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An approach to the impact of weather variables on the growth of *Polylepis* species in the central Andes of Peru

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Abstract

The *Polylepis* genus, endemic to the South American Andes, faces significant threats due to environmental variations, which jeopardize its growth and survival. This situation underscores the urgent need to develop conservation strategies. The present research assesses the influence of meteorological variables, such as temperature and humidity, on the growth and adaptation of various *Polylepis* species in the central Peruvian Andes, aiming to optimize reforestation and sustainable management practices. The study was conducted in experimental plots at the Santa Ana Agricultural Station in Junín, Peru, where *Polylepis* saplings, obtained from different localities, were planted. Over two years, phenotypic variables (height and diameter) and meteorological variables (precipitation, humidity, temperature, and wind speed) were monitored to evaluate the relationship between environmental conditions and plant development. The results showed that high humidity negatively affected all species, however wind speed appears to promote plant growth by creating an ideal microclimate that reduces soil moisture. Precipitation and maximum temperature had limited impact, indicating relative resilience to these factors. It should be noted that the species from Huancavelica and Yauyos have been adapting better to local conditions compared to those from Cerro de Pasco, which are more sensitive to humidity. These findings highlight the importance of considering wind speed and humidity in reforestation planning to improve the adaptability of *Polylepis* species. We conclude that humidity is the most decisive meteorological factor for the growth of *Polylepis* under specific conditions, emphasizing its relevance in planning conservation and reforestation strategies in the Peruvian Andes.

Key words: forest conservation, phenotyping, relative humidity, wind velocity.

Introduction

Climate change represents significant risks to the sustainability of native tree plantations, affecting their survival, productivity, carbon balance, and water use (Cunningham et al. 2015). Consequently, the ecosystem services provided by these trees and their ability to recover from environmental changes are impacted (Ortega-Quispe et al. 2024, Rubilar et al. 2024). *Polylepis* Ruiz & Pav. is a genus unique to the South American Andes (Morales-Aranibar and Morales-Aranibar 2023); nevertheless, 44 of its 47 species are included in the IUCN Red List (IUCN 2024). The fragmentation of *Polylepis* forests in Peru, caused by human activities, threatens the loss of their vegetation cover, making conservation efforts imperative to prevent further degradation and protect this unique ecosystem (Franco-León et al. 2024). However, academics and field practitioners, in their attempt to preserve and restore these natural ecosystems, often work independently to conserve and understand them (Morales Moreno et al. 2018).

Understanding different species growth rates in a model plantation is fundamental to optimize the planting sites selection, taking into account the compatibility with the environment (Morales Moreno et al. 2018). In addition, efficient plantation management requires constant dynamics monitoring, both at the plantation level as a whole and of each individual tree (Flores Garnica and Reyes Cárdenas 2022). The *Polylepis* genus, one of the most representative endemic species of our continent, is gaining relevance due to its endemism and its crucial role in the ecological balance conservation. Among the *Polylepis* studied species are *Polylepis incana* Kunth, native to South America, which has low germination power and slow growth (Canales Gutiérrez et al. 2020). In contrast, *Polylepis racemosa* Ruiz Lopez & Pavon, native to Peru, shows faster growth compared to other species and spreads more easily (Segovia-Salcedo 2011). On the other hand, *Polylepis sacra* T. Boza & M. Kessler has a very distinct climatic niche (Boza Espinoza and Kessler 2022).

It is important to understand in detail these species in relation to the climatic variables that affect their growth and survival in order to know, understand and develop more effective strategies for reforestation and conservation of our natural forests (Acácio et al. 2024). From a technological perspective, this understanding facilitates the assessment of forest regeneration potential at multiple spatial scales, allowing the prediction of specific scenarios or species behaviour (Bedoya et al. 2024, Everingham et al. 2024). This information is key to assess the viability of species in different ecological contexts (Rank et al. 2022), which directly benefits the populations that depend on these ecosystems for their livelihoods and well-being. In addition, commercial forest plantations, using native species, provide multiple ecosystem services, such as timber production, carbon sequestration and biodiversity support (Ugarte-Guerra and Román-Dañobeytia 2020).

Recent forest projections have revealed changes in tree species density and composition as a result of temperature variations (De Fatima et al. 2023, Hsu et al. 2024). It is important to emphasize that our research, as well as other studies, has contributed to broaden the knowledge on the ecology and conservation of *Polylepis* (Renison et al. 1991), demonstrating that these trees present adaptive strategies for their survival (Ramos et al.

2013). In addition, significant differences have been identified between populations in the seedling growth range, influenced by climatic factors, such as light and temperature (Cai et al. 2016). It is important to note that climatic extremes can lead to considerable variations in the seedlings number continuity between species due to their varying sensitivity (Niu et al. 2014).

A key aspect in the high Andean ecosystems dynamics is how forest species respond to environmental conditions and historical land use (Schmitt et al. 2023). In this regard, research has shown that growth rates of various species are influenced both by their intrinsic characteristics and by external factors (Bellemare et al. 2002). A recent study on the growth of four native species in Peruvian Amazon plantations highlights that both species-specific traits and land use history critically influence development. This interaction is especially significant for *Polylepis* species, which thrive in extreme altitudes, where environmental factors like water availability, temperature, and land use impact their survival and growth (Ugarte-Guerra and Román-Dañobeytia 2020).

