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RESEARCH ARTICLE

Effect of liming and fertilizers on the growth and nutrition of 12-month old Teak (*Tectona grandis* L.) grown on acidic soil of Peru

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Abstract

Peru has a great potential for forestry plantations, nevertheless, importations of this type of products are getting very expensive. Soils under forest are acidic and infertile to support sustainable economically valuable forest tree species such as teak. Information is lacking on proper fertility management in forest plantations such as teak. Therefore, the objective of this study was to explore the effect of lime, and organic and inorganic fertilizers on the early growth and nutrient composition of 12-month old teak grown on acidic soil of Peru. The soil under field study was acidic with a pH of 4.99, low in fertility. A factorial design of 2x3: Lime (No Lime and Liming) and fertilizer (organic, inorganic and mixture), with 9 repetitions was adopted. Tree biometric parameters (height, diameter, biomass) and N, P, K, Ca, Mg, Fe, Cu, Mn, Zn foliar concentrations were determined during early the growth of teak. Treatments with addition of dolomite lime favored higher biometric parameters, and use of organic fertilizers promoted more growth than inorganic fertilizers. In the case of nutrients, no major differences were observed between limed and unlimed treatments while organic fertilizer promoted Ca, K and S nutrition. The results show that the application of lime and organic fertilizers is essential for the successful management and establishment of teak plants in acidic soils of Peru.

Keywords: organic fertilizers; forestry nutrition; forest plantations; ultisols; soil fertility.

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1. Introduction

Peru is a country that has an area mainly covered by forests occupying nearly 70 million hectares in the country (MINAM & MINAGRI, 2023). According to Mendiola et al. (2016), Peru possesses the second largest extension of natural forests in Latin America and the ninth in the world, nevertheless, the exports of forest products are less than 1% globally. In 2017, the exportations of forest products reached a FOB value of more than 120 million dollars; however, in the same year, the importation of forest products reached a FOB value of more than 962 million dollars making a negative balance for forest products in Peru despite the high potential to produce forest products in the country (Alberto et al., 2019). Forest exploitations in Peru are mainly due to concessions but it lacks big areas dedicated to forest plantations and this type of area has been dramatically reduced since 1998 (Guariguata et al., 2017). Nevertheless, in the last years the Peruvian government has begun to promote the installation of new forest plantations and many tree species have been considered as potential for domestic use and for exportation such as eucalypt, teak, and others.

Teak (*Tectona grandis* L.) grows naturally in tropical regimes and is characterized by its hardwood that is important economically and socially because it represents nearly 1.5% - 2% of the global cover of planted forests (Fernández-Moya et al., 2014). Also, this species is considered of slow growth since it takes around 20 years for its harvest in comparison to other forestry trees such as *Eucalyptus*; therefore, allometric models have been developed for this species in order to facilitate monitoring of growth and biomass (Dos Santos et al., 2022). Nevertheless, recent research has shown that wood density with half of currently harvest age (24 years) had no significant differences (Shukla & Viswanath, 2023) which could mean in the future a faster harvest age. Management of soil fertility and adequate tree nutrition are key factors for productivity and success in forest plantations. In Peru, forest plantations are mainly established in the humid tropics and, in general, present high soil constraints such as high acidity, low P availability, high aluminum content and low base saturation. In general, many teak plantations have suffered the problems of acidity in early establishment with high death rates associated with poor soil management. The management of tropical acid soils consists of the correction of the acidity, elevation of pH, use of acidity tolerant clones and the application of fertilizers that improve the soil fertility (Arévalo-Hernández et al., 2022; Bolan et al., 2003). However, despite the common use of lime for ameliorating soil acidity, in Peru, because of its use in the production of illegal narcotics, its acquisition for forest farming is limited. Dolomite lime is mainly used not only for its high availability in the market but also to improve the magnesium status of acid soils.

