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Deciphering Environmental History through Alder Rings: Dendroclimatological Exploration

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ABSTRACT

Tree rings in high mountain forests represent a valuable natural archive for climate reconstructions and understanding the impact of climate change on forest ecosystems. In this context, the dendroclimatic potential of Alnus acuminata (alder) was evaluated by selecting 25 trees from seven localities in the Mantaro Valley. Computational programs such as Image-Pro Plus, COFECHA, ARSTAN, Sigma Plot, and the IAWA Standard List were utilized. Densitometry, performed with the QTRS-01X equipment using X-ray technology, provided ring width and apparent density diagrams. Seven chronological periods were identified, covering a span of 37.5 years, with the years 1960-1966, 1972-1978, and 2004-2010 showing the greatest growth, and the years 1966-1970, 1980-1986, and 1999-2005 showing the least growth. Furthermore, the alder exhibited particular sensitivity to low winter temperatures in the higher altitude sampling areas. Samples from Colpar 12-A* and Paca 10-A* showed wall thicknesses of 4.39 and 4.60 µm, respectively, attributable to low temperatures. Additionally, a significant negative correlation was observed between minimum temperature and ring width index (r= -0.38, p<0.005) from 1972 to 2008. In terms of precipitation and ring width index, a positive correlation (r= 0.26, p<0.005) was evidenced from 1949 to 2009, positively influencing its development. These findings underscore the dendroclimatic potential of the species, contributing to the understanding of climatic history and the prediction of future conditions in development areas.

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INTRODUCTION

Climate change induces variations in global temperatures, even doubling under the 1.5 °C global warming scenario (Cyamweshi *et al*., 2024; Hagemans *et al*., 2022), which in turn impact plant growth; given that, plant development is closely linked to environmental conditions, primarily temperature (Hadad *et al*., 2022; Olmedo *et al*., 2023). Thus, tree growth, as a central component of forest ecosystems (Cyamweshi *et al*., 2021; Pérez *et al*., 2023; Quesada-Román *et al*., 2022), emerges as a highly valuable indicator for gaining a comprehensive understanding of the extensive history of trees and forests (Worbes, 2002). This knowledge is essential for addressing forest dynamics and comprehending environmental changes that have occurred in

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the past (Stajić *et al*., 2020).

Dendrochronology is the study of growth ring variability in tree trunks (Daly, 2024; Lipatkin *et al*., 2023) to gather information on past climatic and ecological events (Portal-Cahuana *et al*., 2023; Requena-Rojas, 2015). Characterizing tree growth rings can provide insights into environmental conditions during their development, primarily related to temperature and precipitation (Zafirov *et al*., 2020). This methodology enables climate reconstruction of the study area over the years (Binda *et al*., 2021; Mitchell *et al*., 2020) in regions where climatic data is scarce or nonexistent (Hadad *et al*., 2022). Additionally, tree growth rings offer a wealth of information on tree growth patterns, species behaviour, tree age, and environmental impacts of tree life cycles, as well as the potential to predict future climate changes and forest dynamics (Muqarrab *et al*., 2023; Worbes, 2002).

The trees of the alder, of *Alnus* genus are distributed across various locations worldwide (Saucedo *et al*., 2020); they have been present in northern Peru since before the Holocene, more than 9000 years ago (Weng *et al*., 2004). They are found in Canada (Maillet *et al*., 2022), Mexico (Franco-ramos *et al*., 2018; Scherrer *et al*., 2021), Ecuador (Armijos *et al*., 2017), Moscú (Lipatkin *et al*., 2023), among others (Saucedo *et al*., 2020). Species of the *Alnus* genus show great potential for dendrochronological studies and are underexplored in this regard (Maillet *et al*., 2022). In a study conducted in Huancayo, the dendrochronological potential of alder was evaluated, revealing a wide spatial distribution range as well as a positive correlation with climatic changes in the Huancayo valley (Requena-Rojas, 2015).

The aim of this study was to assess the dendroclimatic potential, based on trunk ring structure, in seven zones of the Mantaro Valley, encompassing different regional environmental characteristics. This would enable a better understanding of the climatic history of this valley in Peru.

MATERIALS AND METHODS

Study Site

The study was conducted in the eyebrow of the jungle and jungle regions, specifically in the provinces of Chanchamayo and Satipo. These areas encompass various zones including San Pedro de Chunan, Paca, Julcán, Quilcas, Colpar, San Pedro de Saños, and Chupurro, where cross-sectional samples of the Alder species were collected. The selection of these locations was based on the theoretical principles of dendrochronology and was carried out considering the principle of location as a determining factor (Fig. 1).

Weather of the Area

Chanchamayo and Satipo have mountainous topography with elevations ranging from lowlands to higher hills and mountains, resulting in numerous rivers and streams. The provinces have a warm and humid climate for much of the year, with average annual temperatures ranging from 20°C to 26°C. The rainy season from November to May brings constant and heavy precipitation, occasionally leading to floods, while the drier season from June to October sees less rainfall and sunnier conditions. The high rainfall during the rainy season supports a lush tropical jungle environment. Different altitudes within the region experience varied microclimates, influencing temperature and precipitation patterns. Meteorological data from stations such as Huayao, Santa Ana, and Jauja provide information on precipitation and temperature in the Mantaro Valley.