Therefore, this work aims to demonstrate the influence of climatic variables on phenotypic characteristics, in order to develop conservation and sustainable management strategies that will facilitate the adaptation of native forest species, such as *Polylepis*. The results of this research will provide concrete evidence that significantly contributes to the Sustainable Development Goals (SDGs), particularly SDG 13 and SDG 15, by evidencing improvements in ecosystem management in response to climate variations and promoting the conservation of mountain ecosystems in the Peruvian central.

Material and Methods

The study was conducted in three primary phases. In the initial phase, the planting of three *Polylepis* species was completed. The second phase focused on the collection of meteorological and phenotypic data. Finally, the third phase involved the analysis of the collected data (Fig. 1).

The plantation was established in demonstration plots managed by the Santa Ana Agrarian Experimental Station attached to the National Institute of Agrarian Innovation in the Paccha district, Jauja province, Junín region, Peru, as seen in Figure 2. The Jauja depression is a basin formed by Quaternary deposits, located at altitudes between 3100 and 3300 m a.s.l. (Ccopi-Trucios et al. 2023, Cáceres et al. 2024). This basin is drained by the Mantaro River and two secondary tributaries, the Ricrán and Tulumayo rivers. The climate of this region is characterized by a dry and hot season from April to November, and a continuous rainy season from December to March. However, the duration of these seasons may vary due to various factors associated with the Andes and the Andean region.

As shown in Table 1, the study was carried out in three plots, where three species of *Polylepis* (*P. sacra*, *P. racemosa* and *P. incana*) were planted. The seedlings, 2-year-old and with average size of 30 cm total with a black polyethylene bag, were obtained from nurseries located in three different locations. The climatic characteristics of the source nurseries are presented based on the average values of variables recorded in 2022. This information comes from both the producers own records and data from the National Meteorology and Hydrology Service of

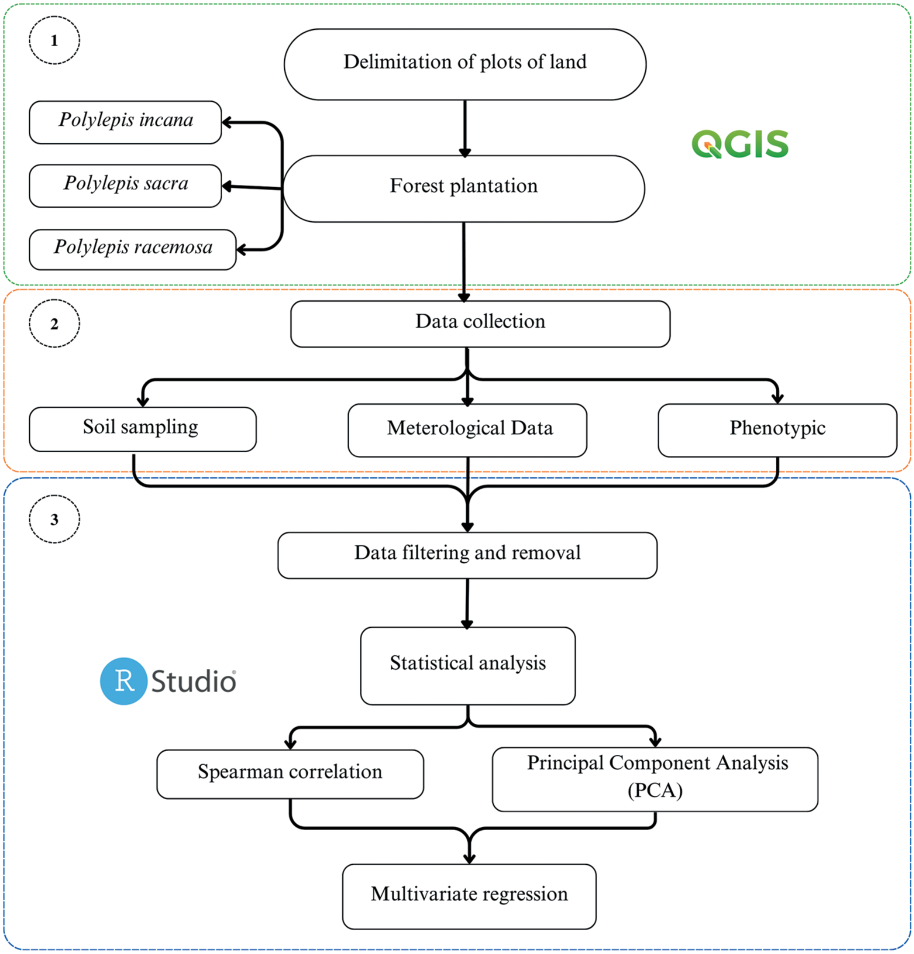

Fig. 1. Flow chart of the research process.

Peru, accessed through their official portal (SENAMHI 2024).

The soils where *Polylepis* was planted have a sandy loam texture, which limits water and nutrient retention, although the high sand content (54–58 %) allows for good drainage. Organic matter ranges between 1.4 and 1.8 %, which contributes to soil fertility, while variations in nitrogen (1.4 to 3.0%), phosphorus (0.07 to 0.15 mg·kg^{-1}) and potassium (13.6 to 72.5 mg·kg^{-1}) can limit growth. Soil analyses were carried out in the soil and foliar laboratory (LABSAF) of the Santa Ana – Huancayo Experimental Station.