According to Da Favare et al. (2012), teak nutrient requirements in shoots are related as follows: N>Ca>K>Mg>P>S>Fe>Mn>B>Zn>Cu, while in roots Behling et al. (2014), indicates that requirements in roots are in the order of K > Ca > N > Mg > P > S, in both cases Ca is the second most demanded nutrient, showing that teak is Ca sensitive species, and, liming is a key step on its establishment and growth, especially in acid soils which lack sufficient Ca. Despite liming importance, other nutrients are required for optimal productivity since this species could respond positively to the application of nitrogen, phosphorus and potassium, promoting growth and trunk diameter (Abod & Siddiqui, 2001; Siddiqui et al., 2009; Zhou et al., 2012). Also, even though less studied, organic fertilizers such as compost, manures, sewage sludge, biochar and humic acids could have promoted the growth and development of early teak plantations in terms of nutrition and efficiency (Sandro et al., 2016; Smitha et al., 2016). Furthermore, the effect of the rhizosphere soil in terms of C/N, N and K has a major effect on nutrition of C, N and P in teak (Zhang et al., 2023). In general, teak is a high nutrient demanding plant species so fertilizers programs are important to obtain high yields, however, in Peru, most growers don't implement fertilizer programs, not even in the early stages of the plantations, therefore yield and growth is compromised. Considering the importance of fertilization and liming we aimed to explore the effect of lime, organic and inorganic fertilizers in the early growth and nutrient composition of teak growing in acid soils in Peru.

2. Materials and methods

Location

The experimental field was located experimental station "Juan Bernito" of the Instituto de Cultivos Tropicales, in the district of La Banda del Shilcayo in San Martin Region, Peru at 06° 30' 28" S 76° 00' 18" W, at an altitude of 333 m.a.s.l. At the site, the average annual rate of precipitation is 1150 mm with a mean annual temperature of 26°C and is in the Pre-Mountain Tropical Dry Forest (BSPmT).

The total experimental area was previously used for fishery purposes and had a perimeter of 260 meters and 3000 m^2. The experimental area determined for the experiment was divided into three subplots (blocks) of different sizes (32x20 m; 35x15 m and 35x20 m) and with a separation in distance of 50 m, each area was cleaned by mechanical means and plants surrounding the effective area were pruned. A general soil sample was taken from each subplot to calculate the requirement for lime and fertilizer application. The results for the samples taken are presented in Table 1.

Table 1
Main physical and chemical characteristics of the soils in each block after soil preparation

Properties	block 1	block 2	block 3	Mean±sd	Methods (Anderson & Ingram, 1993; EMBRAPA, 2009)
pH in wáter	5.22	5.02	4.99	5.07±0.12	Potenciometer (1:2.5)
C. E (dS/m)	0.07	0.06	0.06	0.06±0.01	Conductimeter (1:2.5)
$CaCO_3$ (%)	<0.3	<0.3	<0.3	<0.3	Volumetric Gas
O.M. (%)	1.51	1.38	1.61	1.50±0.12	Walkley y Black
P (ppm)	15.06	12.06	13.95	13.69±1.52	0.5 M NaHCO3
Texture Class	Arc	Arc	Arc	Arc	Bouyucos Method
CEC (cmol/kg)	8.16	7.69	7.61	7.82±0.30	1 N $NH_4CH_3CO_2$
Ca^{2+}	2.38	2.09	2.08	2.18±0.17	1 N $NH_4CH_3CO_2$
Mg^{2+}	0.90	0.53	0.68	0.70±0.19	1 N $NH_4CH_3CO_2$
K^+	0.20	0.14	0.13	0.16±0.04	1 N $NH_4CH_3CO_2$
Na^+	0.09	0.09	0.08	0.09±0.01	1 N $NH_4CH_3CO_2$
Al^{+3}	0.05	0.15	0.18	0.13±0.07	1 N KCl
Base Saturation, %	44%	37%	39%	40.00±3.61	Calculation

Table 2
Chemical analysis of amendments used in the experiment

Products	N (%)	P_2O_5 (%)	K_2O (%)	Organic Matter (%)
Organic Amendments				
Chicken Manure	3.0	3.96	3.33	41.11
Seabirds guano	10.14	10.01	2.30	25.33
Inorganic Amendments				
Dolomite	-	-	-	-
Urea	44.00	-	-	-
Triple Superphosphate	-	45.40	-	-
Potassium Chloride	-	-	58.30	-
Potassium Sulfate	-	-	49.10	-