Selection of trees

From the selected tree trunks, cross-sectional samples were extracted, obtaining two samples per tree when the original sections were not suitable for visualizing growth rings. In total, 54

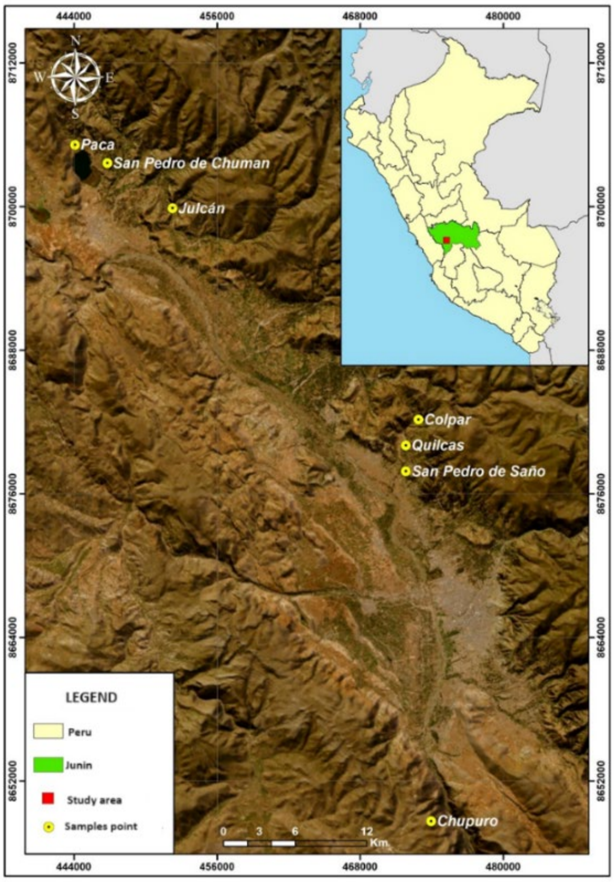

Fig. 1. Location of the study area and sample points in the Mantaro valley.

growth rings from 23 trees of the species in question were collected from the study areas, which were: Chunán (8), Chupuro (7), Colpar (16), Paca (3), Quilcas (12), Saños (5), and Julcán (3).

Sample preparation and annual growth measurements

Cross-sectional trunk samples ranging from 8 to 10 cm were collected, which were polished using a grinder equipped with a No. 36 sandpaper (Hadad *et al*., 2022). Subsequently, an orbital sander was used to polish the transverse plane, starting with wood sandpapers No. 40, 60, 80, 100, and 120 (Olmedo *et al*., 2023), followed by water sandpapers numbered 180, 220, 240, 260, 280, 320, 360, 400, and 600, respectively. After this procedure, radial sections with clearer ring visibility were selected and delineated using a 10X hand lens (Franco-ramos *et al*., 2018), and then scanned at 600 dpi (Björklund *et al*., 2020).

Anatomical characterisation of the wood of alder

Macroscopic characterisation. To collect data, cross-sectional trunk samples were directly observed. Measurements of growth ring widths were conducted using Image Pro-Plus software, following the orientation of the medullary rays in each sample (Björklund *et al*., 2020). Additionally, these measurements were compared with those obtained using the Velmex Inc dendrometer, which has a precision of 0.001 mm (Almonacid *et al*., 2023; Franco-ramos *et al*., 2018; Maillet *et al*., 2022). At a macroscopic level, anatomical characterization was performed by examining the polished samples (slices) (Olmedo *et al*., 2023). Aspects such as color, odor, taste, visibility of growth rings, and wood hardness were considered.

Microscopic characterisation. To conduct the anatomical analysis, 1.5 cm-sided cubes were obtained and properly oriented. These cubes were used to create mounts of the three cutting planes, facilitating the corresponding anatomical analysis (Björklund *et al*., 2020). Additionally, for the wood tissue maceration study, samples were taken from four parts of the original sample. Densitometry analyses of radial samples of Alder were carried out using the QTRS-01X equipment, which employs X-ray technology to measure the ring growth increment in trees (Björklund *et al*., 2020; Rodriguez *et al*., 2015). At the microscopic level, 1.5 cm-sided cubes were prepared from radial samples destined for dendrochronological study, ensuring proper orientation. These cubes were used for anatomical analysis at the microscopic levels, including tangential, transverse, and radial cutting planes (Olmedo *et al*., 2023). Additionally, wood tissue maceration splinters were obtained. Microscopic evaluation was made through microphotographs captured with a microscope equipped with an integrated camera (Björklund *et al*., 2020). Fiber measurements were performed using Image Pro Plus software.

Getting the time series of the growth rings

To measure the width of the growth rings, Image-Pro Plus software was used to analyze previously scanned images. Upon loading the IPWIN32 software, the boundaries of the growth rings previously delineated in the images were clearly visualized. Additionally, the Velmex dendrometer was employed to record measurements of growth ring widths. The resulting data from these analyses were analyzed using COFECHA software, which allowed for the determination of the baseline chronology of the evaluated trunk rings (Semenyak & Dolgova, 2023). These data were standardized using the ARSTAN program (Zafirov *et al*., 2020).

X-ray densitometry analysis

The cross-sectional samples were affixed to wooden mounts to facilitate the cutting process. These sections were cut to a thickness of 1.7 mm using a double circular saw (Björklund *et al*., 2020). After cutting, the cross-sectional samples were arranged on a wooden board and individually weighted to prevent any deformation (Olmedo *et al*., 2023). Subsequently, they were conditioned in climate-controlled chambers at a temperature of 20°C with a relative humidity of 50% until they reached a moisture content of 12%. The radial samples, 1.7 mm thick, were scanned using a densitometer and a QTRS-01X device, from which data were generated to create diagrams of apparent density and growth ring width.