The seedlings were established on December 13, 2021 at the Los Andenes site of the Agrarian Experimental Station (EEA) and the Masajcancha community in Jauja.

Soil preparation was carried out through localized tillage during 2021, which involved digging 30 × 30 × 30 cm holes. In each hole, a substrate composed of a mixture of 20 % organic fertilizer and native soil was applied, providing essen-

Fig. 2. Location of the experimental development site.

Table 1. Origin of the plantations.

Provenance	Species	Climatic characteristics					Number of seedlings
		Tmax, °C	*Tmin*, °C	*Hum*, %	*Ws*, $m\cdot s^{-1}$	*P*, $mm\cdot yr^{-1}$	
Yauyos	*Polylepis sacra*	25	10	62	2.3	2396.4	235
	Polylepis racemosa						201
Huancavelica	*Polylepis incana*	23	5	73	2.6	750.2	304
Cerro de Pasco	*Polylepis racemosa*	20	3	57	3.2	1182.7	246
	Polylepis incana						222

Note: Provenance in provinces of the central high Andean zone of Peru. The climatic characteristics correspond to the average of each parameter for the year 2022.

tial nutrients and improving the structure of the soil to promote plant growth. Seedlings, which measured approximately 15 to 18 cm in height with bare roots, were obtained from certified nurseries in each collection region.

The design is represented by a distance of 3 m between horizontal rows, each row contains the seedlings spaced 2 m apart, which allowed sufficient space for root development and efficient management. Irrigation was carried out by flooding during the first six months of the dry season, providing uniform and deep hydration of the soil during this critical establishment stage. During the rainy season, irrigation was not necessary and measures were taken, such as installing a fence with barbed wire to protect the plants from small animals, avoiding damage to leaves and tips.

Additionally, weeding was carried out every three months to control weed competition. Pest control was implemented using natural extracts, helping to reduce environmental impact compared to agrochemical use. In the second year, formative pruning was conducted to promote the plant's vertical growth, providing a strong structure suitable for future development.

Field activities involved measuring tapes, GPS devices, and cultivation tools, with safety measures implemented for the operators. The evaluations covered two years (2021–2022), continuing to date, and included measurements taken in March and December (rainy season) and June (dry season), focusing on height, diameter, shoots, and leaflets.

Meteorological data were obtained from the Santa Ana station (2019–2024) using a Davis Vantage Pro2 measuring device, informing evaluations and allowing for the calculation of averages. Data processing was done in RStudio Team (2020), applying initial data cleaning and the interquartile range (IQR) method to handle outliers and ensure quality.

To analyse the relationship between climatic variables and phenotypic development, Spearman's correlation was used, as it identifies monotonic relationships without assuming a normal distribution (Rovetta 2020). This method is valuable in forestry studies, as it addresses irregular or non-linear patterns in climatic variables that affect species growth (Mendivelso 2022, Bocianowski et al. 2024). By detecting non-linear relationships, this approach clarifies species' responses to climate changes (Allen et al. 2010).

A multivariate regression was conducted to assess the influence of climate on the growth of forest species, focusing on phenotypic variables, such as tree diameter and height. The aim was to evaluate how temperature, precipitation, and relative humidity simultaneously affect both diameter and height, providing insights into the phenotypic responses to climatic fluctuations (Pretzsch 2014, Dudenhöffer et al. 2018).

A Principal Component Analysis (PCA) was conducted to explore the relationships between climatic and phenotypic variables across different localities. Additionally, scatter plots were created to illustrate the relationships between climatic variables (precipitation, wind speed, humidity, and maximum temperature) and two phenotypic traits of *Polylepis* species: height and diameter.

Results and Discussion

Table 2 presents descriptive statistics for *Polylepis* from Cerro de Pasco, Yauyos, and Huancavelica. Cerro de Pasco has an average height (*H*) of 76.76 cm and a diameter (*D*) of 13.36 mm, with temperatures between 9.4 °C and 12.7 °C and average humidity of 73.0 %. Yauyos has a greater average height of 89.7 cm but a similar temperature range and humidity. Huancavelica features the highest average height at 114.6 cm and a diameter of 18.7 mm, suggesting more favourable

Table 2. Provenance of plantations.

n	Indicator	*H*, cm	*D*, cm	*T*max, °C	*T*min, °C	*Hum*, %	*W*s, m·s^{-1}	*P*, mm·h^{-1}
				Cerro de Pasco				
	mean	76.7	13.3	11.2	11.0	73.0	1.9	11.5
	max	127.0	33.2	12.7	12.6	81.7	2.2	28.2
468	min	35.0	3.9	9.4	9.2	64.7	1.4	3.0
	StD	17.3	5.8	1.3	1.3	6.9	0.3	10.0
	Median	76.0	12.8	11.3	11.2	72.8	1.9	7.5
				Yauyos				
	mean	89.7	12.2	11.2	11.0	73.0	1.9	11.5
	max	135.0	28.2	12.7	12.6	81.7	2.2	28.2
436	min	28.0	2.8	9.4	9.2	64.7	1.4	3.0
	StD	22.20	4.49	1.30	1.31	6.96	0.3	10.0
	Median	92.00	11.61	11.31	11.20	72.89	1.9	7.5
				Huancavelica				
	mean	114.6	18.7	11.2	11.0	73.0	1.9	11.5
	max	192.0	38.2	12.7	12.6	81.7	2.2	28.2
304	min	54.0	4.4	9.4	9.2	64.7	1.4	3.0
	StD	27.7	8.2	1.3	1.3	7.3	0.3	10.0
	Median	115.0	18.6	11.3	11.2	72.8	1.9	7.5

Note: *n* is number of samples, *H* is height, *D* is diameter, *T*max is maximum temperature, *T*min is minimum temperature, *Hum* is humidity, *W*s is wind speed, *P* is precipitation.

growing conditions. Humidity remained relatively constant across all locations, underscoring its significance for the phenotypic development of the species.

