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Analysis of growth rings of *Terminalia oblonga*: Chronology and its relationship with climatic factors in an Amazonian flooded forest in Peru

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A R T I C L E I N F O

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A B S T R A C T

Dendrochronology has proven fundamental for studying climate change in tropical forests. This study assessed the dendrochronological potential of *Terminalia oblonga*, a common species in the eastern Amazon of Peru, and its response to local and large-scale climatic and hydrological variations. A 94-year chronology (1929–2022) was constructed through the analysis of growth rings from 16 trees, correlated with local climatic variables (precipitation and temperature) and oceanic atmospheric circulation indices such as the Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO), and Western Hemisphere Warm Pool (WHWP). A negative correlation was observed between precipitation and growth, particularly in the months of February, August, September, October, and November, suggesting that excess water may inhibit the species' growth. In contrast, temperature showed a significant positive correlation throughout most of the year, indicating that higher temperatures favor the growth of *T. oblonga*. Significant correlations were also found between the growth of *T. oblonga* and the AMO and WHWP indices, particularly between July and September, suggesting a considerable influence of these atmospheric patterns. Additionally, sea surface temperature (SST) was significantly and positively correlated with the species' growth, especially in the tropical Atlantic. This indicates that warmer temperatures promote the development of *T. oblonga*. The El Niño-Southern Oscillation (ENSO) phenomenon was analyzed using four indices: El Niño 1 + 2, El Niño 3, El Niño 3.4, and El Niño 4. The El Niño 1 + 2 index exhibited the strongest correlation with *T. oblonga* growth, suggesting a more direct impact of the eastern Pacific region on local climate conditions. In contrast, the influence of PDO and TSA was less consistent over time, and excessive precipitation had a negative effect. These findings confirm the potential of *T. oblonga* as an indicator of climate change and highlight the importance of continuing research on the interaction between climate change and forest dynamics in the Amazon. This study provides a solid foundation for future research on sustainable forest management and climate reconstruction in the region.

Introduction

Dendrochronology, a field that has significantly evolved in recent decades, has expanded into tropical forests, revealing unique growth patterns and specific challenges within these ecosystems. In more than 20 tropical countries, as noted by Worbes (2002), the presence of annual rings reflects tree growth synchronized with extreme climatic events, such as intense droughts and prolonged floods (Zuidema et al., 2020). This approach has enabled a deeper understanding of the influence of phenomena such as El Niño on tree growth and the longevity of broadleaf species in tropical lowlands, contributing to the knowledge of the dynamics of these complex ecosystems (Locosselli et al., 2020;

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Portal-Cahuana et al., 2023a).

The study of tropical trees is essential for forest conservation and sustainable management, as highlighted by Rozendaal and Zuidema (2011). Despite the challenges associated with weaker seasonal marking in the tropics, the use of techniques such as dendrometric measurements, cambial wounding, and radiocarbon dating has considerably advanced the understanding of the relationship between climate and tree growth. Brienen et al. (2016) demonstrated that in the tropics, ring formation is more closely linked to seasonal variations in precipitation or flooding regimes than to temperature. Although the sensitivity of tropical trees to climate is moderate, growth ring studies provide crucial information on the effects of climate change in these forests (Roquette et al., 2023).

Marcelo-Peña et al. (2020) and Schöngart et al. (2017) have reinforced the relevance of growth rings for understanding forest ecology and dynamics, as well as their application in the sustainable management of forest resources. In Peru, recent studies such as those by Portal-Cahuana et al. (2023a) have demonstrated how growth ring chronologies in tropical trees can reconstruct the environmental history of the Neotropics, highlighting the Amazon as a natural laboratory due to its high tree diversity. Additionally, research on specific species, such as Zanthoxylum rhoifolium, has emphasized its potential for dendrochronological studies in the Peruvian Amazon (Portal-Cahuana et al., 2023b), reinforcing the need to assess additional species with suitable anatomical characteristics for climate studies.