RESULTS AND DISCUSSIONS

Macroscopic description of the rings of alder

The comprehensive macroscopic examination of the cross-sectional slices of alder unveiled a distinctive feature where the growth rings display a slightly darker zone at their boundaries, particularly accentuated in trees from tropical regions (Marcelo-Peña *et al*., 2020). The sapwood and heartwood of the samples generally displayed a pinkish-white color, except for those from Chupuro, where the heartwood appeared brownish. The wood surface had a moderate luster and texture, with grains ranging from straight to diagonal. It was moderately hard and lightweight, making it suitable for construction and various woodworking tasks (Almonacid *et al*., 2023). Some challenges were identified, such as the presence of false rings, merged rings, difficult-to-distinguish ring boundaries, and thin, slightly defined ring boundaries, which were also encountered in another study with alder (Requena-Rojas, 2015), posing a challenge in ring counting (Gautam *et al*., 2020). A study conducted on Brazilian jungle species found that the demarcation of growth rings is identifiable by the presence of initial axial parenchyma with semicircular pores. This feature facilitates the measurement and evaluation of wood density variations within and between growth rings, particularly when employing X-ray densitometry techniques (Tomazello *et al*., 2004). Another study on *Pinus peuce* found that ring visibility was strongly linked to the climatic variability of the study area (Zafirov *et al*., 2020), showing environment impact in ring formation.

Microscopic description of alder

A diffuse porosity arranged in chains of up to 15 cells was found, with diameters showing relative uniformity across the growth rings. In another study conducted in Ecuador, similar anatomical characteristics were also observed (Barrera-Jiménez *et al*., 2018), indicating that despite different geographical locations, this species maintains its anatomical traits. Well-defined growth rings were characterized by the presence of pores, fibers with thicker walls, and radially arranged parenchyma cells, consistent with latewood, an important feature in timber trees like *Cedrela odorat* (Tomazello *et al*., 2004). Early rings showed fibers with relatively open lumens and larger pores, positioned radially in various configurations. These pores appeared solitary or arranged in clusters of different shapes, including oval, rectangular, and triangular, similar to findings in another anatomical study of alder (Armijos *et al*., 2017). The wood displayed scalariform perforation plates with between 10 and 17 bars and a slope between 60 and 70 degrees. These plates could indicate an attack by some pest, which would affect this species in the study area (Vásquez *et al*., 2017).

Mainly apotracheal parenchyma was identified, although paratracheal parenchyma was also found. The wood exhibited clustered rays (Fig. 2) as part of its anatomical feature, similar characteristics were found in another study with alder, in Ecuador, where uniseriate rays, ranging from one to three series, and rays of two different sizes were recorded (Barrera-Jiménez *et al*., 2018).

The analysis of the rings reveals clear boundaries by parenchymal cells between earlywood and latewood, which are also irregular and composed of fibers and pores. However, in another anatomical study of alder, parenchymal tissue was not found (Armijos *et al*., 2017). On the other hand, earlywood fibers are thinner, with diffuse vessels and a wide lumen, which is common in earlywood even in other species, such as *Pinus sylvestris* (Björklund *et al*., 2020) and *Adesmia pinifolia* (Hadad *et al*., 2022). Conversely, latewood features thick-walled fibers flattened radially, with abundant vessels and a darker coloration compared to earlywood (Almonacid *et al*., 2023; Marcelo-Peña *et al*., 2020). The presence of numerous vessels, larger in size than those in earlywood, is also observed, accompanied by a band of lignified fibrous structures with thicker cell walls at the end of the latewood ring (Marcelo-Peña *et al*., 2020).

Anatomical characterisation of the alder ring's

Alder is characterized by having a wall thickness of 4.72 µm. Similarly, samples from Colpar 12-A and Paca 10-A* show thicknesses of 4.39 and 4.60 µm, respectively, indicating a trend to be lower than the other samples. This phenomenon could be attributed to the sensitivity to low temperatures of these two samples. Latewood with thicker-walled fibers and rectangular shape, with the shorter side being radial. Presence of acicular traces, polygonal inter-vascular punctuations. Additionally, in the trunk growth characteristics, well-defined and poorly defined rings are observed (Fig. 3). This is possible, given that in another study conducted in Ecuador, in the heart of the tropics, the rings of alder were not clearly identified (Armijos *et al*., 2017), while in another study carried out in Peru (Requena-Rojas, 2015), the rings of this species were identified, which shows that markedly differentiated rings are associated with climatic variation, while in tropical zones the identification of rings in the trunk of tree species is more complicated (Tomazello *et al*., 2004).

The anatomical properties of alder fibers exhibit, on average, a wall thickness of 4.72 µm. Additionally, samples originating from Colpar 12-A* and Paca 16-B* show wall thicknesses of 4.39 and 4.60 µm, possibly attributable to susceptibility to low temperatures affecting species development (Gautam *et al*., 2020; Weng *et al*., 2004). Samples from Chunán show better

