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COMUNICACIÓN

Influence of mycorrhizal fungi and nitrogen on the growth and yield of white maize in Ecuadorian Andes

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ABSTRACT

White maize is a staple food for Andean populations in Ecuador, particularly in rural and impoverished areas. This study aimed to assess the potential impact of mycorrhizae fungi and nitrogen fertilization on the growth and yield of white maize in the Andean conditions of Loja, Ecuador. The field trial was conducted in Loja, Ecuador, using a completely randomized design arranged in a bifactorial scheme. The first factor involved the mycorrhizae inoculation, comprising three doses: 0 (control), 330 and 660 spores per plant of the mycorrhizal fungi. The second factor focused on nitrogen fertilizer, with three doses: 0 (control), 40 and 80 kg ha^{-1} of nitrogen applied throughout the crop cycle. The combination of mycorrhizal inoculation and nitrogen fertilization promoted plant height and stem diameter: the best results were attained when applying 330 spores per plant of mycorrhizae and 80 kg ha^{-1} of nitrogen. Independent nitrogen and mycorrhizal application significantly increased the cob number per plant, grain weight and yield, reaching a maximum of 9.9 t ha^{-1}. Notably, mycorrhizae inoculation significantly increased grain nitrogen content by 7 % compared to the control, which suggests its potential to enhance the dietary quality and food security of the Andean population.

Keywords: soft maize, grain nitrogen, Andean Mountain, productive variables, fertilization

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RESUMEN

El maíz blanco desempeña un papel fundamental en la alimentación de las comunidades andinas de Ecuador, especialmente en las áreas rurales y empobrecidas. Este estudio evaluó el impacto de las micorrizas y la fertilización nitrogenada en el crecimiento y rendimiento del maíz blanco en las condiciones andinas de Loja, Ecuador, usando un diseño aleatorizado con arreglo bifactorial. El primer factor implicó la inoculación de micorrizas, comprendiendo tres dosis: 0 (control), 330 y 660 esporas por planta. El segundo factor se centró en el fertilizante con tres dosis: 0 (control), 40 y 80 kg/ha de nitrógeno. La combinación de micorrizas y fertilización nitrogenada favoreció la altura de las plantas y el diámetro del tallo: los mejores resultados se lograron al aplicar 330 esporas por planta y 80 kg/ha de nitrógeno. La aplicación independiente de nitrógeno y micorrizas incrementó el número de mazorcas por planta, el peso del grano y el rendimiento, alcanzando un máximo de 9,9 t/ha. Notablemente, las micorrizas elevaron significativamente el contenido de nitrógeno del grano en un 7 % en comparación con el control, lo que sugiere su potencial para mejorar la calidad de la dieta y la seguridad alimentaria de la población andina..

Palabras clave: maíz suave, nitrógeno de grano, montaña andina, variables productivas, fertilización

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INTRODUCTION

Maize (*Zea mays* L.) is one of the world's most vital cereal crops, ranking among the top five most consumed worldwide (Erenstein et al., 2022). In Ecuador, soft white maize is key in ensuring food security, serving as a dietary staple for the national population, particularly in rural and underserved regions. Approximately 12 % of Ecuadorian maize cultivation is dedicated to soft white maize, representing around 95 % of maize production in the Andean region, harvested in fresh or dry grain (Agricultural Public Information System of Ecuador [Sistema de Información Pública Agropecuaria del Ecuador, SIPA], 2023). However, the 2022 national yield of soft maize, at 1.07 t ha^{-1} in dry seed and 3.22 t ha^{-1} in fresh seed, falls significantly below that of neighbouring South American countries (Food and Agriculture Organization Statistics of the United Nations, 2023), raising concerns about the adequacy of maize production to meet the needs of the population. There is a need to improve yield considering the limited availability of arable area due to the orographic and edaphoclimatic conditions of the Andean region which is characterized by a rugged topography, with strong changes in climate over short distances and a high risk of erosion of the soil (Ochoa et al., 2016). In Ecuador, around 40 % of the population is concentrated in rural areas, particularly in the Andean region, leading to increased strain on natural resources such as soil and water (Mihai et al., 2023). Therefore, it is indispensable to apply innovative agricultural production technologies and understand how they work under Andes conditions.