Figure 3 presents the correlation matrix for the three studied localities, where it is observed that humidity is negatively related to growth in height and diameter of *Polylepis* plants, especially in Cerro de Pasco and Huancavelica. This suggests that high humidity levels may not be favourable for the development of this species in its new environment. Regarding the relationship between height and diameter, a positive correlation is found in all localities, being strongest in Huancaveli-

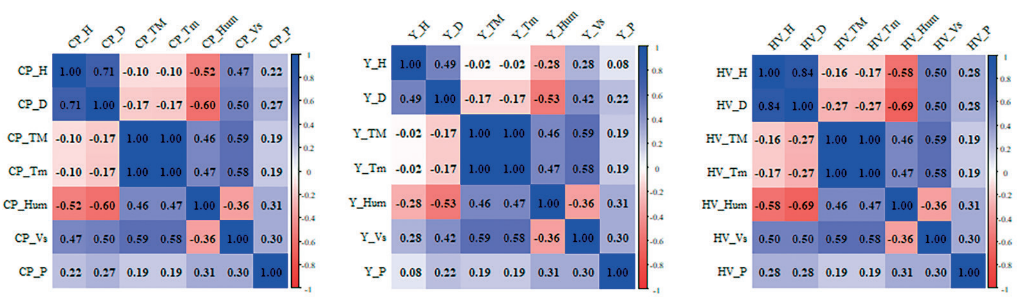

Fig. 3. Correlation matrix.

Note: The index (CP, Y, HV) that accompanies the variable represents: CP is Cerro de Pasco, Y is Yauyos, HV is Huancavelica.

ca (0.84), indicating that in this species, height growth is closely associated with diameter.

On the other hand, extreme temperatures (maximum and minimum) have minimal influence in Cerro de Pasco and Yauyos, while in Huancavelica, a slight negative correlation is observed. This suggests that the effect of temperature on the growth of *Polylepis* varies according to the species' adaptability. The results indicate that the growth of *Polylepis* is affected differently depending on the locality of origin and species, highlighting humidity as a relevant factor, particularly in higher-altitude localities, where this variable appears to limit plant development in terms of height and diameter.

Figure 4 shows the principal component analysis (PCA), illustrating how climatic variables influence the phenotypic characteristics (height and diameter) of *Polylepis* species from Cerro de Pasco, Yauyos, and Huancavelica. The points represent individual observations grouped by region, while the ellipses around each group indicate the general trend of the species in each locality. The *Polylepis* species from Yauyos show a closer association with maximum temperature (*T*max) and precipitation (*P*), suggesting that these climatic conditions positively impact height (*H*) growth and diameter (*D*) development in this region. This implies that in *Polylepis* species from Yauyos, height and diameter are particularly influenced by temperature and precipitation.

In contrast, the *Polylepis* species from Cerro de Pasco and Huancavelica appear more closely associated with relative humidity (*Hum*). In these species, humidity seems to play a more significant role in the development of height and diameter. This suggests that, in climates where humidity is the dominant factor, height and diameter growth patterns may differ from those observed in environments more influenced by temperature and precipitation. Overall, this analysis indicates that climatic variables have a differentiated impact on height and diameter development across regions, highlighting the im-

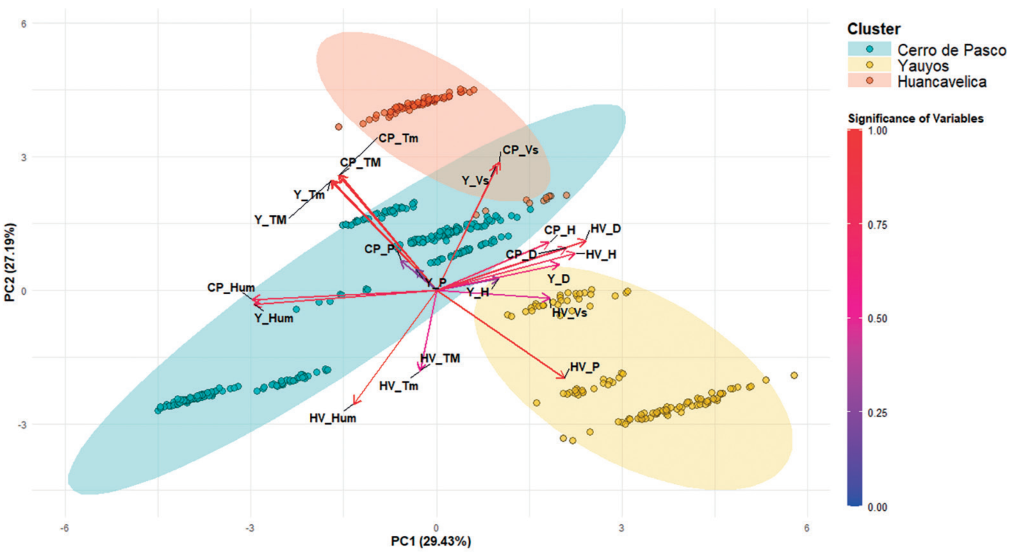

Fig. 4. Principal component analysis (PCA).

portance of considering specific environmental conditions in each locality to fully understand the phenotypic development of *Polylepis* species.