Lime, Organic and inorganic fertilizers
In the case of lime, dolomite lime was the source used. For inorganic fertilizers, urea, triple superphosphate and potassium sulfate were used. For organic fertilizers, seabird guano and chicken manure were selected. The chemical analysis (N, P_2O_5, K_2O and organic matter) for each amendment was performed following the procedures described elsewhere by EMBRAPA (2009). The results of chemical analysis are presented in Table 2.

Plant Material
Plant material was acquired from a local certified greenhouse dedicated to the production of forest trees to guarantee the quality of the seedlings, the plants were propagated from seeds and grown for two months. At the moment of acquisition, the Teak (*Tectona grandis* L.) plants had a height of 12 cm and a diameter of 1.5 cm. Teak was planted at plant spacing of 3 (between plants) x 2 (rows) m, totalizing 1666 trees ha^{-1}. This spacing was performed taking into consideration the recommendations reported by da Silva et al., (2016).

Experimental Design
The experiment was a Complete Random Block Design (CRBD) arranged in a factorial scheme with three blocks, the treatments consisted of the application of lime (l), with two levels: application of lime and control without lime, and a fertilizer treatment (f) with four levels: no fertilizers, inorganic fertilizer, organic fertilizer, and a combination of 50% inorganic fertilizer + 50% organic fertilizer (I/O). So, in total there were 8 treatments: Only Lime, Lime + Organic fertilization, Lime + Inorganic fertilization, Lime + 50% organic and 50% inorganic fertilization, No Lime, No lime + Organic fertilizer, No lime + Inorganic fertilization and, No lime + 50% organic and 50% inorganic fertilization, with 3 experimental units per block and 9 per treatment. In order to prevent interplot contamination the border lines were not used for assessment and only 3 plants were in the center of each treatment in each block.

For the application of lime, the base saturation approach was used (Gonçalves et al., 2020), considering a saturation base of 80% in the field as described in the following equation.

$$NL = CEC * \frac{(V2 - V1) * d}{RNPL}$$

NL: Lime necessity t ha^{-1}; *V*2: Base saturation (%) goal; *CEC*: Cation exchange Capacity of soil in $cmol^{+}\ kg^{-1}$; *V*1: Soil actual Base saturation (%); *RNPL*: Relative Neutralization Power of Lime; *d*: Depth in m.

For the calculation of fertilizers, the procedures described by Pontes (2011) were used and resulted in a formula of 100 N, 50 P_2O_5 and 100 K_2O, this formula was used both for the requirement of inorganic and inorganic fertilizers, although due to the composite nature of the organic fertilizers, some nutrients were applied more than needed. The application of fertilizer for N and K was carried out on three applications (40%, 30% and 30% of the total demanded fertilizer), starting two months after the transplantation in the field. In the case of P, the application was divided into two doses (50% at the moment of transplantation and 50% two months after establishment in the field).

Biometric Measurements
After two months of transplantation, the biometric variables such as height (cm) and diameter (cm) were measured for 12 months each month. At the end of the experiment, some plants were sacrificed for measuring the total biomass in the trees. Plants were cut, collected and dried at 60 °C until a constant weight was achieved. Afterward, each plant was weighted (g) to report leaf dry biomass (LDB), stem dry biomass (SDB) and root dry biomass (RDB).

Soil analysis after experiment
After the experiment was finished, 500 g of soil was collected from each block and treatment for soil chemical analysis (pH, CE, $CaCO_3$, Organic Matter (OM), Total N, Available P, Exchangeable Ca^{+}, Mg^{+}, K^{+} and Na^{+}) using the methods described in Table 1. pH and CE were determined by a potentiometer,

OM by titration, Available P was determined using UV-Vis Spectrophotometer (670 nm) while exchangeable Ca^+, Mg^+, K^+ and Na^+ were obtained in an atomic absorption spectrophotometer (AAS; Varian model "Spectra 55B", Made in Australia).