Nitrogen (N) stands out as a crucial nutrient for crop growth and development, frequently representing the limiting factor for yield (Malinas et al., 2022). In Ecuador, substantial amounts of N are applied to corn crops in one or two applications per cycle, and only about 50 % of the supplied N is used by the plant. Simultaneously, the rest is lost through volatilization as ammonium, denitrification, or leaching as nitrate (Robertson and Groffman, 2015; Prabhu et al., 2023). The low amounts of nitrogen used by the crop indicates that the supply is superior to the N plant requirement or that the uptake is inefficient (Anas et al., 2020). Consequently, nitrogen fertilization remains a significant concern for Ecuadorian agriculture, particularly in the southern region. Despite growing evidence supporting increased nitrogen use efficiency through precise crop management on cereals, such as the correct timing and amount of fertilizer application (Tabak et al., 2020; Dhakal et al., 2021), few studies have explored whether mineral nitrogen fertilization can be optimized to enhance crop yield and quality when combined with beneficial soil microorganisms, particularly within Andean ecosystems.

Previous studies have determined the potential benefits of microorganism application in agriculture, including improved nutrient uptake (Sotomayor et al., 2019; Rui et al., 2022; Zhang et al., 2023), protection against plant antagonists (Wang et al., 2022), and positive influences on yield and quality (Cobb et al., 2016; Zhang et al., 2017; Cao et al., 2021; Sisalima-Ortega et al., 2023). Notably, arbuscular mycorrhizal fungi (AMF) have achieved importance among the microorganisms used in agriculture, as they enhance root system volume, facilitating improved water and nutrient absorption, particularly phosphorus, in various crops (Tawaraya et al., 2012; Kheyri et al., 2022). Trejo et al. (2021) reported increased fruit mass and improved organoleptic qualities in pineapple when mycorrhizal fungi were combined with 50 % fertilization (N-P-K), suggesting the potential to reduce chemical fertilizer application by half without compromising yield or quality. However, the effects of the AMF and fertilization interaction still need to be clarified per crop and soil. Concerning phosphorus, AMF inoculation and phosphate fertilization promoted benefits to the maize crop (De Souza et al., 2023), indicating the potential to increase yield, but excessive Phosphorus (P) concentrations in the soil can inhibit the mycorrhizal establishment and root colonization by AMF and decrease the mycorrhizal growth response (Bonneau et al., 2013). Therefore, the response of crops to doses of inoculation and fertilization needs to be adjusted for each environmental condition.

Moreover, substantial uncertainty surrounds the relationship between mycorrhizae and crops, particularly within Andean conditions. Loján et al. (2017) reported that AMF did not significantly increase potato yield in the Ecuadorian Andes, which is attributed to inoculation technique, agricultural practices, biotic and abiotic conditions, and competition with native AMF species. The widespread agricultural use of AMF-based inoculants remains limited due to high costs and efficacy constraints, working effectively only for specific AMF species and in certain environmental conditions (Ijdo et al., 2011). Additionally, the benefits observed in the field tend to be less pronounced than in controlled environments or greenhouses (Lekberg and Koide, 2005).

The combination of nitrogen and mycorrhizal inoculation could potentially enhance the growth, yield, and quality of soft white maize. Therefore, this study aims to assess the potential interaction between nitrogen application and mycorrhizal inoculation at different doses to improve the development, grain yield, and quality of white maize in the Ecuadorian Andes. This research can contribute to supporting the livelihoods of rural farmers in the Ecuadorian Andes, mitigate environmental contamination through improved fertilizer efficiency, and safeguard food security in the region.

MATERIALS AND METHODS

Study area

The present study was conducted in 2020 and 2021 in the La Argelia experimental farm in the Loja province, one of the main maize-producing regions of the southern Ecuadorian Andes. The experimental area is at a latitude of 4° 00' 00.0'' S, a longitude of 79° 27' 00.0'' W, and an altitude of 2138 m a. s. l. (Figure 1). The climate in the region is temperate oceanic climate (Cfb), warm and temperate, with an average temperature of 16.1 ºC, average annual rainfall of 1089.3 mm and relative humidity of 77.5 % (Rubel and Kottek, 2010). The soil of the experimental site has a clay loam texture, with a pH of 4.8 and 1.37 % of organic matter (Table 1).

