas where Zn is immobilized due to pH or organic matter interactions (Alloway, 2009). When it comes to distribution patterns and environmental implications, the skewness values for Mn (1.86), Zn (1.52), and Al (2.03) suggest positively skewed distributions with some extremely high values. This indicates

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that while most of the samples have moderate nutrient concentrations, a few have exceptionally elevated levels, which may lead to nutrient toxicity or reflect underlying issues such as over-fertilization or poor drainage [22]. Aluminum levels averaged 806.17 mg/kg and exhibited substantial variability (CV = 53.83%). As emphasized earlier, the elevated and variable Al levels are particularly concerning in acidic soils, where aluminum toxicity can impair root development and nutrient uptake. The kurtosis values reinforce this interpretation, especially for Al (kurtosis = 3.37), indicating a leptokurtic distribution where most values are near the mean, but a few extreme outliers exist. Such patterns warrant close monitoring, as they could mask site-specific issues affecting soil health and crop productivity [19]. In 2023, Born (B) recorded a mean of 0.34 mg/kg, which was the highest among all species assessed in the agricultural fields. However, its variability was also high (C.V. = 74.99%), and the distribution showed moderate right skewness (Skewness = 0.79). The data suggests that while most plots had moderate B levels, a few had markedly high concentrations (maximum = 0.83 mg/kg). Given boron's mobility in acidic soils and maize's moderate B demand, these fluctuations may result from uneven decomposition of plant residues or B leaching losses offset by localized accumulation (Ahmad et al., 2012). Iron (Fe) in soils under *Zea mays* was fairly abundant, with a mean of 147.42 mg/kg, but what distinguishes Fe in this case is its exceptionally low variability (C.V. = 8.48%), the lowest among all micronutrients reported. The distribution was nearly symmetrical (Skewness = –0.20), with a narrow range between the minimum (126.00 mg/kg) and maximum (168.00 mg/kg). This relative stability indicates that Fe is consistently present in sufficient quantities under maize cultivation, likely due to the crop's moderate demand for iron and the commonality of Fe-bearing minerals in tropical soils [30]. Mn displayed a moderate mean value of 4.92 mg/kg, but it was accompanied by high variability (C.V. = 73.31%) and a positively skewed distribution (Skewness = 1.17). This indicates that while most sites had moderate Mn levels, some experienced significantly elevated concentrations, potentially due to local redox conditions or differences in microbial activity. The range of Mn values—from 2.00 to 13.00 mg/kg—suggests notable spatial heterogeneity, likely tied to differences in drainage, organic matter turnover, or fertilizer history. Cu averaged 0.72 mg/kg, with a high C.V. of 60.49% and a right-skewed distribution (Skewness = 0.75). The range spanned from 0.29 to 1.50 mg/kg, with a median of 0.57 mg/kg, showing that a number of sites had enriched Cu levels. These variations may reflect the residual effects of prior pesticide or fungicide applications, as well as uneven organic inputs. Although Cu is required in small amounts, its enrichment in specific sites could signal soil mineral variability as no chemical fertilizer is used by smallholders. Zn had a mean concentration of 0.65 mg/kg, with moderate variability (C.V. = 38.17%), a right-skewed distribution (Skewness = 0.69), and a slightly flattened shape (Kurtosis = –0.56). The range of Zn levels (0.40–1.13 mg/kg) indicates generally adequate levels for maize, although the variability hints at potential deficiencies in some areas if not properly managed. Since Zn availability is sensitive to pH and organic matter content, these results may reflect microsite differences in management or topography. Al registered the highest mean concentration at 609.25 mg/kg, which is consistent with values observed across other agricultural species. However, the high coefficient of variation (C.V. = 43.19%) and marked right-skewed distribution (Skewness = 1.81) indicate significant variability in Al content across sampled plots. With values ranging from 306.00 to 1343.00 mg/kg, the spread is substantial, and the high kurtosis (3.26) further suggests that a few locations had very elevated Al concentrations. As it has been said earlier, these high Al levels, particularly in acidic and highly weathered soils, may pose toxicity risks for maize, which is moderately sensitive to aluminum, especially in poorly buffered soils [19]. In summary, as expected, the soil under *Zea mays* cultivation is characterized by high aluminum and iron concentrations, variable manganese, copper, and boron levels, and moderately stable zinc content. Compared to *Costus lucanusianus* and *Manihot esculenta*, *Zea mays* fields exhibited the lowest variability in iron, but the highest mean boron concentration, suggesting that maize systems may offer more consistent Fe availability while potentially influencing or reflecting spatial fluctuations in boron cycling. These patterns highlight the interplay between crop type, soil properties, and management practices in shaping micronutrient distribution in tropical agricultural systems.