The relationship between phylogeny and the distinctiveness of growth rings, discussed by Marcelo-Peña et al. (2020), suggests a diversity of responses among deciduous and evergreen species to environmental conditions. Bauer et al. (2020) complement this view by analyzing leaf phenological patterns and growth rings in subtropical forests, identifying species with well-defined anatomical boundaries. In the central Amazon of Peru, Beltrán and Valencia (2013) have explored the challenges in the anatomical characterization of growth rings, emphasizing the importance of understanding variability in cellular dimensions to infer the annual formation of rings.

Groenendijk et al. (2014) have evaluated the potential of growth rings in tropical tree species under high-humidity conditions. These studies have demonstrated that even in the absence of pronounced seasonal variation, it is possible to obtain accurate data on tree growth. This underscores the importance of investigating species such as *Terminalia oblonga* in the eastern Amazon of Peru, both to expand knowledge on tropical dendrochronology and to provide valuable information for sustainable forest management and understanding how trees respond to climate change in these ecosystems.

In this context, terra firme forests, which exhibit greater species diversity compared to flooded forests (Myster, 2015), face unique challenges. Annual floods, which can raise water levels by more than 10 m, submerge seedlings and trees for several months, altering the availability of nutrients, oxygen, and toxins, and creating conditions that demand specific adaptations (Parolin et al., 2004). Understanding how these processes impact species such as *Terminalia oblonga* is crucial, especially in the face of current climatic changes affecting tropical forest dynamics (Berthelot et al., 2015; Roquette et al., 2023).

Terminalia oblonga is a widely distributed species in the tropics of Central and South America (Ribeiro et al., 2022). In Peru, it is found at altitudes ranging from 0 to 3000 m above sea level, covering the departments of Amazonas, Huánuco, Junín, Loreto, Madre de Dios, San Martín, and Ucayali. Commonly known as "yacushapana," this species holds commercial importance and predominantly develops in the floodplain forests of the Peruvian Amazon (Baluarte-Vásquez and Álvarez-Gonzales, 2015).

The objective of this research was to assess the potential of *T. oblonga* for climate reconstruction and climate variability prediction in the eastern Amazon of Peru, focusing on how the species' growth responds to climatic and hydrological fluctuations. In this study, we analyzed the relationships between tree growth and local meteorological variables, such as precipitation and temperature, as well as its connection with large-scale atmospheric circulation in the Pacific and Atlantic Oceans. We hypothesized that (1) the growth of *T. oblonga* is influenced by seasonal patterns and changes in local climatic conditions, and (2) there are teleconnections between the growth of *T. oblonga* and large-scale oceanic atmospheric circulations.

Material and methods

Study area

We sampled trees in the southeastern Amazon of Peru, specifically in the department of Madre de Dios, a region of high biodiversity located at the tri-border area with Brazil and Bolivia (Foster et al., 1994; Dominguez-Salcedo and Portal-Cahuana, 2024). The study was conducted in a low terrace forest subject to seasonal flooding, characterized by high aquatic biodiversity, predictable hydrological regimes, and a rich offer of temporary habitats (Martin-Smith, 2004). These floodplain forests typically exhibit lower tree species richness and diversity compared to non-flooded forests (Myster, 2015).

The study area is located on the private property of Mr. Igidio Chávez Cachique, in the Rompeolas sector, approximately 20 mins by boat downstream. The site is georeferenced at $-12°56'62.03''$S, $-69°21'50.73''$W (Fig. 1). The climate of the region is characterized by two well-defined seasons: the rainy season from November to May, and the dry season from June to August, with an annual average temperature of 25 °C and average precipitation of 2441 mm (Araujo et al., 2011). These climatic conditions drive the annual flood cycles, which play a crucial role in shaping the forest structure and tree growth dynamics.