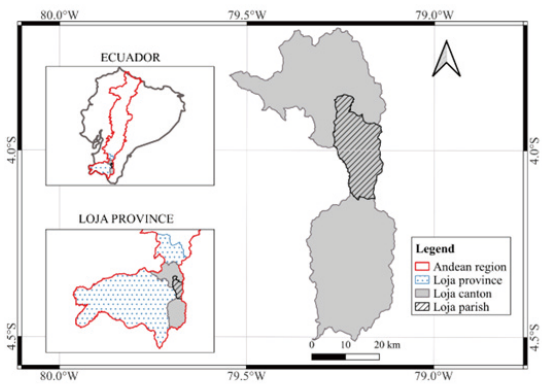

Figure 1. Study area within the Loja Province, Ecuador

Table 1. Main chemical characteristics of the soil before the base fertilization and the application of the treatments

Properties	Measurement unit	Amount
Organic matter (OM)	%	1.50
pH in water		4.80
Nitrogen (ammonium)	ppm	25.00
Phosphorus (P)	ppm	17.00
Potassium (K)	meq/100 ml	0.26
Calcium (Ca)	meq/100 ml	1.88
Magnesium (Mg)	meq/100 ml	0.97
Sulfur (S)	ppm	10.00
Zinc (Zn)	ppm	3.3
Copper (Cu)	ppm	5.2
Iron (Fe)	ppm	313.00
Manganese (Mn)	ppm	34.00
Boron (B)	ppm	0.50
Σ Bases		3.11
Ca/Mg		1.93
Mg/K		3.68
(Ca+Mg)/K		10.78

Vegetal material

The soft white maize of the INIAP-103 "Misqui Sara" variety was used, as it is representative of the maize-producing areas of the southern Andean region of Ecuador, which has contributed to the country's development, sovereignty and food security. The certified seed was bought from the Santa Catalina Experimental Station of the National Institute of Agricultural Research of Ecuador (Instituto Nacional de Investigaciones Agropecuarias [INIAP]). This variety is a floury white grain with high protein quality, high yield and disease tolerance potential. Mishqui Sara was generated in Ecuador from the Aychazara 102 variety from the Pairumani Phytoecogenetic Center of Bolivia (INIAP, 2013).

It thrives in the southern regions of Ecuador, specifically in areas between 1750 and 2650 meters above sea level. The female flowering phase begins around 64 to 80 days after planting, with fresh cob harvest between 100 to 120 days and dry cob harvest at around 230 to 270 days after planting, depending on the environmental conditions (Yánez, 2013).

The sowing date was carried out in the rainy season, the main growing season for white maize in the study region. The sowing density was 62,500 plants ha^{-1}, with a frame of 0.20 m between plants and 0.80 m between rows, placing one seed per hole following the current practice in the study location.

Experimental design and treatments

The experiment was established in a completely randomized design arranged in a factorial scheme with nine treatments (3*3). The first factor consisted of the application of nitrogen, with three doses: application of 50 and 100 % of the recommended dose for the white maize crop and control without nitrogen; the second is inoculation with mycorrhizae with three doses: no inoculation, 100 and 200 % of the recommended dose by the product used (Table 2). Four replicates were considered per treatment, comprising 36 experimental units. Each unit consisted of a plot of 24 m^2 (6m×4m), with a total area of 864 m^2. In order to prevent interplot contamination, the border lines were not used for assessment, and only the two central rows of the plot were considered.

In the case of nitrogen, urea was the source

Table 2. Description of the treatments in the study: doses and application frequency

Treatments	Nitrogen (%)	Mycorrhizae (%)	Nitrogen dose (kg/ha)	Mycorrhizal dose (spore/plant)	Commercial mycorrhizal product dose (g/plant)	Application (DAS*)	
						Nitrogen	Mycorrhizae
Control	0	0	0	0	0	-	-
1	0	100	0	330	1.5	-	at sowing (0)
2	0	200	0	660	3.0	-	
3	50	0	40	0	0	Split into three applications (30, 60 and 90)	-
4	50	100	40	330	1.5		at sowing (0)
5	50	200	40	660	3.0		
6	100	0	80	0	0		-
7	100	100	80	330	1.5		at sowing (0)
8	100	200	80	660	3.0		

* Day after sowing

used, with split application at 30, 60 and 90 days after sowing, a typical practice by farmers in the area. According to INIAP (2013), the recommended dose of nitrogen for white maize is 80 kg ha^{-1}, equivalent to 174 kg/ha of urea. For mycorrhizae, the commercial product ORGEVIT® -Euroagro was selected, a high-quality certified organic fertilizer from the Netherlands, with registration number 1912-F-AGR-A, which contains arbuscular mycorrrhizal fungi (AMF) that penetrates the interior of the root cells or attach to the root surface (EUROAGRO, 2019). Mycorrhizae (endomycorrhizal) were used at doses of 330 and 660 spores per plant for 100 and 200 %, respectively, applied at sowing (Table 2).