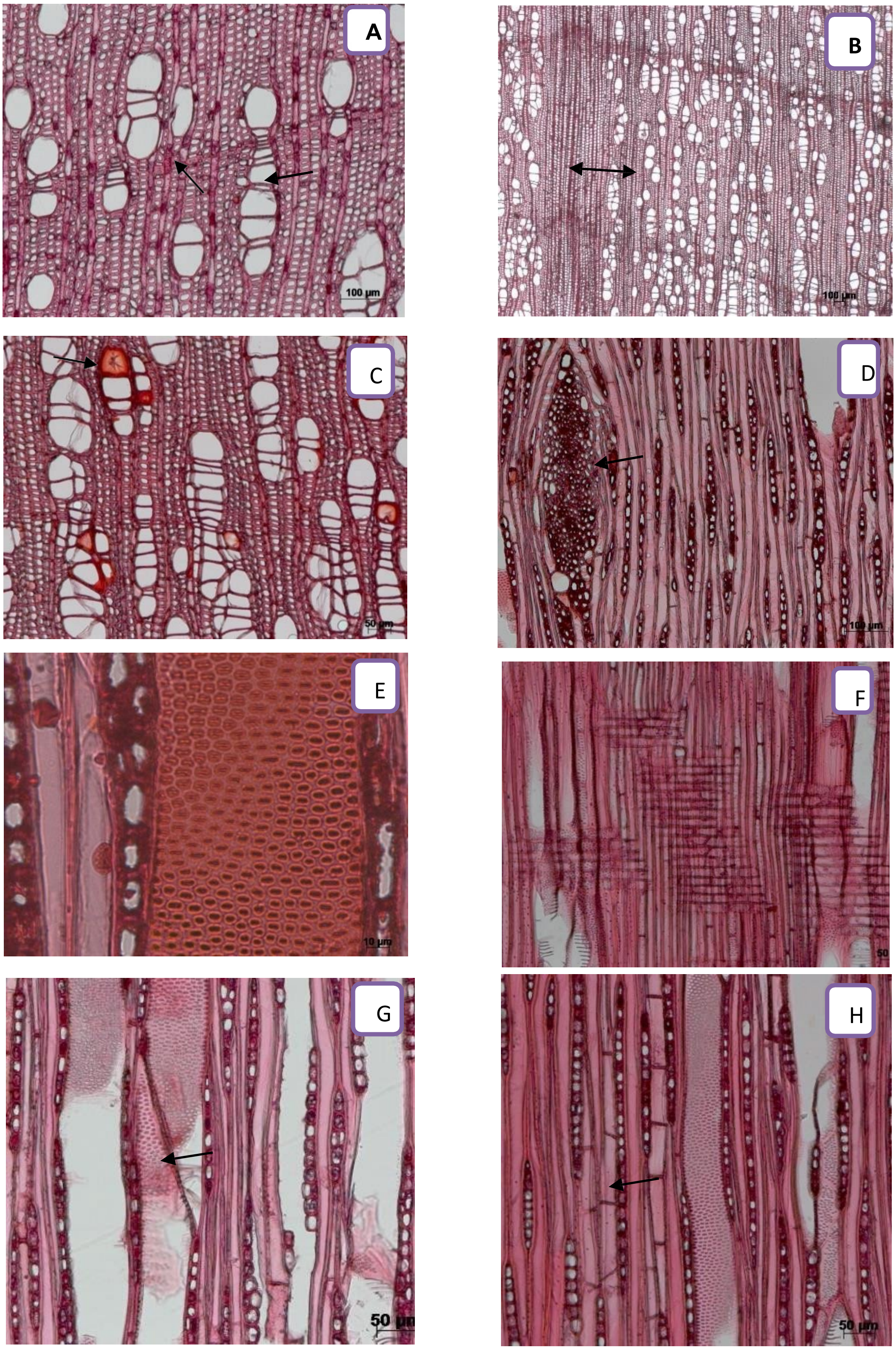

Fig. 2. Transverse sections of alder. A: Growth ring boundary with diffuse porosity arranged in chains. B: Clustered rays. C: Presence of tyloses. D: Acicular tracheids. E: Intervascular pits arranged in opposite and alternate manner. F: Rays with similar appearance. G: Plate with highly inclined angled perforation. H: Apotracheal axial parenchyma with ray width between 1-2 cells.

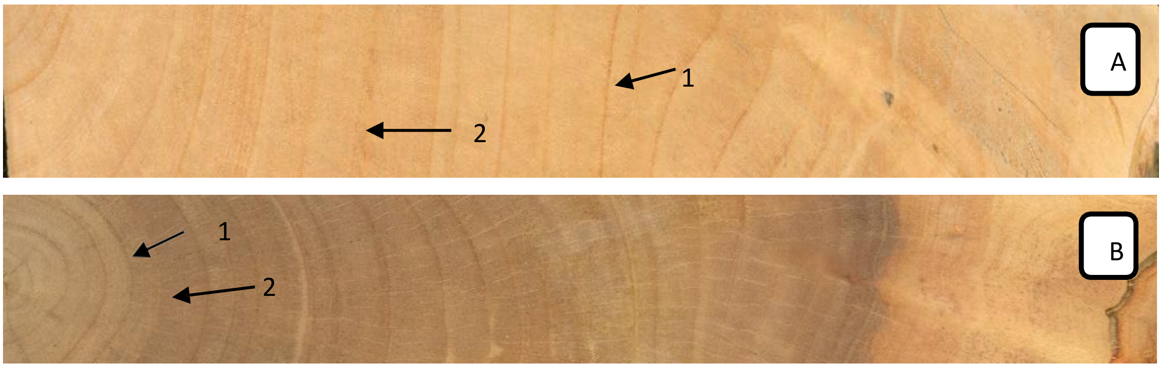

Fig. 3. Attributes of growth rings in a sample where there is no distinction between sapwood and heartwood (A), and another sample that shows a difference (B). The arrows indicate the ring boundaries; 1: clearly defined boundary. 2: ring with weak definition.