The flooding period typically extends from November to May, peaking between January and March, when water levels can rise by more than 10 m, submerging large portions of the floodplain for weeks or months (Parolin et al., 2004; Schöngart et al., 2005). These extreme hydrological conditions create an alternating pattern of cambial dormancy during submersion and active growth following water retreat, leading to the formation of distinct and well-defined annual growth rings (Schöngart et al., 2002; Dezzeo et al., 2003). As a result, flood-adapted species such as *T. oblonga* serve as valuable indicators of hydroclimatic variability, making them ideal candidates for dendrochronological studies.

Species selection

To construct a dendrochronological chronology in the seasonally flooded low terrace forest, 20 tree species were initially evaluated based on their growth rings. The selection was based on abundance in the study area, clear anatomical ring boundaries, ecological importance, and previous dendrochronological potential reported in the literature (Marcelo-Peña et al., 2020; Portal-Cahuana et al., 2023a).

Among the evaluated species, *Terminalia oblonga* (Ruiz & Pav.) Steud. (Combretaceae family) was selected as the most promising due to several factors. First, it was one of the most abundant species in the study area, ensuring an adequate sample size for chronology development. Second, *T. oblonga* exhibited well-defined growth rings, characterized by a marginal parenchyma line and changes in fiber wall thickness, which facilitates accurate ring identification under both macroscopic and microscopic analysis (Schöngart et al., 2017; Marcelo-Peña et al., 2020).

Additionally, *T. oblonga* was one of the top three species with the highest dendrochronological potential among the 20 species analyzed in Ranilla-Huamantuco et al. (2025), due to its distinct ring boundaries and a combination of fiber wall thickening and marginal parenchyma. This study found that only 15% of the species exhibited highly distinct growth rings, placing *T. oblonga* among the most suitable for dendrochronology in the Peruvian Amazon.