Before applying the treatments, a pH correction was performed using agricultural lime at a dose of 1583.3 kg/ha and a correction fertilization (boron, sulfur, and calcium) based on an initial soil analysis of all the experimental units, thus avoiding possible soil deficiency effects (Table 1). All the experimental units received the same agronomic management. Weed control was performed by applying a systemic and selective herbicide based on acetic acid (2,4-dichloro phenoxy) (aminapac) at a dose of 0.5 l ha^{-1} during vegetative development (V3 and V8). In addition, the control of fungal diseases in the leaves during the grain filling was carried out by applying azoxystrobin, derived from ß-methoxyacrylic acid at a dose of 0.75 l ha^{-1}. The crop was rainfed because it was sown in the rainy season.

Variables analyzed

During the trial, growth and productive variables were evaluated. Plant height, stem diameter, number of leaves and leaf area index (LAI) were recorded 30 to 150 days after sowing (DAS) with 30-day intervals. LAI was determined from the ratio of total leaf area (LA) of the plant and the surface occupied by plant. Total green leaf area per plant was calculated by summing individual LA for all green leaves on a plant. LAI, on the five randomly selected plants in the central rows, was determined as: LA = length*width*0.75, with the constant (0.75) according to Elings (2000).

At physiological maturity, the total number of cobs per plant of the two central rows of all the experimental units was determined, and ten cobs were selected in all the replicas to evaluate grains weight, the number of grains per cob, and finally, 1000-grain weight.

At harvest, the yield (t ha^{-1}) was determined by the product of the number of cobs per plant, the number of grains per cob, the average grain weight, and the planting density divided by 1000. Subsequently, the weight was adjusted to 13 % humidity by using the following formula:

$$\text{Adjusted Yield} = \frac{\text{Yield* (100-grain moisture)}}{(100-13)}$$

Finally, the moisture content and nitrogen of the maize grains were analyzed using 100 g of whole grain sample, and expressed as g/100 g dry matter. The Manual of Analytical Methods (Association of Official Agricultural Chemists [AOAC], 2016) was considered. Total nitrogen was measured through the Kjeldahl method following procedure 2001.11, and moisture content was determined using method 930.15.

Statistic analysis

The growth variables (plant height, stem diameter, number of leaves and LAI) were analyzed through a repeated measures model, using MIXED procedure of SAS OnDemand for Academics (SAS Institute, 2021). In the model, nitrogen doses, mycorrhizae dosages, and their interactions were considered as fixed factors and the experimental unit the random variable. In addition, a Heterogenous First-order Autoregressive covariance structure [ARH (1)] was used. To analyze the results of productive traits, yield, and nitrogen content in the grain, an analysis of variance was carried out through the General Linear Model (GLM) procedure of SAS. Main effects (nitrogen and mycorrhizae doses) and interactions were studied. Pre-planned orthogonal contrast comparisons were performed to determine the effects of nitrogen applications (control vs. treatments containing nitrogen) and nitrogen doses (50 vs. 100 %). In addition, the effect of mycorrhizae inclusion (control vs. treatments containing mycorrhizae) and mycorrhizae doses (100 vs. 200 %) were studied. Significant differences ($p \leq 0.05$) between treatment means were separated by the Tukey test.