Table 1. Anatomical Characteristics of Fibers

Samples	**Average fibre dimensions (µm)**			
Codes	F. L.	F.D.	L.D.	W.T.
Quilcas 17-I-B	1003.99	22.79	14.76	4.01
Quilcas 17-II-B	918.66	25.02	16.09	4.47
Chunán 20-B	816.71	31.86	22.04	4.91
Chunán 4	1071.79	29.95	20.92	4.51
Chupuro 4-A	994.76	28.04	18.03	5.01
Chupuro 5-A	1057.16	29.28	18.49	5.39
Colpar 10-A	990.87	26.49	17.07	4.71
Colpar 12-A*	1039.27	25.73	16.96	4.39
Paca 16-B*	1032.29	24.62	15.43	4.60
Saños 18-A	921.96	24.81	14.32	5.24
Mean	984.746	26.859	17.411	4.724
Standar Dev.	78.2498	2.8359	2.5355	0.4181

Where: F.L. = Fibre length. F.D. = Fibre diameter. L. D. = Lumen diameter. W.T. = Wall thickness. *= Samples more sensitive to low T°.

fiber length, fiber diameter, and lumen diameter values, indicating greater trunk development in individuals from this area. Meanwhile, samples from Chupurro and Saños show greater wall thickness, also indicating suitable environmental conditions for their development, as these anatomical parameters are good indicators of these conditions (Björklund *et al.*, 2020).

The presence of fibers with varying lengths and diameters is observed (Table 1), whose variation could be explained by the environmental diversity of each region. Similarly, in a comprehensive study on the anatomical characteristics of the growth zones of 41 tree species in the state of Sao Paulo, Brazil, it is generally noted that the growth zones of nine species are composed of radially compressed fibers with thick walls and narrow lumens in the latewood phase (Tomazello *et al.*, 2004). The anatomical pattern of alder exhibits pronounced irregularity, with a clear distinction in wood development (earlywood and latewood). The composition of

Table 2. Descriptive statistical analysis of the time series using the COFECHA technique

Descriptive statistics of the master series 1949 - 2012	
Number of series	13
Average run length	37.5 years
Average sensitivity	0.452
Standard deviation	3.210
Data time period	1949 – 2012
Optimal common range	From 1981 2001 (21 years) 12 series
Number of rings	487

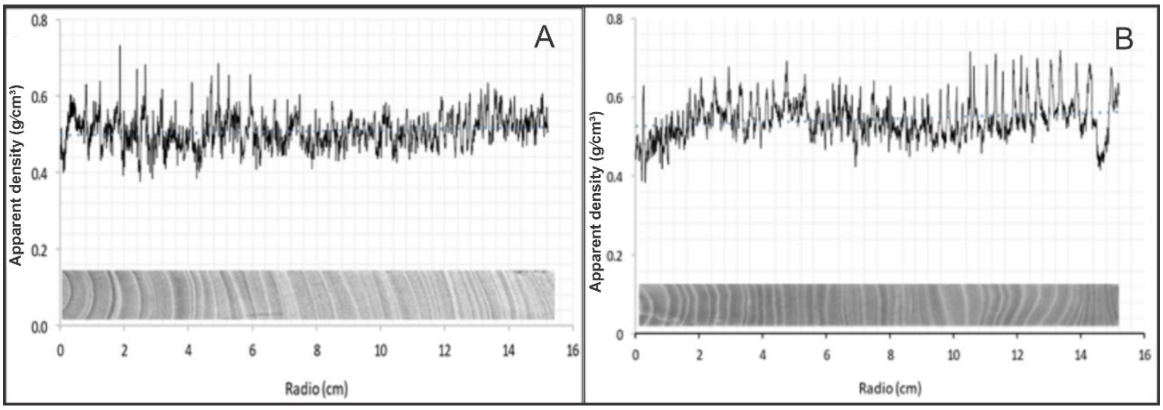

Fig 4. Bulk density of alder. A) Sample Chunán 20. B) Sample Colpar 10-A.

the latewood is characterized by fibers with thick walls and radially flattened, contrasting with the earlywood which displays fibers with thin walls and wide lumens (Björklund *et al*., 2020), a feature also observed in other forest species in Peru (Marcelo-Peña *et al*., 2020), such as *Adesmia apinifolia* (Hadad *et al*., 2022), indicating this as a common characteristic among numerous forest species.

X-ray densitometry for alder

Higher values of apparent density in the radial profile are characterized by tones closer to white (Fig. 4), a feature also observed in *Pinus taeda* (Rodriguez *et al*., 2015). Furthermore, these differences enable the identification of earlywood and latewood density, thereby contributing to delineating tree ring growth (Björklund *et al*., 2020; Rodriguez *et al*., 2015). In another study with *Pinus sylvestris*, an inverse correlation was found between earlywood density, showing an almost opposite response to temperature compared to ring width (Björklund *et al*., 2020). Thus, demonstrating how this methodology enhances our understanding of dendrochronological studies.