Determination of nutrients in plan tissues

Dried samples of plant tissues were weighted (0.5 g each) and digested with HNO_3 (65%) from Merck®. The digestion was conducted on a hot block at 90°C for 1.5 h and then at 135 °C for 8 h. The digested solution was filtered and diluted prior to analysis. The procedures for the determination of the nutrients were based on EMBRAPA (2009), concentrations of Ca, Mg, K, Cu, Fe, Mn and Zn in the filtrate were determined using the AAS described before, while P was determined using UV-Vis Spectrophotometer (420 nm), to guarantee analytical quality three repetitions per sample were performed and the means were used for statistical analysis. Nitrogen was determined by MicroKjeldah method. For the calculation of Uptake, the dry matter was multiplied by the concentration and divided by 10 for macronutrients (g $plant^{-1}$) and by 1 for micronutrients (mg $plant^{-1}$) (Arévalo-Hernández et al., 2022).

Statistical analysis

For statistical analyses, the program R, ver 4.2.1 (R Core Team, 2021) was used. Descriptive statistics (mean and standard deviation) of soil chemical properties (pH, Soil organic matter, P, CEC, Ca^{2+}, Mg^{2+}, K^+ and Al^{+3}), biometric measurements (Height, leaf area, diameter and dry weight), foliar concentrations and uptake of N, P, Mg, K, Fe, Cu, Mn and Zn in shoots were calculated. Afterwards, data were submitted to analysis of variance (ANOVA) for each treatment and, if significate differences were observed, a Scott-Knott test ($P \leq 0.05$) was performed.

3. Results and discussion

Soil attributes after experiment

Soil attributes (pH, OM, P, CEC, Ca^{2+}, Mg^{2+}, K^+ and Al^{+3}) before and after the application of each treatment (lime and fertilizers) are presented in Table 3. In the case of the lime treatments, in general, there were no significant differences ($P > 0.05$) between lime and unlimed treatments with exception of pH and available P. Also, when comparing the initial soil test against lime treatments, pH, P and Al showed significant differences. In the case of pH, initial soil test was higher than no lime treatment and can be partially explained by the acidification and uptake of Ca from the treatments due to plant activity. Also, P availability was higher in treatment with lime in comparison to the initial soil test and no lime. However, in the case of Al^{+3}, both treatments (lime and no lime) showed higher values than the initial soil test and this may be attributed to the biological activity of the plant. For fertilizer factors, in general, organic amendment showed better performance in comparison to the other treatments, with higher values of Ca and OM but without significant differences ($P > 0.05$). However, all treatments showed significant differences ($P < 0.05$) in comparison to the control for pH, P and K, improving overall soil nutrient stocks.

Both treatments, lime and fertilizers altered pH, by either reducing (inorganic fertilizer) or improving it (lime and organic fertilizer). In general, lime elevates pH in soil and improved available macronutrient concentrations in soil solution, such as P and K while it also enhances other physical, chemical and biological properties (Bolan et al., 2003). Also, research has shown that soils with higher pH (near alkalinity) and OM were correlated with higher growth and productivity in teak (Salcedo-Pérez et al., 2019), which partly agrees with the best treatments that were when lime and organic fertilizer were added.

Table 3

Comparison of means by Scott-Knott test at 0.05 for Soil attributes (pH, OM-Organic matter, P, CEC, Ca^{2+}, Mg^{2+}, K^+ and Al^{+3}) measurements in teak plants of 12 months with application of lime and different fertilizers (Organic, inorganic, I/O and control) in experimental field in Peru