RESULTS AND DISCUSSION

Effect on growing variables

Several interactions among nitrogen and mycorrhizae application were found for plant height and stem diameter (Table 3). Ninety days after emergency (DAE), an increase in nitrogen and mycorrhizae doses improved height, being the best treatment 100 % nitrogen combined with 100 and 200 % mycorrhizas, with height values of

Table 3. Growth variables of soft white maize under different doses of nitrogen and mycorrhizal inoculation in the southern Ecuadorian Andes. Different lowercase letters horizontally indicate significant differences at $p < 0.05$

Variable	Days after emer-gency	0% N*			50 % N			100 % N			SEM***	*p-value*		
		0 M**	100 M	200 M	0 M	100 M	200 M	0 M	100 M	200 M		N	M	NxM
Height (cm)	**30**	22.6	24.5	24.2	22.7	24.2	21.7	21.3	22.9	23.1	8.3785	0.9807	0.9717	0.9999
	60	58.7	67.0	63.9	59.5	65.9	62.2	56.2	65.0	66.1	8.3785	0.9929	0.4929	0.9894
	90	130.6^{b}	146.0^{ab}	139.7^{ab}	167.2^{ab}	174.3^{a}	167.9^{ab}	160.1^{ab}	166.9^{ab}	176.9^{a}	8.3785	<.0001	0.2901	0.0006
	120	186.9^{c}	201.6^{abc}	194.2^{bc}	224.2^{ab}	225.2^{ab}	219.7^{abc}	218.1^{abc}	229.3^{a}	226.2^{ab}	8.3785	<.0001	0.4239	0.0014
	150	205.1^{c}	216.3^{abc}	209.5^{bc}	238.9^{a}	241.2^{a}	233.8^{ab}	235.6^{ab}	243.4^{a}	243.4^{a}	8.3785	<.0001	0.5743	0.0023
Stem diameter (cm)	**30**	1.153	1.270	1.228	1.233	1.320	1.193	1.078	1.318	1.340	0.1556	0.9632	0.4952	0.9614
	60	1.745	1.895	1.818	1.853	1.940	1.812	1.633	1.910	1.920	0.1539	0.9073	0.3895	0.9125
	90	2.300^{c}	2.480^{bc}	2.408^{bc}	2.918^{a}	2.915^{a}	2.923^{a}	2.775^{ab}	3.078^{a}	3.015^{a}	0.1311	<.0001	0.3057	<.0001
	120	2.683^{c}	2.853^{bc}	2.813^{c}	3.310^{a}	3.290^{a}	3.285^{a}	3.175^{ab}	3.433^{a}	3.373^{a}	0.1182	<.0001	0.3474	<.0001
	150	2.693^{c}	2.880^{bc}	2.810^{c}	3.313^{a}	3.315^{a}	3.273^{a}	3.178^{ab}	3.460^{a}	3.393^{a}	0.1185	<.0001	0.2701	<.0001
Number of leaves	**30**	3.05	3.28	3.35	2.98	3.13	3.18	2.90	3.03	3.03	0.2282	0.4328	0.4989	0.9156
	60	5.63	5.73	5.65	5.98	6.00	6.00	5.85	6.08	5.88	0.228	0.1818	0.8047	0.8391
	90	7.45	8.03	7.78	8.58	8.78	9.00	8.08	8.98	8.88	0.4582	0.0135	0.2554	0.1442
	120	9.25	9.60	9.28	8.85	9.70	9.60	8.60	9.63	9.25	0.4805	0.8097	0.1647	0.7602
	150	11.30	11.73	11.73	10.85	11.35	11.20	10.70	11.25	11.03	0.3479	0.0987	0.2029	0.4331
Leaf area index	**30**	0.061	0.060	0.086	0.077	0.073	0.077	0.068	0.078	0.085	0.018	0.8460	0.5891	0.9762
	60	0.340	0.300	0.361	0.346	0.376	0.354	0.337	0.411	0.399	0.070	0.6965	0.8598	0.9839
	90	1.300	1.640	1.604	1.474	1.475	1.413	1.176	1.538	1.496	0.620	0.9762	0.8867	0.9999
	120	1.588	2.004	1.960	1.801	1.803	1.727	1.437	1.879	1.829	0.564	0.9573	0.8048	0.9992
	150	1.890	2.385	2.186	2.129	2.131	2.041	1.699	2.221	2.161	0.656	0.9721	0.8126	0.9994

* Nitrogen (%)