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3.1.4. *Triumfetta cordifolia* (2022)

Table 4. shows the descriptive statistics for the effects of *Triumfetta cordifolia* on soil micronutrients and Al levels in agricultural fields during 2022 and 2023 growing seasons. *Triumfetta cordifolia* is a herbaceous species frequently found in cultivated fields or disturbed in fallow zones within tropical environments. Similarly to soils under *Zea Mays*, B, Fe Mn and Al decreased while Cu and Zn slightly increased in 2023 as compared to 2022. The data also show that in 2022, boron was present at a high average concentration of 0.72 mg/kg, with a remarkably low coefficient of variation of 11.75%. This is the trend observed for other crops and suggests a highly uniform distribution of boron across the sampled plots, confirming that as for other crops, *T. cordifolia* might have contributed consistently to boron dynamics through its litter or root activity [21] (Ahmad et al., 2012). Iron (Fe) had a mean of 228.83 mg/kg and a low CV of 14.73%, also indicating a stable and homogeneous presence in the soil. Such consistency in Fe availability is beneficial, as it is a key micronutrient for enzymatic and metabolic functions in plants [30]. However, Manganese had a mean of only 3.25 mg/kg but a very high CV of 113.66%, signifying notable spatial variability. This suggests that Mn availability under *T. cordifolia* is highly site-specific and may be influenced by local soil conditions such as redox potential and moisture content [22]. Copper showed moderate stability, with a mean of 0.47 mg/kg and a CV of 20.62%, while zinc recorded a low mean of 0.28 mg/kg but a very high CV of 182.50%. This extreme variation in Zn levels indicates inconsistent distribution, possibly due to localized differences in pH, organic matter, or microbial activity, all of which are known to influence Zn solubility and plant availability [18]. The skewness values for Mn (1.74), Zn (1.47), and to some extent Al (–0.84), reflect asymmetrical distributions. For Mn and Zn, the positive skewness suggests that while most values are clustered at the lower end, a few plots show much higher concentrations, potentially posing toxicity risks or reflecting uneven nutrient cycling. Aluminum concentrations averaged 595.83 mg/kg with a moderate CV of 19.64%, indicating relatively stable presence across the fields. Nonetheless, elevated Al levels in acidic soils can still limit root elongation and nutrient uptake. The kurtosis for Mn (2.05) and B (1.60) also point to leptokurtic distributions, where the majority of values are tightly clustered around the mean but with a few pronounced outliers. This pattern reinforces the need for close monitoring of these micronutrients in areas where *T. cordifolia* is dominant, particularly to avoid either deficiency or toxicity scenarios [31]. In 20203, B recorded a mean concentration of 0.24 mg/kg, with high variability (C.V. = 77.55%) and a strong right-skewed distribution (Skewness = 1.70). This indicates that while most plots were boron-deficient or near the lower threshold, a few exhibited elevated levels (up to 0.70 mg/kg), likely due to microtopographic differences, organic matter content, or previous inputs. As boron is prone to leaching and is influenced by moisture availability, the spatial unevenness is characteristic of tropical agricultural soils, especially where plant residues decompose at different rates [32]. Fe followed with a mean of 138.42 mg/kg and moderate variability (C.V. = 36.29%). The skewness value of 1.06 indicates a right-tailed distribution, where several plots had considerably higher iron content than the average. This distribution profile, combined with the wide range (from 88.00 to 241.00 mg/kg), suggests patchy enrichment, potentially resulting from localized accumulation of Fe-rich residues or past fertilization events [33]. Compared to soils under other agricultural species such as *Zea mays* and *Manihot esculenta*, Fe concentrations under *T. cordifolia* were moderate but more variable. Mn showed a low mean concentration of 2.00 mg/kg, yet with considerable variation (C.V. = 60.30%). This is notable because Mn is often highly sensitive to microenvironmental conditions such as redox fluctuations and organic content [22]. The values ranged from 1.00 to 4.00 mg/kg, indicating low but inconsistent Mn presence. Skewness was moderate (0.65), reflecting the tendency for a few sites to show above-average Mn concentrations, while the negative kurtosis (–1.13) suggests a broader, flatter distribution—possibly due to the variability in land management intensity or drainage. Cu had a mean of 0.55 mg/kg, with the lowest variability among all nutrients (C.V. = 18.63%), and was also the most symmetrically distributed (Skewness = –0.05). This narrow and balanced distribution implies consistent Cu levels across the sampled plots, likely a result of stable inputs or similar rates of organic matter turnover. The concentration range was tight, from 0.37 to 0.71 mg/kg, indicating that Cu