Factors	pH	OM	P	CEC	Ca^{2+}	Mg^{2+}	K^+	Al^{+3}
	in water	%	mg kg^{-1}	$cmol^+ kg^{-1}$	$cmol^+ kg^{-1}$	$cmol^+ kg^{-1}$	$cmol^+ kg^{-1}$	$cmol^+ kg^{-1}$
Initial soil test	5.07±0.12	1.68±0.12	13.69±1.52	7.82±0.30	2.18±0.17	0.70±0.19	0.16±0.04	0.13±0.07
Lime effect								
Lime	5.24±0.28^a	2.01±0.49	40.53±22.78^a	7.96±1.96	2.28±1.07	0.78±0.14	0.20±0.07	0.75±0.31
No Lime	4.91±0.23^b	1.88±0.19	16.29±12.18^b	6.21±2.21	2.24±0.64	0.60±0.03	0.18±0.09	0.74±0.10
P-value	*	ns	*	ns	ns	ns	ns	ns
Fertilizer effect								
Control	4.98±0.24^b	1.95±0.34	14.05±19.36^c	7.08±2.1	2.26±0.79	0.69±0.14	0.19±0.07^c	0.75±0.55
Inorganic	4.8±0.33^c	1.67±0.21	35.48±10.05^a	6.75±0.52	1.87±0.4	0.63±0.14	0.38±0.6^b	0.79±0.29
Organic	5.54±0.29^a	2.13±0.44	32.62±9.49^b	8.24±1.88	3.26±1.7	0.71±0.24	0.33±0.14^b	0.6±0.75
I/O	5.07±0.19^b	2.14±0.41	35.02±8.58^a	9.48±1.77	2.41±1.34	0.51±0.08	0.54±0.22^a	0.38±0.53
P-value	*	ns	*	ns	ns	ns	*	ns

ns= not significant, *=significant at 0.05, **=significant at 0.01. Different lowercase letters represent significant differences at p<0.05.

Addition of organic amendments tend to improve overall soil fertility conditions because organic matter in soil is related to soil fertility, aggregation, nutrient retention capacity and productivity (Eden et al., 2017). Also, organic amendments, in general tend to increase pH, available P and K in the soil (Lin et al., 2022; Machado et al., 2022; Yi et al., 2022), such an increase is beneficial for teak establishment since literature reports that this species has more preference for soils that tend to be alkaline (Fernández-Moya et al., 2014).

Biometric measurements

Biometric measurements for teak showed different responses to treatments, mean values per treatment are presented in Table 4. In general, no significative interaction ($p > 0.05$) between the type of fertilizer (organic, inorganic, or 50% organic + 50% inorganic) and lime (lime and unlimed) was observed, indicating that these factors for this experiment acted separately. Nevertheless, for all variables, a highly significant difference ($p<0.01$) of fertilizer and lime levels was observed.

Taking into consideration the results of ANOVA, each effect was analyzed separately and the comparison of means by Scott-Knott test at 0.05 are presented in Table 4. For lime effects are possible to observe that the plants that were amended with dolomite lime showed a higher height, leaf area, diameter and dry weight, in comparison to plants that were not amended with lime. In general, the selection of plants for forestry production is carried with the use of the diameter and, in the present experiment, the treatment without lime represented 47% of the mean diameter of the treatment with lime. These results highlight the importance of liming in teak production and may explain why many teak plantations under acidic soils without lime may have failed in the past in this region. There are some studies that highlight the importance of liming in teak plantations and the importance of Ca in teak growth and how even fertilizer with acidic effects could affect teak establishment (Zhou et al., 2012).

However, is important to express that even though soil pH was not modified by dolomite lime in relation to control, the absorption of Ca and Mg may have contributed to the high growth observed in the biometric parameters. Combatt et al. (2016), working with different doses of Lime and Boron in Colombia, observed that during the establishment of teak the application of calcium hydroxide showed positive effects on growth parameters. Also, Wehr et al. (2017), working with the physiology of teak under acidic conditions showed that even though teak is an acidic-sensitive species some clones may have a high tolerance to acidic conditions. Soil acidity has great effects on plant growth due to its effects on the protoplasm of plant root cells, dissolution of toxic elements such as aluminum (Rengel, 2003). Aluminum generally exists in the form of $Al(OH)_3$, which is insoluble in soils, however, it passes to Al^{+3} under acidic conditions ($pH < 4.5$) and represents the most toxic form of Al for plants, which could affect teak establishment in acidic soil.