** Mycorrhizae (%)

*** Standard error of the mean

243.4 cm. In contrast, the control treatment showed smaller plants (205.1 cm). Also, an interaction between nitrogen and mycorrhiza was observed for stem diameter ($p = 0.0001$) from 90 DAE, which improved in 28 % in contrast to the control when 100 % N and 100 % mycorrhizae were applied. Some studies show that one of the main benefits of mycorrhizae is the absorption of nutrients, mainly nitrogen and phosphorus (Coello et al., 2017; Rui et al., 2022; Zhang et al., 2023). The fungus inside the root produces specialized structures in cortical cells, which exchange nutrients obtained from the soil with sugars to grow and synthetize reserve fatty acids (Luginbuehl and Oldroyd, 2017). In addition, the fungus develops towards the outside of the root, which allows it to explore the soil, absorb and transfer nutrients and water to the plant. On the other hand, nitrogen is an essential nutrient for optimal crop growth and development of plants because it is a primary constituent of proteins, enzymes, and nucleic acids, so it is crucial in the structural conformation of plants (Albornoz, 2016). The mycorrhizae could have helped improve the efficiency of nitrogen use, which is often lowered due to leaching and run-off losses and gaseous N emissions. Maize fertilization with nitrogen in different doses could have favoured symbiosis with mycorrhizae. It was observed that supplies with nitrates improve arbuscular mycorrhizal (AM) colonization in rice, sorghum (Wang et al., 2020) and beans (Nanjareddy et al., 2014), increasing the percent root length colonization, reducing the arbuscular size and enhancing ammonia transport without affecting phosphate transport.

It should be highlighted that the soil of this study presented average levels of P, and when N

Table 4. Influence of nitrogen and mycorrhizal inoculation on productive variables of white maize in the southern Ecuadorian Andes

Nitrogen (%)	Mycorrhizae (%)	Variables			
		N.° of cobs per plant	**N.° of grains per cob**	**1000 grain weight (kg)**	**Yield (t/ha)**
0	0	1.07	210.8	0.440	5.381
	100	1.30	258.5	0.530	9.705
	200	1.18	218.2	0.530	7.121
50	0	1.45	232.6	0.488	8.770
	100	1.40	257.0	0.518	9.430
	200	1.18	242.2	0.565	8.081
100	0	1.23	246.7	0.533	8.220
	100	1.60	235.2	0.555	10.334
	200	1.45	266.7	0.553	11.145
SEM*		0.1004	17.964	0.0362	1.3771
Main effect					
Nitrogen (%)					
0		1.18[b]	229.2	0.500	7.402
50		1.34[ab]	243.9	0.523	8.761
100		1.43[a]	249.6	0.547	9.900
Mycorrhizae (%)					
0		1.25	230.0	0.487	7.457
100		1.43	250.2	0.534	9.823
200		1.27	242.4	0.549	8.782
Effects		-- *p–value* ----------------------------------			
Nitrogen		0.0242	0.3948	0.3232	0.0612
Control vs. Others		0.0161	0.1149	0.0418	0.0119
50 vs. 100		0.3189	0.7032	0.4379	0.2526
Mycorrhizae		0.0651	0.4165	0.1230	0.0792
Control vs. Others		0.0295	0.1191	0.0303	0.0125
100 vs. 200		0.0525	0.5963	0.6164	0.2950
Nitrogen*Mycorrhizae		0.1347	0.3527	0.7917	0.3726
Nitrogen vs. Mycorrhizae		0.3286	0.9429	0.5856	0.9455

* Standard error of the mean

was applied, the N:P ratio increased. A rise in the N:P ratio could increase AMF root colonization and extraradical fungal biomass (Pan et al., 2020). So, the amount of soil nutrient is important to control plant–fungus interaction. In contrast, Bonneau et al. (2013) showed that low P and N fertilization systemically induces a physiological state in plants favourable for AM symbiosis. However, in this study, it has been shown that the supply of nitrogen favoured the height and stem diameter of white maize in the Ecuadorian Andes, which could be due to the modification of mycorrhizal morphology and behaviour with plant morphology and the direct transport of N from the soil to the host plant through AM fungal hyphae (Pan et al., 2020). This result demonstrates the positive effect of the combination of mycorrhizas and nitrogen supply, which can increase the utilization of other nutrients by plants. Accordingly, future studies should consider different nutrient interactions and soil fertility status.