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availability under *T. cordifolia* is fairly uniform—an attribute that differentiates it from more intensively cultivated crops like *Manihot esculenta* or *Zea mays*, where Cu values fluctuate more widely [34]. Zn showed a mean of 0.86 mg/kg, with moderate variability (C.V. = 42.56%). The data were only slightly skewed (–0.13), and although values spanned from 0.40 to 1.35 mg/kg, the central tendency remained stable, with a median of 0.91 mg/kg. This reflects a generally adequate Zn supply across plots, albeit with modest variability. Given zinc's mobility in acidic soils and its importance in early plant development, this result suggests *T. cordifolia* is associated with relatively balanced Zn cycling in agricultural soils [18]**.** Al was most abundant, with a mean concentration of 550.33 mg/kg. Despite its high average, aluminum levels varied substantially across sites (C.V. = 45.88%), ranging from 309.00 to 1046.00 mg/kg. The skewness (1.07) suggests that while most values were centered around the mean, a number of plots showed markedly elevated Al concentrations, typical of highly weathered and acidic soils in the region. These patterns are consistent with the general tendency for aluminum to accumulate in surface layers with low pH, a condition often exacerbated by intensive land use as said earlier. In summary, the soil under *Triumfetta cordifolia* is characterized by high aluminum and moderate iron concentrations, consistent copper levels, and notably variable boron and manganese content, with a generally stable zinc profile. Compared to other agricultural species, *T. cordifolia* supports a balanced micronutrient environment but shows less extreme variation than crops like *Manihot esculenta* or *Zea mays*. Its presence in these fields may indicate a stabilization phase in soil chemical dynamics, where nutrient cycling begins to even out following disturbance or harvest.

3.1.5. *Xanthosoma sagittifolium* (2022)

Table 5. presents the descriptive statistics for soil micronutrients influenced by Xanthosoma sagittifolium in agricultural fields during the 2022 and 2023 sampling periods. *Xanthosoma sagittifolium*, a commonly cultivated root crop in tropical agroecosystems. In magnitude, Mn, Cu, Zn and Al increased while B and Fe decreased in 2023 as compared to 2022. Boron had a mean concentration of 0.83 mg/kg in 2022. Although this concentration is beneficial for plant development, especially for cell wall formation and reproductive processes, the coefficient of variation of 37.31% suggests moderate variability in its distribution. The positively skewed distribution (0.60) and relatively wide range (0.46 to 1.37 mg/kg) imply that while most plots maintained adequate B levels, some may have elevated concentrations, which could lead to toxicity under certain soil moisture or pH conditions [32]. Iron also showed a high average concentration of 243.25 mg/kg, with a CV of 21.95%, indicating relatively uniform availability across the plots. This stability is beneficial for plant physiological functions like chlorophyll synthesis and enzymatic activity. The slight positive skew (0.31) and near-normal kurtosis (–0.27) suggest that most Fe values clustered closely around the mean, with few extreme deviations. In contrast, manganese displayed a low mean concentration of 2.42 mg/kg but a high CV of 109.20%, indicating significant spatial heterogeneity. This variability is further emphasized by a skewness of 2.03 and a kurtosis of 3.93, pointing to a distribution with extreme high values. Such irregular distribution of Mn may result from fluctuating redox conditions or uneven organic matter decomposition rates, which can affect Mn solubility[22]. Environmentally, this irregularity could lead to manganese deficiency in some zones and toxicity in others, thereby affecting crop uniformity. Copper, with a mean of 0.19 mg/kg and a very high CV of 85.37%, showed a highly inconsistent distribution across the sampled plots. The negative skewness (–0.22) suggests slightly more data points on the higher side of the mean, though the overall concentration remains low. Zinc, like Cu, was low in concentration (0.12 mg/kg) and displayed a CV of 166.03%, indicating a substantial degree of inconsistency in availability. These fluctuations in Cu and Zn were concerning since both are critical for enzymatic functions and reproductive development in crops. Inconsistent micronutrient supply can affect plant growth stages differently, resulting in patchy crop performance [34]. When it comes to distribution patterns and environmental implications, aluminum recorded a relatively high mean of 730.17 mg/kg, with a CV of 29.14%, suggesting moderate variability in its distribution. The skewness (1.80) and kurtosis (2.88) values imply a right-skewed distribution with