Multivariate regression analysis of climatic effects

Table 3 reveals the impact of climatic variables on *Polylepis* species native to Cerro de Pasco. The intercepts present significant *t*-values, with 15.149 for height and 17.028 for diameter. These results indicate that the evaluated climatic conditions have a significant influence on the growth of the species, evidencing a strong relationship between environmental factors and the phenotypic development of *Polylepis*.

Precipitation positively affects plant growth, which is shown in equation (1), with a 1-unit increase in precipitation producing increases of 0.58 units in height and 0.26 units in diameter, and an increase in 1 unit in wind speed resulting in increases of 8.93 units in height and 2.17 units in diameter. In contrast, a 1 unit increase in humidity results in decreases of 1.59 units in height and 0.67 units in diameter, suggesting that excessive humidity can inhibit growth. Maximum temperature was excluded from the model due to its non-significant relationship.

The multivariate equation for the Cerro Pasco complex is expressed as follows:

$$\left(\frac{H}{D}\right)=\left(\frac{168.80}{55.30}\right)+\left(\frac{0.58}{0.26}\right)P+\left(\frac{8.93}{2.18}\right)Ws+\left(\frac{-1.57}{-0.67}\right)Hum \quad (1)$$

where: *H* is height, m; *D* is diameter, cm; *P* is precipitation, mm; *W*s is wind speed, $m\cdot s^{-1}$; *Hum* is humidity, %.

The effect of climatic variables on *Polylepis* species from Yauyos is demonstrated by significant *t*-values of 7.482 for height and 13.863 for diameter, as shown in Table 4. These results emphasize the strong impact of climatic conditions on species growth, highlighting the correlation between environmental factors and the phenotypic development of *Polylepis*.

Climatic variables influence plant height and diameter (equation 2). A 1-unit increase in precipitation leads to increases of approximately 0.27 units in height and 0.17 units in diameter, indicating that higher precipitation supports growth. Wind speed also positively impacts growth, with increases of 10.08 units in height and 1.23 units in diameter for each unit increase in speed. In contrast, a 1-unit increase in humidity results in decreases of 0.98 units in

Table 3. Multivariate regression with seedlings from Cerro de Pasco.

Indicators		Estimate	Std. Error	*t*-value	Pr (>|t|)
Height	Intercept	168.80989	11.14313	15.149	< 2e-16
	P	0.58045	0.06989	8.305	1.11e-15
	*W*s	8.92997	2.32553	3.84	0.00014
	Hum	-1.5861	0.1184	-13.397	< 2e-16
Diameter	Intercept	55.30394	3.24786	17.028	< 2e-16
	P	0.26286	0.02037	12.903	< 2e-16
	*W*s	2.16762	0.67781	3.198	0.00148
	Hum	-0.67257	0.03451	-19.49	< 2e-16

Note: Pr is *p*-value associated with a t-test; the variables mentioned: *P* is precipitation, *W*s is wind speed, *Hum* is humidity.

Table 4. Multivariate regression with seedlings from Yauyos.

Indicators		Estimate	Std. Error	*t*-value	Pr (>|t|)
Height	Intercept	138.7598	18.5468	7.482	4.14e-13
	P	0.2716	0.1163	2.335	2.00e-02
	*W*s	10.0777	3.8706	2.604	0.00954
	Hum	-0.9788	0.1971	-4.967	9.80e-07
Diameter	Intercept	41.5395	2.99651	13.863	< 2e-16
	P	0.17287	0.0188	9.197	< 2e-16
	*W*s	1.22651	0.62536	1.961	0.0505
	Hum	-0.46088	0.03184	-14.476	< 2e-16

Note: Pr is *p*-value associated with a t-test; the variables mentioned: *P* is precipitation, *W*s is wind speed, *Hum* is humidity.

height and 0.46 units in diameter, suggesting that high humidity may hinder growth. Maximum temperature was excluded from the model, indicating it has no significant influence.

The multivariate equation for the Yauyos set is expressed as follows:

$$\left(\frac{H}{D}\right)=\left(\frac{138.76}{41.54}\right)+\left(\frac{0.27}{0.17}\right)P+ +\left(\frac{10.08}{1.23}\right)Ws+\left(\frac{-0.98}{-0.46}\right)Hum \tag{2}$$

The climatic variables influence on *Polylepis* species from Huancavelica (Table 5), indicating significant *t*-values of 16.07 for height and 21.256 for diameter. These results suggest that the analysed climatic variables substantially impact species growth, reflecting a strong relationship between environmental conditions and the phenotypic development of *Polylepis*.

Plant height and diameter are influenced by climatic variables (equation 3). A 1-unit increase in precipitation results in increases of approximately 1.23 units in height and 0.43 units in diameter, indicating that higher precipitation enhances growth. Wind speed also positively impacts growth, with increases of 10.02 units in height and 0.95 units in diameter for each unit increase in speed. In contrast, a 1-unit increase in humidity leads to decreases of 3.06 units in height and 1.13 units in diameter, suggesting high humidity may negatively affect growth. Maxi-

Table 5. Multivariate regression with seedlings from Huancavelica.