Nitrogen and mycorrhizae did not significantly affect the number of leaves per plant and the LAI. The white maize presented an average of 11.24 leaves per plant and a LAI between 1.7 and 2.4 at 150 DAE when the foliage was completely developed. LAI depends on plant varieties and cultural practices (Karaca and Buyuktas, 2021), and specially on water and fertilizer stress (Cheng et al., 2022). In this study, the field trial was performed under the same weather conditions and during the rainy season, without water stress; thus, there were no significant differences in this variable. Moreover, LAI was lower than that reported for this crop due to the plant density used (62500 plants ha^{1}), which tends to increase with the sowing density (Lykhovyd et al., 2019). Furthermore, the low values could be due to the low temperature of the Andean mountains that varied from 16 °C during the day to 10 °C at night with highly variable rainfall (Emck et al., 2006). Maize plants may adapt to keep an unaltered radiation use efficiency. It is possible that cultivars exhibit changes in their genetic makeup over time simply through the cultivation process (Goldman, 2024).

Effect on productive variables

The productive variables were not affected significantly by the interaction of nitrogen and mycorrhizae under field conditions. Its main effects are described and discussed in Table 4.

It is worth noting that the number of cobs increased significantly with increasing rates of nitrogen application (p = 0.0242). The highest number of cobs per plant was obtained with 100 % of the nitrogen fertilization required by the crop, raising 21 % more than the control (Table 4). Cobs per plant varied between 1.18 and 1.43 across treatments. In the same way, N application positively affected the grains weight (p = 0.0418) and therefore yield (p = 0.0119). The application of nitrogen improved the 1000-grain weight by 7 % (0.535 kg) and the yield by 26 % (9.33 t/ha) when compared to non-fertilized plots (0.5 kg and 7.4 t ha^{-1}, respectively). So, the increase of white maize grain yield was associated with the number of cobs per plant and grain weight under Andean conditions.

Nitrogen fertilization affects the productive parameters of maize under different conditions (Amanullah et al., 2016; Lucas et al., 2019). There is a linear and quadratic relationship between N application rates and grain yield, but increasing N application rate is not a strategy for attaining maximum N use efficiency (Mohkum et al., 2022). Nitrogen plays a vital role in many physiological and metabolic processes because it is crucial in the structural conformation of plants (Maathuis, 2009). The application of N increases the number of cells and the volume per leaf, accelerating the formation of chlorophyll and increasing the biomass of the plants during crop growth (Mohkum et al., 2022). Maintaining photosynthate source and N uptake throughout the grain-filling period could improve the maize yield (Asibi et al., 2019).

Regardless of mycorrhizae, their application increased cobs per plant in white maize (p = 0.0295) and the grain weight of maize by 11 % compared to the control (p = 0.0303). As a result, yield increased between 18 % and 31 % approximately (p = 0.0125). The maximum yield obtained with mycorrhizae was 9.82 t/ha, between the range reported by INIAP (2013) for this variety. This study showed that mycorrhizae increased by 24.5 % in mean white maize crop yield under Andean conditions, which is in correspondence with previous studies in different crops (Zhang et al., 2017; Wu et al., 2022). Wu et al. (2022) reported that the crop yield increased between 16 and 30 % after AMF inoculation in rainfed agriculture, improving yield on N-fixing crops more than on non-N-fixing crops. In accordance with the present results, Zhang et al. (2017) demonstrated that AMF inoculation significantly increased rice grain yield by 28.2 %.

Symbiosis with mycorrhizae can promote greater vegetative development of plants by boosting root growth, expanding the absorption zone of the rhizosphere and thus, increasing water and nutrient uptake (De Souza et al., 2023). This leads to greater production, quality, fruit size and better physical and chemical soil properties (Cao et al., 2021). Mycorrhizal fungi could increase Mg uptake, increasing the total chlorophyll content, leading to higher production in photosynthate and improving the biomass and yield (Mathur et al., 2018). Markedly under low temperatures, as in the Andes mountains, the mycorrhizae could improve photosynthesis and chlorophyll fluorescence, promoting host plant growth and increasing host plant biomass (Zhu et al., 2010).

In this study, no differences were detected when mycorrhizae vs. N treatments were compared in any of the productive variables, which suggests that mycorrhizae could be an option to use in the management of the white maize crop under Ecuadorian Andean conditions. The reduction or substitution of inorganic fertilization through AMF can represent a viable practice that promotes greater profitability and the agroecological conservation of production systems (Díaz et al., 2019). Therefore, the application of AMF could contribute to improving production and be used as a strategy for the organic management of the crop on the Andean Mountain.