some extreme outliers. Elevated levels of Al, especially in acidic soils, are often associated with reduced root elongation and poor nutrient uptake, potentially constraining the productivity of sensitive crops [31]. In 2023, Boron had a lower mean concentration of 0.17 mg/kg, which is among the lowest in the agricultural dataset, yet displayed moderate variability (C.V. = 25.14%). The distribution was positively skewed (Skewness = 1.17), suggesting that most plots had limited boron, with a few sites reaching higher values (maximum = 0.25 mg/kg). As boron is mobile and easily leached in tropical climates, its uneven distribution may reflect site-level differences in moisture and organic matter retention. These results diverge from the other micronutrient trends and are consistent with findings that B is often added through fertilizers or ash in cultivated areas [35]. Elevated B in agricultural plots could also be attributed to species-specific uptake and release during decomposition. Nonetheless, recent evidence cautions that excessive B in sandy or acidic soils may cause toxicity and should be monitored [36]. Fe was also moderately abundant, with a mean of 122.08 mg/kg and low variability (C.V. = 16.92%), indicating a relatively uniform distribution across plots. The near-normal skewness (0.22) and flat distribution (Kurtosis = –0.07) confirm that Fe levels were consistently maintained within a narrow range. This likely reflects stable iron availability in the agricultural topsoil, regardless of the presence of Xanthosoma, which may neither significantly accumulate nor deplete this element. Mn showed a mean concentration of 5.25 mg/kg, but with notable variation (C.V. = 77.11%), consistent with other agricultural crops. The distribution was mildly right-skewed (Skewness = 0.50), with Mn levels ranging from 1.00 to 12.00 mg/kg. This variability may be linked to soil moisture dynamics and decomposition of organic residues, given Mn's sensitivity to redox fluctuations. As a shallow-rooted species with substantial biomass, *Xanthosoma* may indirectly influence Mn cycling by modifying the organic content and microbial activity in its rhizosphere. In contrast, Cu in soil under *Xanthosoma* was remarkably high, with a mean of 1.40 mg/kg, the highest among all agricultural species assessed. Despite this, Cu levels were highly variable (C.V. = 66.90%), with a wide range from 0.30 to 2.94 mg/kg. The distribution was only slightly skewed (0.19), indicating fairly consistent distribution across most plots but punctuated by some high-Cu locations, potentially due to legacy effects of copper-based agrochemicals or intensive organic inputs in specific zones. Zn also exhibited elevated values, averaging 1.03 mg/kg, and was highly variable (C.V. = 92.43%). With Zn values ranging from 0.40 to 3.00 mg/kg and a strong positive skew (Skewness = 1.14), the data suggest that certain plots were significantly enriched, possibly due to organic input. Given zinc's importance in early crop development and its limited mobility in acidic soils, the presence of such enrichment zones could offer agronomic benefits, though the high variability signals the need for careful nutrient monitoring. Aluminum (Al) exhibited the highest mean concentration (879.33 mg/kg)—the most elevated Al level recorded among all species in the agricultural field's dataset. In addition, Al showed substantial variability (C.V. = 43.65%), with a wide range from 483.00 to 1660.00 mg/kg. The right-skewed distribution (Skewness = 1.22) and mild kurtosis (0.12) suggest the presence of frequent Al-enriched plots, possibly tied to the soil's natural acidity and weathering stage, combined with the crop's tolerance for such edaphic conditions [36]. In summary, the soil under *Xanthosoma sagittifolium* in agricultural fields appears to influence elevated boron and iron levels with relatively stable distributions, which may support crop growth. However, the high variability observed in manganese, copper, and zinc highlights the need for tailored micronutrient management. The soil is also marked by very high aluminum levels, the highest recorded copper concentration, and substantial variability in zinc and manganese availability, while iron remains relatively stable and boron is both low and modestly variable. Compared to other species, *Xanthosoma* stands out for its association with intensely enriched micronutrient profiles, particularly Cu and Al, reflecting either its tolerance for harsh soil conditions or the effects of past management practices in areas where it is cultivated.

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3.2. Analysis of Variance for the Effect of Soil Sampling Depth and Plant Species on Soil Micronutrients in Agricultural Fields in June 2022