Fertilizer effects have different results, but the organic fertilizer treatment was superior for improving all biometric parameters (height, leaf area, diameter and dry weight), in comparison to all treatments. Surprisingly, the inorganic fertilizer had less effect for height, and root dry weight and was similar in leaf dry weight to the control. In comparison to the best treatment (organic fertilizer only), the control had 69.6% of the diameter, being the organic fertilizer responsible for more than 30% of the diameter. These results indicate the importance of the use of organic fertilizer under acidic conditions since in similar nutrient requirements inorganic fertilizer had less effect on diameter and biometric parameters and the results were similar to the control.

Table 4
Comparison of means by Scott-Knott test at 0.05 for biometric measurements in teak plants of 12 months with application of lime and different fertilizers (Organic, inorganic, I/O and control) in experimental field in Peru

Factors	Height	Leaf Area	Diameter	Leaf Dry Weight	Stem Dry Weight	Root Dry Weight
	cm	cm^2	cm	g	g	g
Lime effect						
Lime	261.6±64.6[a]	1845.6±1252[a]	23.1±8.1[a]	1328.9±105.0[a]	602.91±48.2[a]	619.9±37.3[a]
No Lime	85.9±21.3[b]	636.0±698[b]	10.9±6.0[b]	119.2±15.7[b]	63.08±10.1[b]	146.7±12.7[b]
Pvalue	**	**	**	**	**	**
Fertilizer effect						
Control	197.02±38.6[c]	838.5±761.0[c]	14.7±7.1[c]	36.2±53.5[c]	13.9±18.9[c]	23.8±15.4[c]
Inorganic	171.53±62.2[c]	945.6±1127.5[c]	15.6±9.2[c]	36.9±54.7[c]	14.0±18.8[c]	20.7±24.9[c]
Organic	306.31±59.1[a]	1948.8±1236.7[a]	21.1±10.1[a]	100.4±116.9[a]	48.9±62.0[a]	53.2±40.3[a]
I/O	261.29±63.7[b]	1248.8±1297.6[b]	17.4±10.5[b]	67.7±118.3[b]	34.2±46.5[b]	30.0±45.1[b]
P-value	**	**	**	**	**	**

ns= not significant, *=significant at 0.05, **=significant at 0.01. Different lowercase letters represent significant differences at $p < 0.05$.

The results on inorganic fertilizer may be due to the use of Urea which has an acidic reaction in the soil and may have contributed to the stress in teak plants in the early stages. Also, is important to mention that as observed by Zhang et al., (2023), organic matter in the soil promoted growth in teak and these species tend to improve general OM in the soil since the rate of decomposition of teak litter in tropical soils is slow because of the higher content of insoluble lignin (Cavalcante et al., 2021). In general, organic matter in the soil has great importance in teak growth, since the volume of production is directly linked to this variable (Neto et al., 2020) and this phenomenon has also been observed in Eucalyptus trees (Barry et al., 2015). Other trees species increase their productivity as well, using organic fertilizers for nutrients in comparison to inorganic fertilizers such as yellow poplar (*Liriodendron tulipifera* Lin.) (Han et al., 2016), Eucalyptus (Abreu-Junior et al., 2017; Barry et al., 2015; Laclau et al., 2010) and Pine trees (Palviainen et al., 2020). Organic amendments such as biochar have been observed to have a direct effect on plant survival in the field (de Farias et al., 2016). Also, organic fertilizers improve soil chemical characteristics by increasing pH and reducing the exchangeable and soluble Al and, increasing plant growth by reducing monomeric Al and by complexation of acid ions (Naramabuye & Haynes, 2006).