Indicators		Estimate	Std. Error	*t*-value	Pr (>|t|)
Height	Intercept	304.9475	18.9704	16.07	< 2e-16
	P	1.2312	0.119	10.35	< 2e-16
	*W*s	10.0154	3.959	2.53	0.0119
	Hum	-3.0624	0.2016	-15.19	< 2e-16
Diameter	Intercept	94.85085	4.4624	21.256	< 2e-16
	P	0.43108	0.02799	15.401	< 2e-16
	*W*s	0.94664	0.93128	1.016	0.31
	Hum	-1.13473	0.04741	-23.933	< 2e-16

Note: Pr is *p*-value associated with a t-test; where: *P* is precipitation, *W*s is wind speed, *Hum* is humidity.

mum temperature was excluded from the model, indicating it does not significantly impact this dataset. These results underscore the importance of understanding climatic influences on plant phenotype for optimizing agricultural practices and improving crop yields.

The multivariate equation or the Huancavelica set is expressed as follows:

$$\left(\frac{H}{D}\right)=\left(\frac{304.95}{94.85}\right)+\left(\frac{1.23}{0.43}\right)P+ +\left(\frac{10.01}{0.94}\right)Ws+\left(\frac{-3.06}{-1.13}\right)Hum \tag{3}$$

Scatter plots in figures 5a, 5b and 5c illustrate the relationships between climatic variables – precipitation, wind speed, humidity, and maximum temperature – and two phenotypic characteristics of *Polylepis* species: height and diameter. Each plot includes a trend line showing the linear fit and a coefficient of determination, indicating the strength of the correlation between climatic and phenotypic variables.

The results show that humidity is the climatic variable most strongly correlated with the phenotypic growth of *Polylepis* species, particularly diameter, while precipitation and maximum temperature have a less significant impact. The figures indicate that humidity significantly influences the diameter and height. However, both precipitation and maximum temperature exhibit poor correlations with these traits, suggesting that other factors may contribute to their variability.

Discussion

The study found varied responses to climate changes in different locations, showing that these plants exhibit unique behaviours depending on their environment while growing. These results are consistent with previous research analysing how *Polylepis* adapts to different conditions at high altitudes in the Andes.

For instance, the *Polylepis* species from Cerro de Pasco appear to benefit from the winds in their environment. We found that the vertical growth of these plants has a positive relationship with wind speed (r = 0.47), suggesting that the winds help them grow taller. This finding aligns with that of Marcora et al. (2021), who observed that in Andean ecosystems, wind can create microclimates that reduce humidity around plants, which is beneficial in poorly drained soils, such as the study site, which had a clayey, compact texture and high water saturation.

However, humidity is another important factor for these species, as their height and diameter growth significantly decrease in very humid environments (with negative correlations of r = -0.52 and r = -0.60, respectively). Cáceres et al. (2021) also observed this effect, indicating that high-altitude species like *Polylepis* can experience developmental issues in high-humidity conditions, as they may be at a greater risk of fungal diseases and water stress.

The *Polylepis* plants from Yauyos, on the other hand, displayed more neutral responses to temperature variations. The near-zero correlation between their height and maximum temperature (r = -0.02) suggests that these species are more tolerant of temperature fluctuations, likely due to thermal adaptation mechanisms similar to those described by Allen et al. (2010). They found that mountain plants develop cellular structures that allow them to withstand a wide range of temperatures. However, similar to the Cerro de Pasco species, the Yauyos species are also negatively affected by high humidity, with negative correlations in