Table 6 presents the results of the ANOVA for the effects of soil sampling depth and plant species on soil micronutrients and Al concentrations in agricultural fields in June 2022. Figure 2 shows micronutrients and Al distribution across depths. Except for boron (B) and aluminum (Al), all micronutrients were significantly affected by soil sampling depth. Notably, iron concentrations varied significantly with depth ($p = 0.0227$), where the highest mean value was recorded at the 10–20 cm depth (245.20 mg/kg), followed by 20–30 cm (219.60 mg/kg) and 0–10 cm (195.90 mg/kg). This suggests that Fe accumulation might be greater in sub-surface layers, potentially due to leaching from the topsoil or reduced plant uptake at those depths [33]. Manganese (Mn) exhibited the most pronounced depth related variation ($p= 0.0001$), with a substantially higher mean concentration at 0–10 cm (12.30 mg/kg) compared to lower values at both 10–20 cm (1.40 mg/kg) and 20–30 cm (1.30 mg/kg). This surface-level enrichment is likely due to organic matter decomposition and microbial activity, which are more intense in upper soil layers and directly influence Mn solubility and availability [22]. Similarly, copper ($p = 0.0188$) and zinc ($p = 0.0001$) showed significant variations with soil depth. Cu levels were highest in the 0-1- cm topsoil depth (0.63 mg/kg) and declined in 10-20 cm and levelled in 20-30 cm, indicating a strong influence of organic matter, which binds Cu near the surface. Zn concentrations followed the same trend, with 1.02 mg/kg at 0–10 cm and nearly negligible values at deeper layers, reinforcing the surface retention pattern commonly associated with immobile micronutrients like zinc. In contrast, Boron and Aluminum did not show statistically significant depth-related variation ($p = 0.1695$ and $p = 0.1183$, respectively), although their mean values fluctuated slightly across layers. In contrast to soil sampling depth, only copper was significantly affected by plant species in 2022 ($p = 0.0001$). The soils under *Manihot esculenta* and *Zea mays* recorded the highest Cu concentrations at 0.72 mg/kg and 0.68 mg/kg, respectively, while *Xanthosoma sagittifolium* showed the lowest Cu value (0.19 mg/kg). This indicates that crop-specific nutrient uptake and rhizosphere processes strongly influence Cu availability in soils. Slight increases in Cu in Agricultural Fields may result from localized fertilizer or pesticide residues, which can temporarily elevate Cu levels [37]. Though aluminum and zinc did not show statistically significant differences among plant species ($p = 0.0845$ and $p = 0.1001$), it is worth noting that *Zea mays* soils had the highest mean Al concentration at 806.17 mg/kg, possibly due to its tolerance for more acidic soil conditions. The interaction effects between soil sampling depth and plant species (SD × PS) were mostly non-significant across nutrients, except for zinc ($p = 0.0244$) and marginally manganese ($p = 0.0915$). This suggests that the influence of depth on micronutrient availability may be modulated to some extent by the specific plant species present, particularly for Zn. The significant interaction in Zn levels may reflect different root architectures or exudate compositions that alter micronutrient mobilization at various depths. Zn availability is closely tied to soil organic matter and microbial biomass, both of which are richer in undisturbed forest soils [38]. Recent studies also suggest that Zn may be mobilized by certain crop root exudates, which might explain the relatively high Zn levels under *Arachis hypogaea* [39].

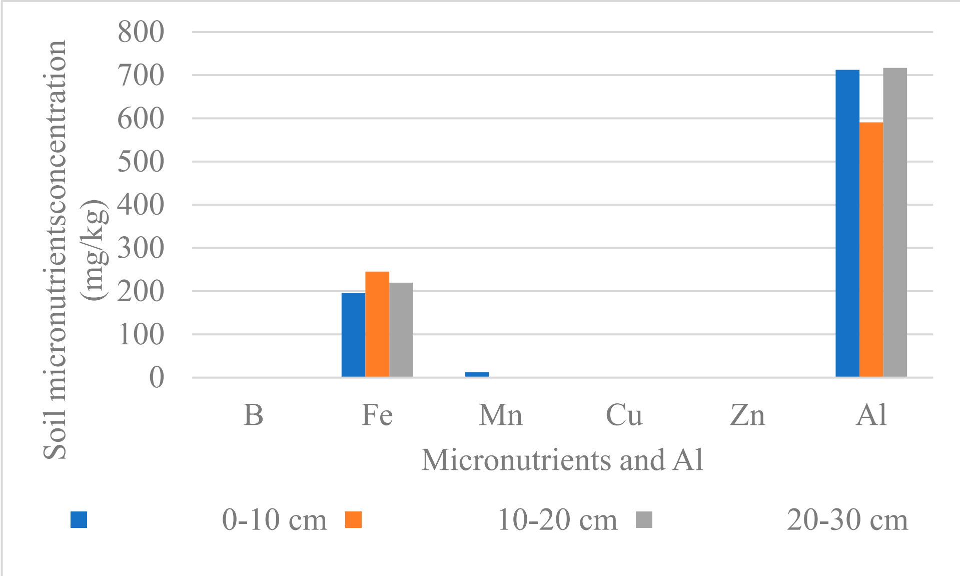

Figure 2. Soil micronutrients and Al across depths in agricultural fields at Masako Forest in June 2022.

Table 6. Analysis of variance for the effect of soil sampling depth and plant species on soil micronutrients and Aluminum in Agricultural Fields in June 2022.