Moreover, *T. oblonga* is highly adapted to seasonally flooded

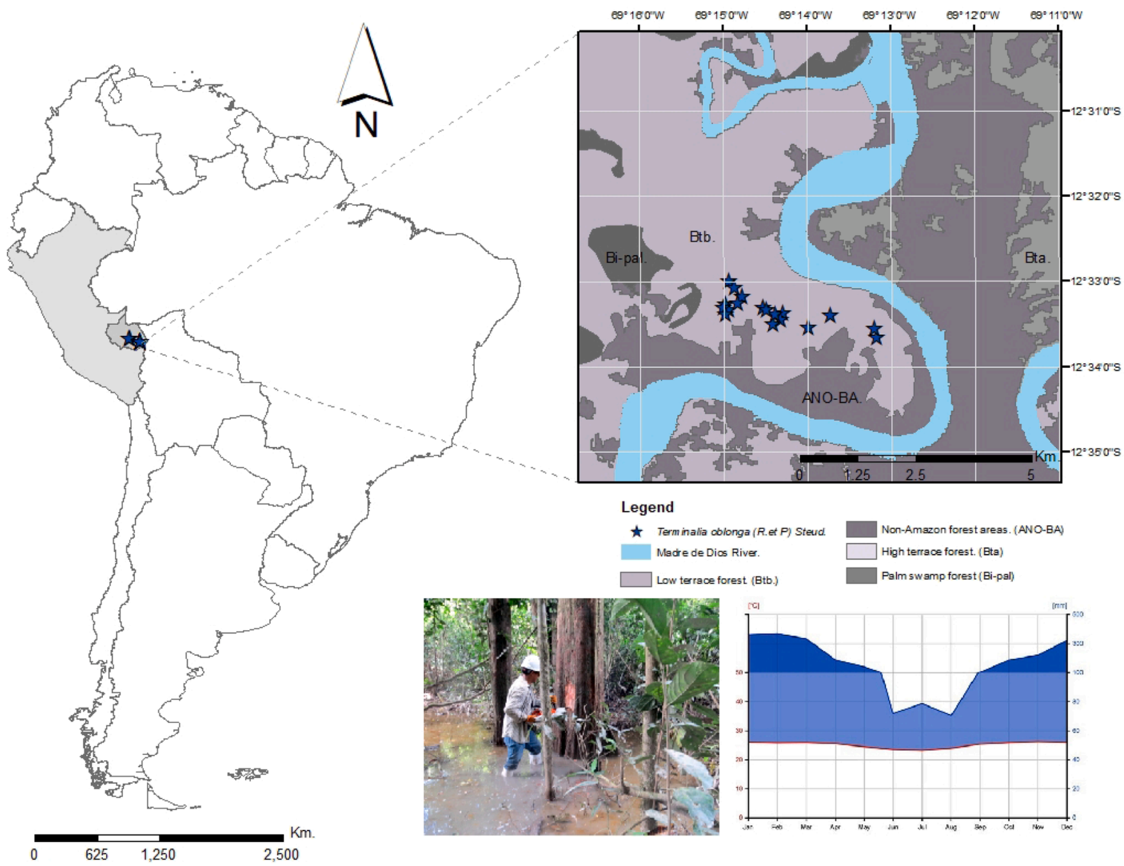

Fig. 1. Location of the study site in the Madre de Dios department, in southeastern Peru, within the seasonally flooded low terrace forest. The blue stars indicate the location of the sampled trees. Additionally, a climate diagram for the period 1993–2022 (Zepner et al., 2020) is presented for the study area: the red line represents the mean monthly temperature, the blue line shows the average precipitation, the light blue area indicates the rainy season, while the dark blue area highlights periods with precipitation exceeding 100 mm. An illustrative image of the study site and the non-destructive sampling process is also included.

environments, where its growth is strongly influenced by annual hydrological cycles. This characteristic makes it an ideal candidate for dendroclimatic studies, as it allows for the assessment of tree response to variations in precipitation, flooding, and temperature (Ranilla-Huamantuco et al., 2025).

Previous studies have confirmed the dendrochronological potential of closely related species, such as *T. amazonica, T. catappa, T. guyanensis, T. quintalata*, and *T. superba*, all of which exhibit clear and measurable annual rings (Brienen et al., 2016; Marcelo-Peña et al., 2020). However, no long-term chronologies had been previously established for *T. oblonga* in the Peruvian Amazon, making this study an important contribution to the field of tropical dendrochronology.

Dendrochronological analysis

Samples of *T. oblonga* were collected through convenience sampling (Otzen and Manterola, 2017) by selecting trees with different diameters at breast height ranging from 22 to 72 cm, with straight trunks, free of decay or poor phytosanitary condition, and with complete canopies, etc. A gasoline-powered motorized drill (Stihl BT45) with a hollow metal bit of approximately 15 mm in diameter was used for non-destructive samples (cores) (Aragão et al., 2022; Marcelo-Peña et al., 2019), and a Stihl chainsaw was used for destructive samples (discs). Four radial samples were collected per individual. These samples had varying lengths from the bark to the pith, depending on the diameter of the individual. Sixteen individuals were sampled (14 with the non-destructive method and 2 with the destructive method). Botanical samples were collected from all trees and identified in the MOL herbarium of the National Agrarian University La Molina.

The collected samples were placed on wooden supports and secured with twine. If fragmented, they were carefully assembled before drying at room temperature, which prevented distortions and potential pathogen attacks. Subsequently, the cross-sections were identified, adhered with synthetic glue, and fixed to the wooden supports using twine and adhesive tape. The samples were then sanded with sandpapers of grits ranging from 80 to 1000, allowing for proper visualization of the growth ring boundaries using a hand lens and stereomicroscope (Islam et al., 2018; Schöngart et al., 2004). Finally, samples from the discs were selected for microscopic characterization of the growth ring boundary anatomy (cf. Aragão et al., 2019; Marcelo-Peña et al., 2019).