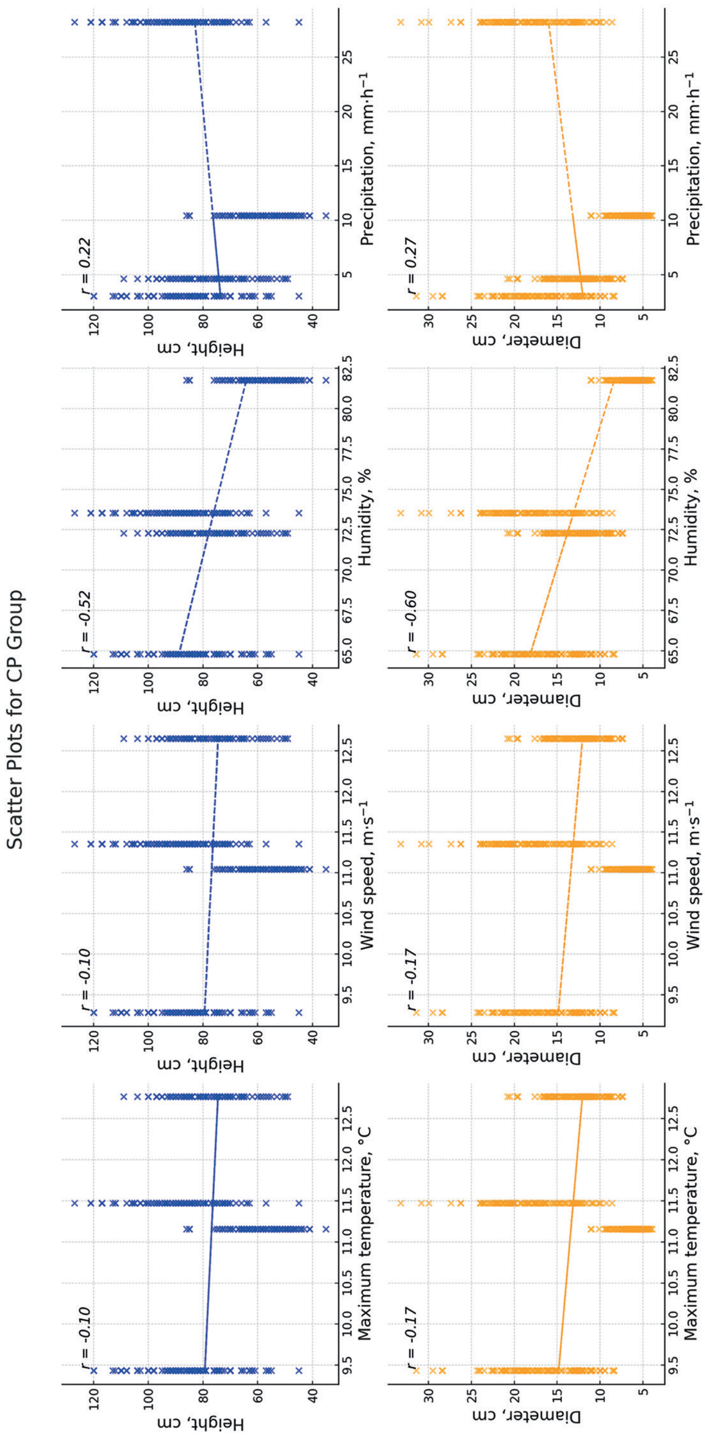

Fig. 5a. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Cerro de Pasco.

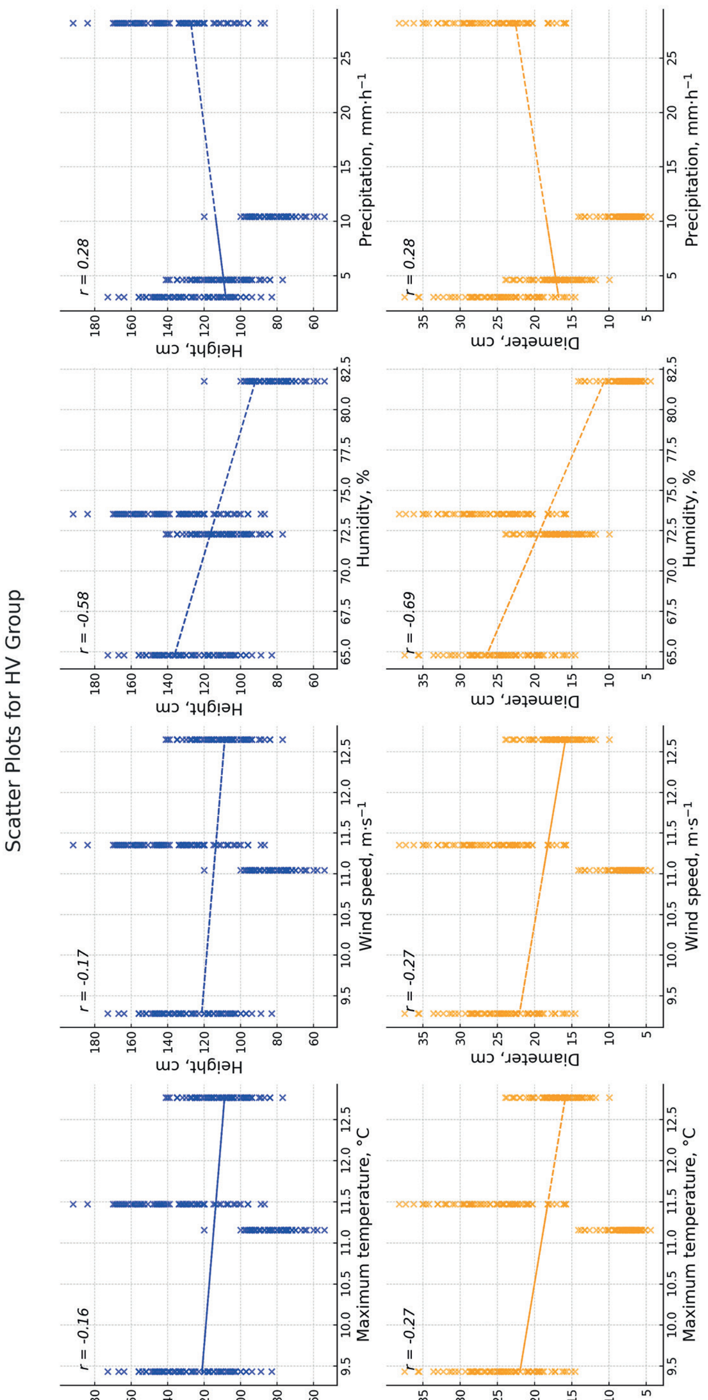

Fig. 5b. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Yauyos.