Concentrations and uptake of nutrients

Lime and fertilizers variables didn't show significant interaction ($P > 0.05$), however, their isolated effects presented significant differences ($P < 0.05$), especially in uptake measurements, that could be related to the dry weight effect. The concentration and uptake of nutrients (N, P, K, Ca, Mg, S, Cu, Fe, Mn and Zn) with lime application are presented in Table 5. In general, the concentration of the different macro and micronutrients presented no significant differences ($P > 0.05$) for lime treatment except for Fe, however, higher concentration values of P, K, Ca were observed in limed plants. The results of the concentration of nutrients indicate that similar values of elements were observed in both limed and unlimed treatments. Fe was observed in lower values (40% less) in limed plants in comparison to non-limed plants. In general, liming applications tend to diminish micronutrient availability such as Fe, Cu and Mn while also reducing soil exchangeable Al (Bolan et al., 2003; Børja & Nilsen, 2009). In general, high concentrations of Fe (>500 mg kg^{-1}) can affect overall plant metabolism, causing internal damage, mainly related to the formation of ROS (Reactive oxygen species) (Marschner, 2011). Also, Fe can alter morphological, metabolic and physiological characteristics of plants and generate oxidative stress (Lapaz et al., 2022).

Concentration and uptake of nutrients (N, P, K, Ca, Mg, S, Cu, Fe, Mn and Zn) with the different amendments (No Fertilizer-Control, Inorganic, Organic and I/O-50% Inorganic + 50% Organic fertilizer) is presented in Table 6. In the case of the fertilizer effect, Ca, S and K presented significant differences ($P < 0.05$). The organic fertilizer showed a higher concentration in comparison to the other treatments. However, for K, the inorganic treatment showed a higher concentration in plants, followed by the combination of the inorganic and organic fertilizer, indicating that in terms of K nutrition, inorganic amendments may be preferred in relation to organic fertilizers.

For the content of nutrients, little evidence exists for plants of this age (12 months), most research has presented plants with older ages (>3 years) (Fernández-Moya et al., 2017, 2014), except for the work of Dos Santos et al. (2022), which develops allometric models of nutrient contents from 15 months to 75 months.

Table 5
Nutrient concentration and Uptake of leaves of teaks plants of 12 months with application of lime and No lime in acid soil in Peru

Treatment	N	P	K	Ca	Mg	S	Cu	Fe	Mn	Zn
	dag kg^{-1}						mg kg^{-1}			
No Lime	2.27±0.52	0.20±0.07	1.25±0.76	0.61±0.27	0.13±0.09	0.20±0.04	13.96±8.69	534.91±229.17^{a}	87.50±39.36	42.87±10.23
Lime	2.01±0.48	0.23±0.13	1.40±0.83	0.68±0.25	0.12±0.06	0.17±0.04	9.80±6.77	321.23±307.30^{b}	87.17±31.37	40.06±19.38
P	ns[||]	ns	ns	ns	ns	ns	ns	*	ns	ns
	Uptake mg $plant^{-1}$									
No Lime	272.1±373.9^{b}	30.5±47.6^{b}	162.8±305.8	117.1±233.0^{b}	16.3±30.5^{b}	31.7±52.2^{b}	0.2±0.3^{b}	6.7±16.0^{b}	0.9±1.3^{b}	0.6±0.8^{b}
Lime	3267.6±3005.9^{a}	316.0±279.5^{a}	1852.6±1564.3^{a}	971.5±1114.4^{a}	189.4±195.9^{a}	292.8±328.5^{a}	1.6±1.9^{a}	100.5±107.2^{a}	14.7±16.0^{a}	7.6±11.5^{a}
P	**	**	**	**	**	**	**	**	**	**

ns= not significant, *=significant at 95%, **=Significant at 99%.

Table 6
Nutrient concentration and Uptake of leaves of teaks plants of 12 month with application of different fertilizers (Organic, inorganic, I/O and control) in an acidic soil in Peru