Treatment		**B (mg/kg)**	**Fe (mg/kg)**	**Mn (mg/kg)**	**Cu (mg/kg)**	**Zn (mg/kg)**	**Al (mg/kg)**
Soil sampling depth (SD)							
0-10 cm		0.68	195.90b	12.30a	0.63a	1.02a	712.35
10-20 cm		0.79	245.20a	1.40b	0.44b	0.06b	590.85
20-30 cm		0.74	219.60ab	1.30b	0.54ab	0.01b	716.60
Plant species (PS)							
Costus lucanusianus		0.71	200.33	6.00	0.62ab	0.26	626.92
Manihot esculenta		0.74	210.17	6.00	0.72a	0.63	607.25
Triumfetta cordifolia		0.72	228.83	3.25	0.47b	0.28	595.83
Xanthosoma sagittifolium		0.83	243.25	2.42	0.19c	0.12	730.17
Zea mays		0.68	218.58	7.34	0.68a	0.51	806.17
Analysis of Variance							
Sources de Variation	dl						
Rep	3						
SD	2	0.1695	*0.0227*	*0.0001*	*0.0188*	*0.0001*	0.1183
PS	4	0.3452	0.3554	0.1707	*0.0001*	*0.1001*	0.0845
Interaction							
SDxPS	8	0.9344	0.9708	0.0915	0.7418	0.0244	0.0672
Error	42						
Total	59						

B= Borum; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

3.3. Analysis of Variance for the Effect of Soil Sampling Depth and Plant Species on Soil Micronutrients and in Agricultural Fields in June 2023

Table 7 shows the Analysis of variance for the effect of soil sampling depth and plant species on soil micronutrients and Al in agricultural fields in June 2023. Figure 3 shows micronutrients and Al concentrations in soil grown to 5 plant species. Starting with the effect of soil sampling depth, Table 7 shows that Zn was the only nutrient significantly affected by SD ($p = 0.0004$). The highest Zn concentration occurred in the topsoil (0–10 cm) at 1.22 mg/kg, while levels declined in the 10–20 cm (0.73 mg/kg) and 20–30 cm (0.60 mg/kg) layers. This vertical stratification likely results from zinc's

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association with organic matter and surface applied amendments, emphasizing the importance of shallow layers for Zn availability in cropped systems. All other nutrients—B, Fe, Mn, Cu, and Al—did not show statistically significant variation across depths ($p > 0.1$), although numerically, elements like Cu and Al slightly increased with depth, suggesting that certain nutrients may redistribute downward over time due to leaching or tillage practices, even if not significantly so. The effect of plant species on soil micronutrients and Al was more pronounced, particularly for Fe, Mn, Cu, and Al, each showing statistically significant differences (p-values ranging from 0.0057 to 0.0099). Among these, the soil under *Manihot esculenta* followed by *Zea Mays* had the highest mean iron concentrations (171.42 mg/kg) and (147.42 mg/kg), significantly higher than *Costus lucanusianus*, *Triumfetta cordifolia*, and *Xanthosoma sagittifolium*, all of which had Fe values below 140 mg/kg. This suggests that *M. esculenta* may promote or retain Fe through enhanced root exudation or its influence on soil microbial activity. For Mn, the soil under *Costus lucanusianus* was distinctly different, recording a much higher mean (22.75 mg/kg) than all other species, which ranged between 2.00 and 5.75 mg/kg. This finding strongly suggests that *C. lucanusianus* plays a unique role in Mn cycling, potentially due to its influence on redox conditions or its capacity to mobilize manganese through specific root traits. The results for Cu further reinforce species-driven nutrient variability. The soil under *Xanthosoma sagittifolium* exhibited the highest Cu concentration (1.40 mg/kg), statistically greater than all other species (ranging from 0.55 to 0.89 mg/kg). This may reflect the crop's high demand or tolerance for Cu, or it could point to management practices associated with its cultivation, such as more intensive and localized organic inputs. In the case of Al, the soil grown to *Xanthosoma sagittifolium* again stood out, with a mean of 879.33 mg/kg, significantly higher than values observed under the other species, which ranged between 451.92 and 609.25 mg/kg. This suggests that *Xanthosoma* may either thrive in Al-rich conditions or contribute to Al accumulation through its interaction with acidic soils. The elevated Al levels under this species are consistent with its ecological adaptation to poorly buffered tropical soils [31]**.** Interestingly, neither boron nor zinc showed statistically significant differences across species ($p = 0.1814$ and 0.3724, respectively), despite numerical variation. For example, boron ranged from 0.17 mg/kg under *Xanthosoma* to 0.34 mg/kg under *Zea mays*, but these differences were not large or consistent enough to reach statistical significance. Lastly, there were no significant interaction effects between soil sampling depth and species for any of the nutrients, with all interaction p-values above 0.1. This indicates that the effect of species on nutrient concentration was consistent across all depth layers, and vice versa. In other words, soil depth and plant species exerted independent, rather than synergistic, effects on soil micronutrients and Al distribution. Taken together, the analysis showed that plant species identity is a stronger driver of soil micronutrient variability than depth, particularly for iron, manganese, copper, and aluminum. The role of species such as *Costus lucanusianus* and *Xanthosoma sagittifolium* in enhancing specific nutrients underscores the importance of crop selection in managing soil fertility. Meanwhile, the observed zinc stratification emphasizes the importance of shallow soil layers for micronutrient retention, especially in systems with limited nutrient replenishment or organic cover. The comparative analysis across five agricultural species—*Costus lucanusianus*, *Manihot esculenta*, *Zea mays*, *Triumfetta cordifolia*, and *Xanthosoma sagittifolium*—reveals pronounced differences in soil micronutrients and Al concentrations, shaped by species-specific traits, soil conditions, and land management practices. Fe concentrations were highest under *Manihot esculenta* (171.42 mg/kg), indicating its potential role in enhancing iron retention or mobilization, possibly due to its extensive root system and interaction with microbial communities. *Zea mays* and *Triumfetta cordifolia* followed with moderate Fe levels, while *Costus lucanusianus* and *Xanthosoma sagittifolium* had the lowest, suggesting less contribution to Fe cycling under these species. Mn was overwhelmingly concentrated under *Costus lucanusianus* (22.75 mg/kg), far exceeding all others and suggesting a strong capacity to influence Mn solubility and cycling, likely through effects on redox processes or organic input. Other species such as *Triumfetta cordifolia* (2.00 mg/kg) and *Zea mays* (4.92 mg/kg) had significantly lower Mn levels, indicating more stable or less dynamic Mn pools. Mn is known to be more bioavailable in acidic, organic-rich forest soils, where redox processes and microbial activity enhance its solubility [36]. In