Dendrochronological potential of alder

The findings reveal the presence of seven chronological features, covering a period of 37.5 years, from 1949 to 2012, with a total of 487 rings recorded (Table 2). Additionally, in a nearby area to the location of this study, a chronology of 46 years was identified (Requena-Rojas, 2015), exceeding the temporal extent found in our research. These results indicate the existence

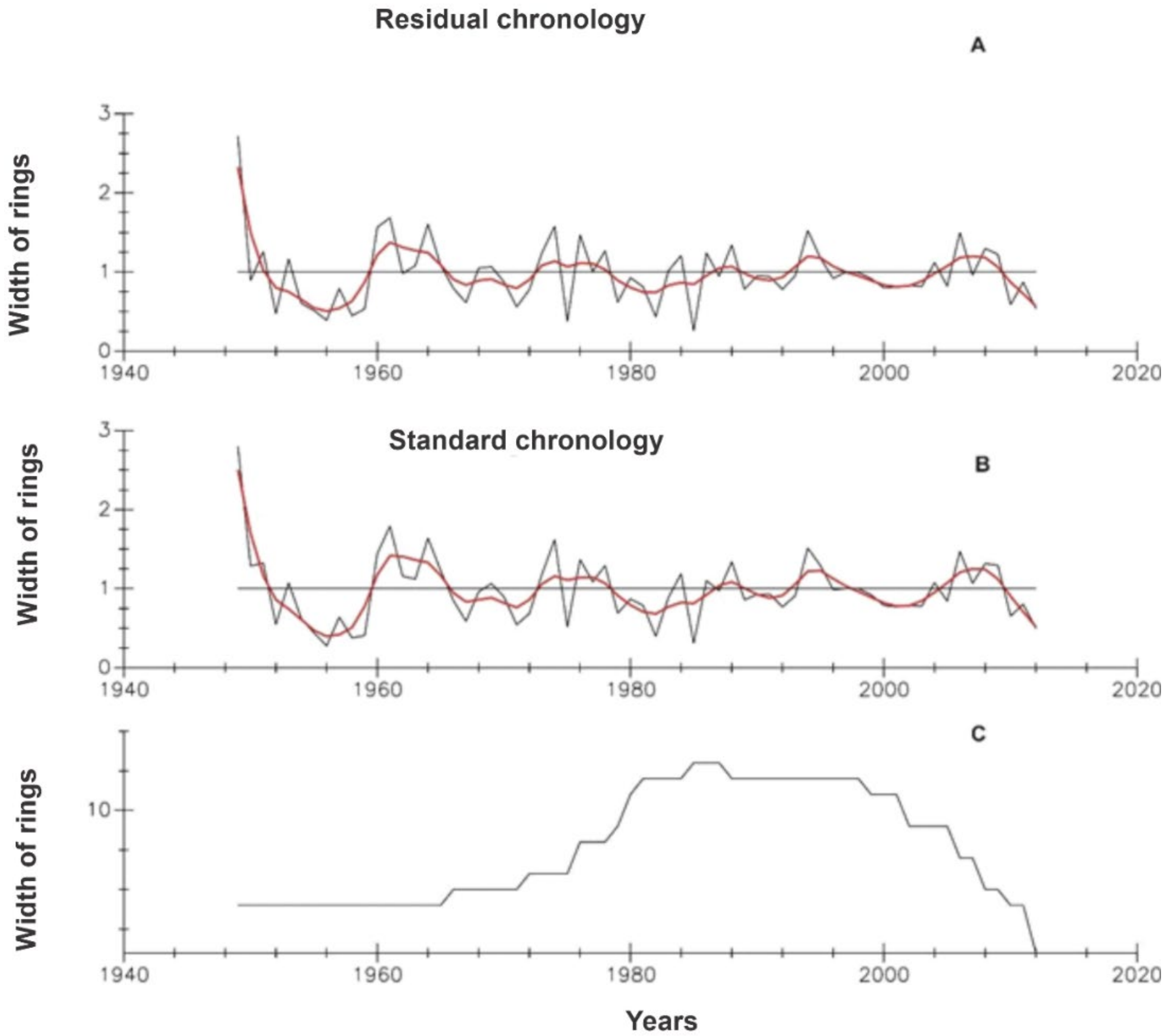

Fig. 5. Residual chronology (A), standard (B) and number of growth series (C) of alder for the Mantaro Valley.

of a considerable population of individuals of this species in the studied valley. Another study even demonstrated that, during the Holocene, the population of alder was greater than the one existing today, attributing this expansion to better environmental conditions (Weng *et al*., 2004).

There are topographic, physiographic, and distance variations between the sampling points in the Mantaro Valley, resulting in noticeable fluctuations in air temperature, particularly the minimum, primarily influenced by topography. This results in cold conditions year-round in areas above 4000 meters above sea level. Additionally, precipitation also exhibits significant variations in the region ((Requena-Rojas, 2015), which could have impacted these findings.

Fig. 5 illustrates the chronologies of the ring width index of alder, presented in both residual (Fig. 5A) and standard forms (Fig. 5B), elucidating the preservation of the low-frequency signal in the former and the preservation of the high-frequency signal in the latter. Distinct periods of growth above and below the mean are discernible, with the years 1960-1966, 1972-1978, and 2004-2010 representing peaks of growth, and the years 1966-1970, 1980-1986, and 1999-2005 signifying troughs. Fig. 5C illustrates the number of series within the chronology, revealing that from 1965 onwards, there are more than 5 series, thereby optimizing the chronology in terms of repetitions. The chronologies depicted in the figures demonstrate that 1964 represents the peak year, while 1985 represents the nadir of log growth.