Treatment	N	P	K	Ca	Mg	S	Cu	Fe	Mn	Zn
	dag kg^{-1}						mg kg^{-1}			
Control	2.02± 0.46	0.29± 0.12	0.94± 0.54	0.71± 0.38	0.17± 0.12	0.16± 0.04	13.72± 6.75	409.54± 272.38	59.25± 35.26	43.34± 14.33
Inorganic	2.25± 0.74	0.23± 0.15	1.96± 0.72	0.64± 0.16	0.12± 0.03	0.18± 0.03	8.74± 10.80	286.06± 113.95	96.65± 31.12	39.97± 11.40
Organic	2.01± 0.50	0.18± 0.04	1.05± 0.54	0.77± 0.15	0.13± 0.05	0.23± 0.04	10.36± 1.80	565.54± 443.60	92.76± 39.79	34.45± 7.99
I/O	2.29± 0.30	0.17± 0.04	1.32± 0.98	0.46± 0.18	0.09± 0.06	0.16± 0.02	14.70± 9.71	451.15± 214.92	100.68± 21.85	48.11± 23.41
P	ns	ns	*	*	ns	*	ns	ns	ns	ns
	Uptake mg plant^{-1}									
Control	940.8± 1208.3	106.0± 109.9	578.5± 985.7	362.7± 593.3	86.7± 158	73.5± 99.1	0.6± 0.6	32.6± 64.1	2.5± 3.1	1.5± 1.5
Inorganic	1109.2± 1763.2	160.8± 261.6	1323.0± 2038.3	292.8± 400.2	67.9± 116.5	76.6± 103.3	0.2± 0.3	18.2± 27.5	3.7± 4.8	2.1± 3.4
Organic	2787.9± 2891.1	265.8± 309.3	1482.7± 1612.8	1229.7± 1529.1	210.3± 248.7	351.3± 426.0	1.4± 1.4	107.3± 122.0	14.2± 16.4	4.9± 5.2
I/O	2241.4± 3894.4	160.4± 287.1	646.8± 721.7	292.1± 349.0	46.4± 49.7	147.6± 248.6	1.3± 2.5	56.3± 105.7	10.8± 19.5	7.7± 16.7
P	**	**	**	**	**	**	**	**	**	**

ns= not significant, *=significant at 0.05, **=significant at 0.01. Different lowercase letters represent significant differences at $p < 0.05$.

In general, there is little work on fertilization in teak related to different sources of fertilizers, inorganic fertilizers are the main preference in different fertilization experiments with teak (Abod & Siddiqui, 2001; Combatt et al., 2016). Organic fertilizers are in general more expensive in terms of logistics since density and nutrient concentration is low in comparison to inorganic fertilizer. Nevertheless, the contribution to the growth and development of teak may require this type of amendment, especially in acid soils in the tropic. In a Multidimensional study Silva et al. (2015), observed that limiting nutrient factors for teak plants growth were Ca, P and Mg. The organic treatments favored better Ca and S nutrition, alleviating Ca deficiency in these acidic soils that are characterized by their low available Ca and low P; also, teak is known for being a high Ca demanding species for good growth (Zhou et al., 2012). In general, organic amendments increase carbon stocks and cation exchange capacity which is important for retaining nutrients and making them available to plants (Diacono & Montemurro, 2010). Organic amendments tend to improve general soil fertility by improving P nutrition and S nutrition, especially by the concentration of these elements in organic amendments. Also, some other studies have shown positive effects on other forest trees improving overall N, P, K and Mg nutrition for *Quercus ilex* (Cellier et al., 2014), P and K for eucalyptus and exceeding the effects in relation to mineral fertilization (Rosa et al., 2022) as observed in the present research.

4. Conclusions

The paper presents the effect of organic and inorganic amendments on the growth and nutrition of 12-month-old teak (*Tectona grandis*) plants grown on acid soil of the Peruvian Amazon. Teak is a highly calcium-demanding species, and we observed no interaction between lime and fertilizers in the present work for all assessed variables. Treatments with the addition of dolomitic lime favored biometric parameters of teak in relation to other treatments with no lime and, the use of organic fertilizers promoted more growth than inorganic fertilizers. In the case of nutrients, no major differences were observed between lime and no lime treatments while organic fertilizer promoted Ca, K and S nutrition. The results indicate that teak is a high acidity-sensitive species, but this problem can be solved by the application of lime and organic fertilizers, especially in tropical soils where acidity is a common problem and, in this way, help to improve the management and the establishment of teak plants in this type of soils.

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Conflict of interest

The authors declare that they have no conflict of interest.

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