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addition, The decline under agricultural use is consistent with research showing that cultivation and soil disturbance often lower Mn concentrations by altering redox potentials and reducing organic matter inputs [40]. In terms of Cu, *Xanthosoma sagittifolium* stood out with a mean of 1.40 mg/kg—the highest among all species—suggesting either a greater Cu demand or residual accumulation from past inputs. In contrast, *Triumfetta cordifolia* had the lowest (0.55 mg/kg), reflecting less influence on Cu availability or uptake. *Manihot esculenta*, *Costus lucanusianus*, and *Zea mays* clustered closely in the 0.72–0.89 mg/kg range. Zn levels peaked under *Xanthosoma sagittifolium* (1.03 mg/kg), followed closely by *Manihot esculenta* (0.92 mg/kg) and *Triumfetta cordifolia* (0.86 mg/kg), pointing to the relatively strong role of these species in Zn availability. *Zea mays* showed the lowest Zn levels (0.65 mg/kg), perhaps reflecting higher Zn uptake rates or poor retention in plots where maize is grown. B concentrations varied less drastically but were highest under *Zea mays* (0.34 mg/kg), followed by *Manihot esculenta* (0.25 mg/kg) and *Triumfetta cordifolia* (0.24 mg/kg). *Xanthosoma sagittifolium* registered the lowest boron level (0.17 mg/kg), suggesting that this species may be less associated with B accumulation or may thrive in low-B conditions [32]. Finally, Al levels were most elevated under *Xanthosoma sagittifolium* (879.33 mg/kg), substantially higher than all others. This reinforces its ability to tolerate or accumulate Al in highly weathered, acidic soils [31]. Other species like *Zea mays* (609.25 mg/kg) and *Manihot esculenta* (607.08 mg/kg) also recorded high Al, while *Costus lucanusianus* had the lowest (451.92 mg/kg), possibly due to differing tolerances or soil stabilization effects. In summary, *Xanthosoma sagittifolium* exhibited the most enriched and variable micronutrient profile, particularly for Cu, Zn, and Al, while *Costus lucanusianus* strongly influenced Mn availability [40].