The temporal sequence of ring expansion in the Jauja region, encompassing samples from

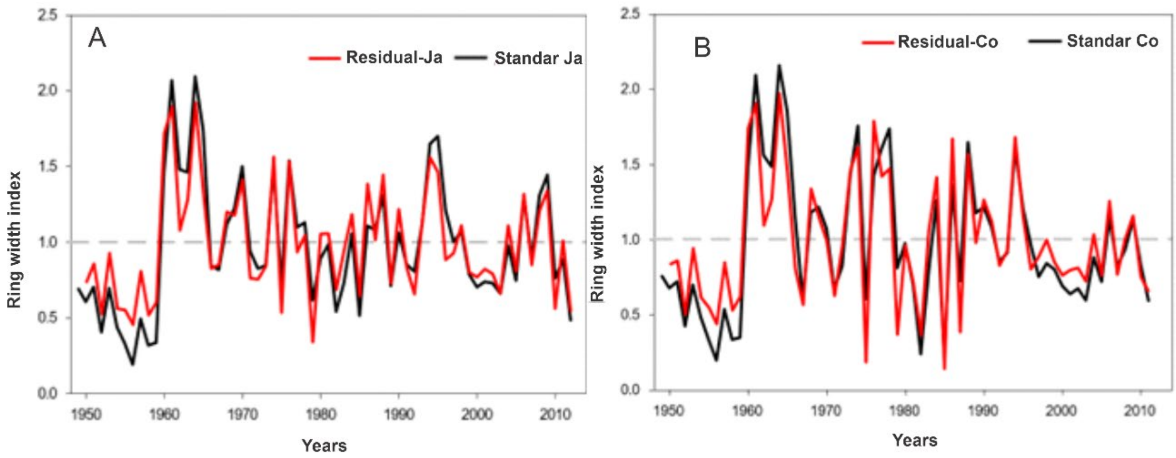

Fig. 6. A) Ring width chronology of alder for Jauja. B) Alder ring width chronology for Colpar.

the Julcán, Paca, and Chunan areas from 1949 to 2012, is illustrated (Fig. 6A). This sequence comprises 5 groups, each consisting of 4 trees, with the years between 1960 and 1965 highlighted as the years of maximum growth and between 1999 and 2003 as the years of lowest growth. Additionally, the ring width index in residual form is depicted by the red line, while the black line represents the standard version (Fig. 6B).

The comparisons spanned from January of the previous year to December of the study year, with the letter "p" added to each month for identification purposes; significance of correlations is indicated by red lines. According to the analysis, the growth of alder is positively correlated with the monthly precipitation of both January of the previous and current year ($r=0.35$, $p<0.05$) (Fig. 7A). Additionally, a positive correlation is observed with September of the previous year, and a negative correlation with the minimum temperature in May. The mean temperature in winter and spring of the current year positively influences radial growth (Fig. 7). On the other hand, it is noted that the radial growth of alder exhibits a positive relationship with the month of September of the previous year. Simultaneously, a negative correlation is observed with the monthly minimum temperature during winter, with this pattern being particularly notable in May (Fig. 7C). Furthermore, a significant and positive influence of the mean temperature during the winter and spring seasons of the current year is evidenced in the radial growth of the trees (Fig. 7D).

These findings highlight the complex interaction between the growth of alder and climatic conditions, providing a more detailed perspective of the factors affecting its development over time, primarily temperature and precipitation, which are negatively correlated with minimum temperatures and precipitation and positively correlated with mean temperatures and precipitation (Lipatkin *et al.*, 2023; Stajić *et al.*, 2020; Wilson *et al.*, 2021). Similarly, another study showed that the climatology of the Mantaro Valley was strongly influenced by topography, with minimum temperatures occurring in winter, particularly in June and July, which also affected the development of alder (Requena-Rojas, 2015). Furthermore, another study highlighted the population expansion of alder in favourable environmental conditions, while decline was associated with temperature decrease (Weng *et al.*, 2004). These variables have the most significant influence on the development of alder, with differentiated effects throughout the months of the year, as observed in other forest species as well (Gautam *et al.*, 2020).

Regarding minimum temperature and ring width index, a significant negative correlation ($r= -0.38$, $p<0.005$) is observed from 1972 to 2008 (Fig. 8 A). In this context, a study conducted in the summer in Finland found that ring width was positively related to July temperatures,