The samples were examined using a stereomicroscope to characterize, visualize, and delineate the growth ring boundaries in the samples. Subsequently, the wood cross-sections were scanned at a resolution of 1200 dpi using an EPSON V1200 scanner in ".tif" format. The widths of the growth rings from the four radii per tree were measured with an accuracy of 0.01 mm, using Cybis CooRecorder and CDendro version 7.8 software (Larsson, 2014). A statistical quality control of the cross-dating was then performed with the COFECHA software (Holmes, 1983), and finally, the chronology was constructed using R software along with the dplR and ggplot2 packages.

Teleconnections and climatic indices

Teleconnections refer to large-scale climatic interactions that link meteorological phenomena occurring in distant geographical areas, influencing temperature, precipitation, and hydrological cycles in the Amazon Basin (Schöngart et al., 2004; Marengo et al., 2021). These climate patterns drive regional climate variability, affecting tree growth by altering moisture availability, flooding cycles, and temperature extremes.

This study analyzed the impact of several major teleconnection indices on *T. oblonga* growth. The Atlantic Multidecadal Oscillation (AMO) is a long-term oscillation in North Atlantic sea surface temperatures, which modulates precipitation in the Amazon (Marengo et al., 2021). The Pacific Decadal Oscillation (PDO) is a multi-decadal pattern of sea surface temperature anomalies in the North Pacific, influencing tropical rainfall patterns (Brienen et al., 2016). The Western Hemisphere Warm Pool (WHWP) represents a thermal anomaly in the Caribbean and tropical Atlantic, associated with changes in moisture transport and atmospheric circulation affecting South America (Marengo et al., 2021). The Tropical Southern Atlantic (TSA) is a sea surface temperature variability pattern in the South Atlantic, which impacts precipitation regimes in the Amazon (Schöngart et al., 2004).

To analyze the influence of large-scale oceanic-atmospheric circulation on *T. oblonga* growth, we examined four El Niño-Southern Oscillation (ENSO) indices, each representing different regions of the equatorial Pacific: El Niño 1 + 2 (0°−10°S, 90°−80°W): Measures sea surface temperature (SST) anomalies in the easternmost Pacific, with strong influence on rainfall patterns along the western Amazon. El Niño 3 (5°N-5°S, 150°W-90°W): Captures SST variations in the central Pacific, often associated with Amazon drought intensity. El Niño 3.4 (5°N-5°S, 170°W-120°W): The most commonly used ENSO index, integrating both eastern and central Pacific SST anomalies, serving as the primary indicator for defining El Niño or La Niña events. El Niño 4 (5°N-5°S, 160°E-150°W): Represents western Pacific warming, which can moderate or amplify El Niño impacts on the Amazon Basin. These indices were obtained from the NOAA Climate Prediction Center (https://psl.noaa.gov/data/climateindices/list/). Pearson correlation coefficients were calculated between the ring-width index (RWI) and each ENSO index to assess their impact on tree growth.

For statistical analysis, linear regressions were performed between RWI and each ENSO index, covering the period from November of the previous year to June of the current year, to evaluate the lagged effects of ENSO variability on tree-ring formation. Regression equations, R^2 values, and statistical significance levels (p-values) were computed to quantify the strength of these relationships. The density plots above each regression (Fig. 7) illustrate the distribution of ENSO index values, with vertical dashed lines indicating the mean SST anomaly for each dataset.

To analyze the relationship between *T. oblonga* growth and large-scale climate variability, monthly sea surface temperature (SST) anomalies were examined for the tropical Atlantic and Pacific Oceans. Data from 1960 to 2022 were obtained from the KNMI Climate Explorer (http://climexp.knmi.nl/) (Trouet and Van Oldenborgh, 2013), while historical ENSO index data were sourced from the NOAA Climate Prediction Center (https://psl.noaa.gov/data/climateindices/list/).