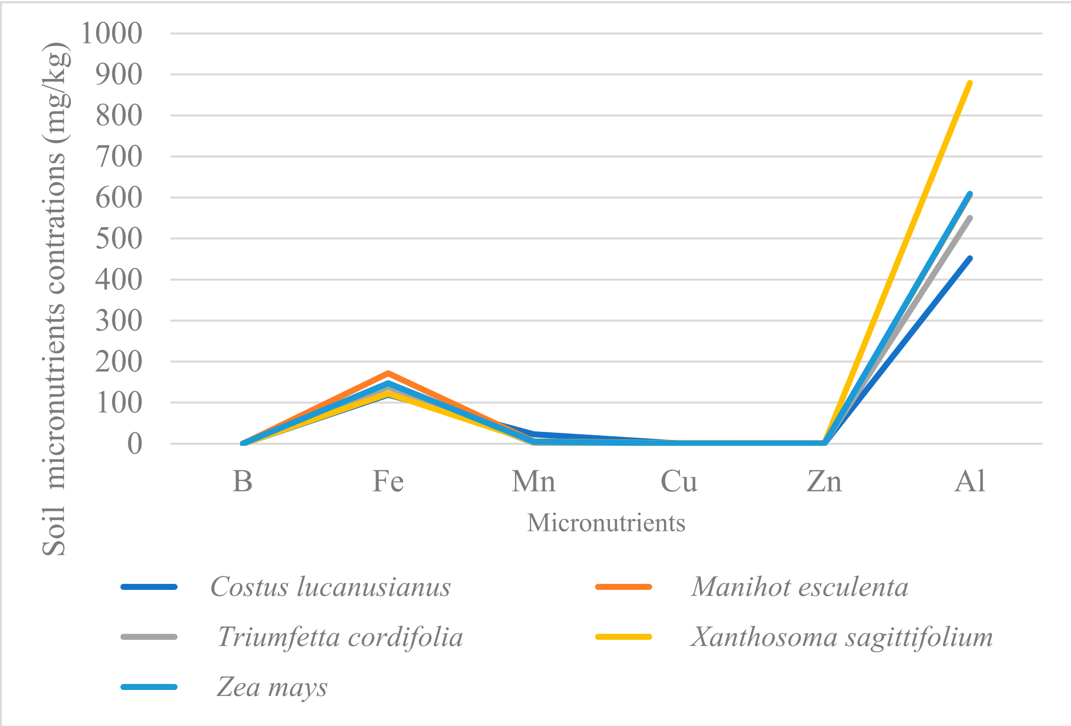

Figure 3. Micronutrients and Al concentrations in soils grown to 5 plant species at Masako Forest.Reserve in June 2023.

Table 7. Analysis of variance for the effect of soil sampling depth and plant species on soil micronutrients and Aluminum in Agricultural Fields in June 2023.

Treatment		B (mg/kg)	Fe (mg/kg)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	Al (mg/kg)
Soil sampling depth (SD)							
0-10 cm		0.25	140.85	12.05	0.83	1.22a	605.70
10-20 cm		0.24	142.50	8.15	0.87	0.73b	620.45
20-30 cm		0.23	135.75	4.20	0.95	0.60b	632.60
Plant species (PS)							
Costus lucanusianus		0.20	119.17b	22.75a	0.87b	0.78	451.92b
Manihot esculenta		0.25	171.42a	5.75b	0.89b	0.92	607.08b
Triumfetta cordifolia		0.24	138.42b	2.00b	0.55b	0.86	550.33b
Xanthosoma sagittifolium		0.17	122.08b	5.25b	1.40a	1.03	879.33a
Zea mays		0.34	147.42ab	4.92b	0.72b	0.65	609.25b
Analysis of Variance							
Sources de Variation	dl						
Rep	3						
SD	2	0.9027	0.8383	0.2529	0.799	*0.0004*	0.9503
PS	4	0.1814	*0.0093*	*0.0099*	*0.0094*	0.3724	*0.0057*
Interaction							
SDxPS	8	0.7252	0.9157	0.9341	0.907	0.4308	0.883
Error	42						
Total	59						

B= Boron; Fe= Iron; Mn = Manganese; Cu = Copper; Zn = Zinc and Al = Aluminum.

4. Conclusion

Our results highlight the complex interplay between soil depth and vegetation type in shaping micronutrient dynamics in agricultural fields at Masako Forest Reserve. Understanding these interactions is crucial for improving nutrient management in diverse agricultural systems in the tropics, especially when dealing with micronutrients that are highly sensitive to both biotic and abiotic factors. Soils under plant species such as *Manihot esculenta* and *Zea mays* showed more balanced micronutrient profiles, and *Triumfetta cordifolia* emerged as relatively stable but micronutrient-moderate. These patterns further illustrate the influence of crop type on micronutrient distribution and highlight the importance of tailored nutrient management in tropical agricultural systems. Aluminum exhibited a distinct increasing trend in agricultural fields. This pattern is attributed to soil acidification, which is more prevalent in cultivated fields due to fertilizer use, organic matter depletion, or base cation leaching

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