Nitrogen concentrations on grains

Concerning the nitrogen content in the grain, mycorrhizal inoculation significantly increases grain nitrogen (p = 0.0042) by 7 % compared to the control. However, no significant effect was observed between the 100 and 200 % doses (p = 0.1314) (Figure 2). The maximum nitrogen content obtained with mycorrhizae was 1.512 %, which represents 9.45 % of protein. AMF can affect the quality of sugars, organic acids, proteins and secondary metabolites in fruits and grains (Giovannetti et al., 2012; Cobb et al., 2016; Zhang et al., 2017; Cao et al., 2021). The Mishqui Sara

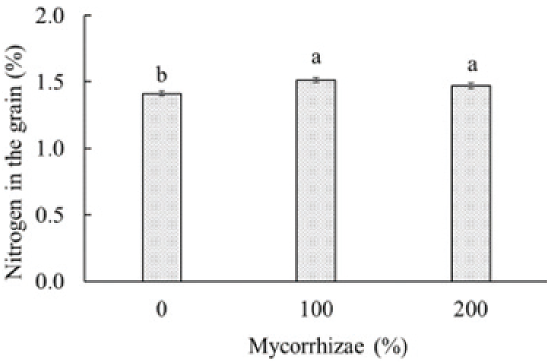

Figure 2. Effect of different doses of mycorrhizae inoculation on the nitrogen content expressed as g/100g of white maize grain under Andean conditions. Different lowercase letters show significant differences between the different doses of mycorrhizae ($p < 0.05$)

variety used in this study, adapted to Andean conditions, was more responsive to mycorrhizae than N manuring. In this regard, Cobb et al. (2016) reported that sorghum cultivars were significantly more affected by mycorrhizal inoculation than commercial hybrids, which showed in enhanced nutrient uptake and subsequent grain production and quality. This finding is important since white maize is the main food source for the Andean rural population, consumed daily in the form of grain or prepared with other foods. Malnutrition is a serious public health problem in Ecuador, especially for infants, children and teens, affecting 27.2 % of children under two years, mainly due to inadequate and insufficient nutrition. The Mishqui Sara variety contains high levels of the essential amino acids tryptophan and lysine, similar to maize varieties such as OPACO-504 with high protein quality (Yánez, 2013).

Increasing the nitrogen content in maize grains can enhance their protein concentration, improving their nutritional value for human consumption. Several studies have found that the nitrogen-to-sulfur ratio plays a crucial role in increasing maize yield, protein concentration, and the concentration of important amino acids such as lysine, tryptophan, and methionine (Liu et al., 2020; Wang et al., 2023). A significant correlation has been found between grain protein and cysteine concentration in maize (Liu et al., 2020). This helps regulate the ratio of other amino acids, promoting better nutritional quality of maize while maintaining a consistent increase in protein concentration (Wang et al., 2023). Mycorrhizas can enhance sulfate uptake and transfer it to mycorrhizal roots, thus increasing root sulfur contents by 25 % even in moderate sulfate concentrations (Allen and Shachar-Hill, 2009) and improving the nutritional quality of maize (Mobasser et al., 2012; Liu et al., 2021). Therefore, mycorrhizas may be a viable alternative to improve the nutritional quality of maize for rural populations in the Ecuadorian Andes.

CONCLUSIONS

This study demonstrates that field inoculation with mycorrhizae fungi and nitrogen fertilizer promoted plant height and stem diameter of white maize in the Andean mountains. The most effective treatment was applying 330 spores per plant of mycorrhizae (100 %) and 80 kg ha^{-1} of nitrogen (100 %). Furthermore, the independent application of nitrogen and mycorrhizae positively affects the productive variables, increasing the number of cobs per plant, the grain weight and overall yield. Nitrogen increases the yield of white maize by 26 %, while mycorrhizae inoculation improves the yield on average by 24.5 %. This study highlights the viability of mycorrhizal application as an effective strategy for white maize crop management in the Andean Mountain region, sustaining crop productivity and assuring food security for the local population. This research revealed a notable benefit in the form of a 7 % increase in grain nitrogen content when mycorrhizae were applied, suggesting the potential to enhance the nutritional quality of maize in the Andean diet.

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Conflict of interest

The authors declare that they have no conflict of interest.

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