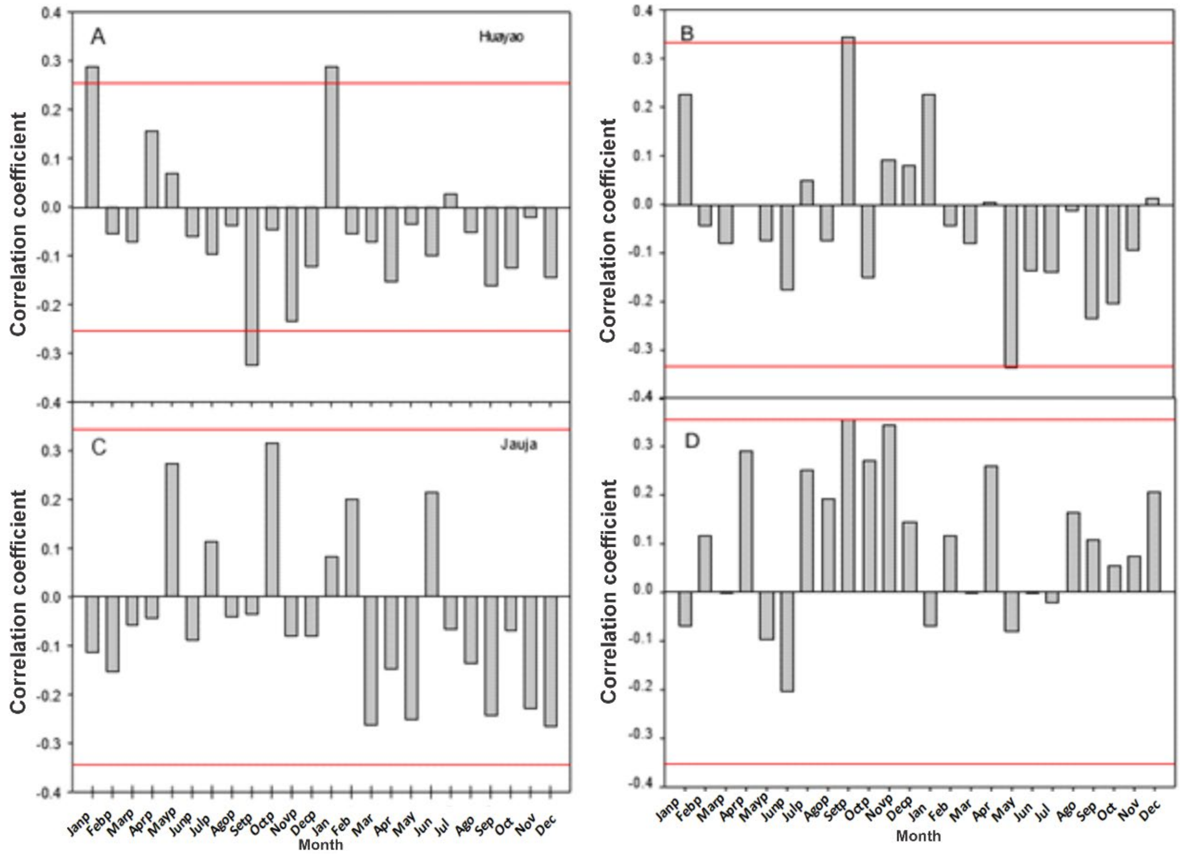

Fig. 7. Correlations of the ring width chronology of alder with: A) monthly precipitation of Huayao, B) monthly precipitation of Jauja, C) monthly minimum temperature of Huayao, and D) mean temperature of Huayao.

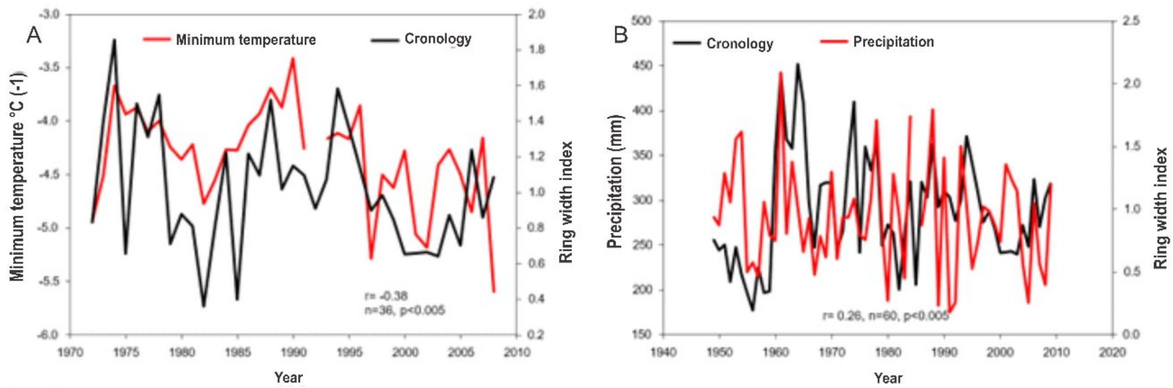

Fig. 8. A) Contrast of the radial growth chronology and the Huayao monthly minimum temperature series (1972-2008) and B) with the Huayao quarterly precipitation series (1949-2009).

indicating that summer temperatures influence wider ring widths (Björklund *et al*., 2020). Similarly, another study conducted on *Pinus peuce* found positive relationships between ring widths and high summer temperatures, while the relationship was negative between winter minimum temperatures and ring width (Zafirov *et al*., 2020). This clarifies that lower minimum temperatures result in narrower ring widths, while higher temperatures lead to wider ring widths.

In relation to precipitation and the ring width index, a positive correlation ($r= 0.26$, $p<0.005$) is evident, spanning the period from 1949 to 2009 (Fig. 8 B). In a dendroclimatic study conducted on *Adesmia pinifolia* in the pre-Andean foothills, it was found that this species correlates positively with precipitation more than temperature (Hadad *et al*., 2022). This indicates that precipitation is an important factor for plants that develop in the Peruvian Andes.

CONCLUSIONS

The research findings indicate that alder exhibits well-defined annual growth rings, with some displaying fainter markings. Variations in ring width are influenced by environmental factors such as monthly and quarterly precipitation, as well as minimum and mean temperatures. Macroscopic analysis of alder reveals growth rings with a slightly darker zone at their boundaries, showing particular sensitivity to low winter temperatures in higher altitude areas. Microscopic examination highlights diffuse porosity, fibres with thicker walls in latewood, and the presence of both apotracheal and paratracheal parenchyma, indicating consistent anatomical characteristics despite differing geographical locations. X-ray densitometry reveals differences in apparent density between earlywood and latewood, aiding in the delineation of growth rings and providing valuable information for dendrochronology. The ring width chronology spans 37.5 years, with notable growth periods between 1972-1978 and 2004-2010, and periods of reduced growth between 1966-1970, 1980-1986, and 1999-2005. Earlywood density correlates positively with monthly precipitation from both the previous and current January, while winter and spring mean temperatures positively influence radial growth. Dendrochronology reveals a substantial population of alder in the valley, with a chronology surpassing previous studies, indicating the species' adaptability to varying environmental conditions. These findings contribute to understanding climatic history and predicting future conditions in development areas, underscoring the dendroclimatic potential of alder in Andean forests.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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