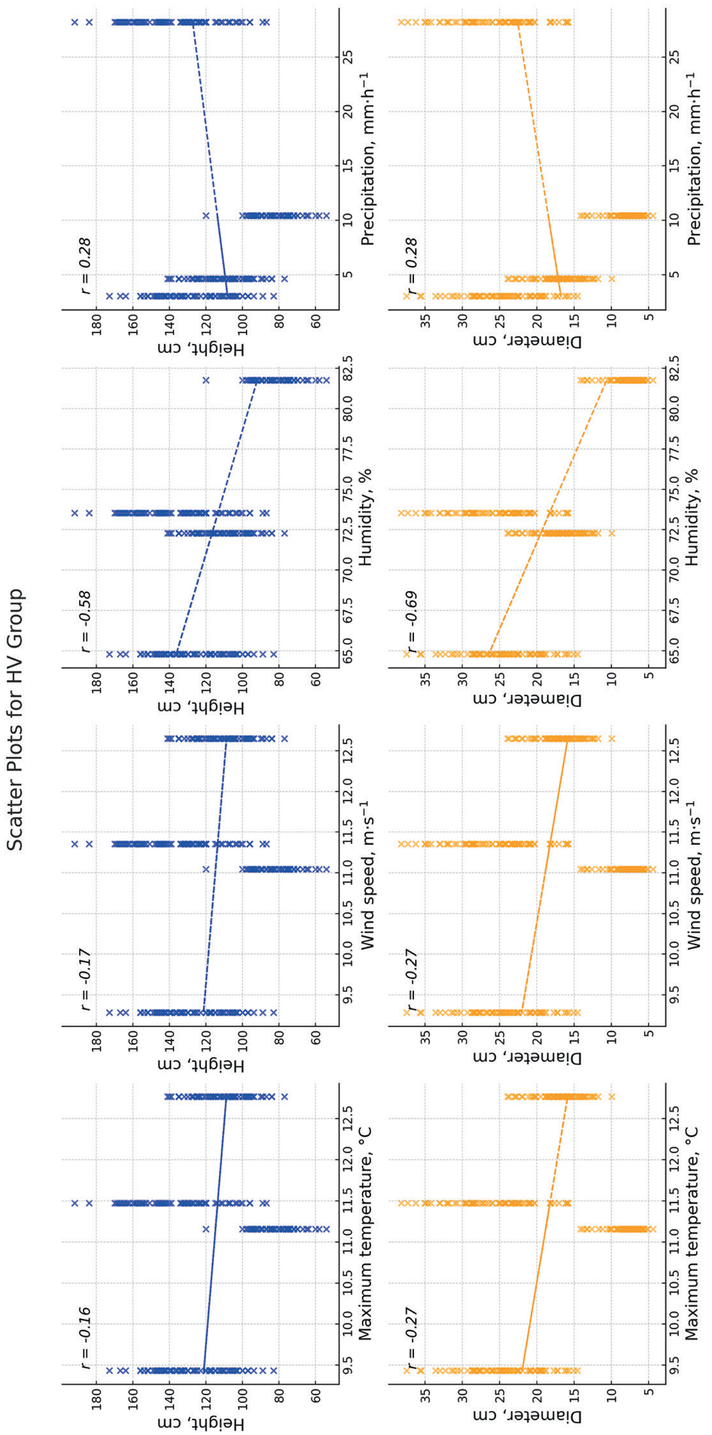

Fig. 5c. Variance plot representing the relationship between weather variables (precipitation, wind speed, humidity and maximum temperature) with height and diameter – location Huancavelica.

height (*r* = -0.28) and diameter (*r* = -0.53). This pattern is commonly seen in studies of high-altitude plants, where excessive humidity can hinder growth (Boza Espinoza et al. 2019).

The *Polylepis* plants from Huancavelica exhibited a behaviour similar to the Cerro de Pasco plants regarding wind (positive height correlation, *r* = 0.50). However, they are also highly sensitive to humidity, as indicated by strong negative correlations with height (*r* = -0.58) and diameter (*r* = -0.69). Previous studies, such as that by Rovetta (2020), found that many forest species in the region are highly susceptible to humidity, especially in areas with intense rainfall. Interestingly, these species showed a slight positive correlation with precipitation (r between 0.22 and 0.28 for height and diameter), suggesting that they benefit from a moderate amount of water without reaching excess levels. This aligns with findings by Carabajo-Hidalgo et al. (2023), who emphasized the importance of maintaining a balanced water regime to provide healthy growth without creating stress conditions for the plants.

A principal component analysis (PCA) further confirms these patterns, grouping species according to their climate responses: Cerro de Pasco is primarily associated with wind adaptability, Yauyos with a more balanced and tolerant response, and Huancavelica with a high dependence on precipitation and marked sensitivity to humidity. These findings suggest that moderate wind and precipitation levels favour the adaptation of these species in their new environments, while excessive humidity is a common barrier to growth across all evaluated species (Boza Espinoza et al. 2019). These insights are essential for understanding the ecological needs of each species, helping to inform effective management and conservation strategies in Andean habitats.

Conclusion

The comparative analysis of *Polylepis* populations from Cerro de Pasco, Huancavelica, and Yauyos, planted in Huancayo, reveals that wind speed and relative humidity are the most influential climatic factors in the phenotypic development of these species. Wind speed appears to promote plant growth by creating an ideal microclimate that reduces soil moisture, while high humidity tends to inhibit this same process. Precipitation and maximum temperature, on the other hand, show minimal influence, indicating that, under high Andean conditions, these variables do not play a key role in modulating the *Polylepis* phenotype. These findings underscore the importance of considering the specific environmental conditions of the populations' origin when evaluating the phenotypic response of species in new environments.

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