Climate anomaly maps were generated to identify positive and negative SST deviations, where warm colors (yellow, orange, red) indicate positive temperature anomalies, and cool colors (blue) represent negative anomalies. These SST variations were analyzed seasonally (March-May and November-May) to assess their impact on precipitation and tree growth patterns in the Amazon.

To quantify the influence of SST anomalies on *T. oblonga* growth, Pearson correlation coefficients were calculated between the ring-width index (RWI) and SST anomalies across different oceanic regions. The correlations were computed using the KNMI Climate Explorer, allowing for a spatial assessment of climate-growth relationships and identifying key teleconnections affecting Amazonian forest dynamics.

Results

Marking of growth rings in Terminalia oblonga

The growth rings of *Terminalia oblonga* are easily visible to the naked eye, which is a crucial aspect of dendrochronological studies. These rings are primarily delineated by notable changes in fiber wall thickness, making them distinctly recognizable. Additionally, a fine marginal parenchyma line is observed, typically composed of one or two cells in width, which contributes to the clear definition of each annual ring (Fig. 2). Annual flooding in areas where *T. oblonga* grows has a profound impact on the formation of growth rings. These conditions lead to an alternation between periods of slowed growth during flooding and accelerated growth following the retreat of the waters.

Chronology and synchronization of growth rings

Visual synchronization and cross-dating of the growth rings in *Terminalia oblonga* allowed for the establishment of a chronology spanning 94 years (1929–2022). The ages of the trees ranged from 48 to 93 years, with chronologies including 2 to 4 radii per tree. The series intercorrelations varied between 0.33 and 0.57, while the average sensitivity ranged from 0.33 to 0.50. The average interseries correlation between trees (rbar) was 0.28, and the Expressed Population Signal (EPS) reached an average value of 0.79 (Fig. 3). These results confirm the high dendrochronological potential of *T. oblonga* and provide a solid foundation for future research in the eastern Amazon of Peru.

Detailed analysis of fourteen trees revealed high intercorrelation and sensitivity, validating the quality of the chronology synchronization, as it showed intercorrelations exceeding 0.32, the critical value for COFECHA. These results not only enhance our understanding of the species' growth but also establish an essential platform for future dendrochronological research in the region.

Correlation with precipitation and temperature

A negative correlation was observed between precipitation and the growth of *Terminalia oblonga* in various months of the year (Fig. 4), particularly in February, August, September, October, and November. During these months, the correlation values fell below 0, indicating that an increase in precipitation is associated with a decrease in tree growth. This suggests that periods of high precipitation could negatively affect the growth of *T. oblonga*, possibly due to excess water in its seasonally flooded environment.

Regarding Temperature, the correlation is positive throughout most of the year, especially in January, February, March, April, May, June, July, August, September, October, November, and December. These results indicate that higher temperatures are associated with greater tree growth, highlighting the importance of this climatic factor in the development of *T. oblonga* in this environment.

Similarly, most of the correlations with temperature were statistically significant (exceeding the levels of $p < 0.05$, and several even with $p < 0.01$), which reinforces the idea that the growth of *T. oblonga* is strongly influenced by temperature variations.

The regressions between precipitation and the growth of *T. oblonga* did not show a significant effect of precipitation on growth in the seasonally flooded forest, with an almost zero slope and a low correlation between both variables (Fig. 5). In contrast, the regressions between maximum temperature and growth revealed a significant positive effect, with similar slopes in all cases. Seasonal maximum temperature had a positive impact on the growth of *T. oblonga*, suggesting that this species responds favorably to higher temperature conditions in this ecosystem.

Correlations with Sea Surface Temperature (SST)

The results revealed significant positive SST anomalies in the tropical and subtropical Atlantic during the period March to May, suggesting that warmer conditions prevailed in these months (Fig. 6). The strongest positive anomalies extended from northern South America to the Caribbean, which may be linked to El Niño-related atmospheric patterns affecting Amazonian climate variability.

In contrast, negative SST anomalies were detected in parts of the

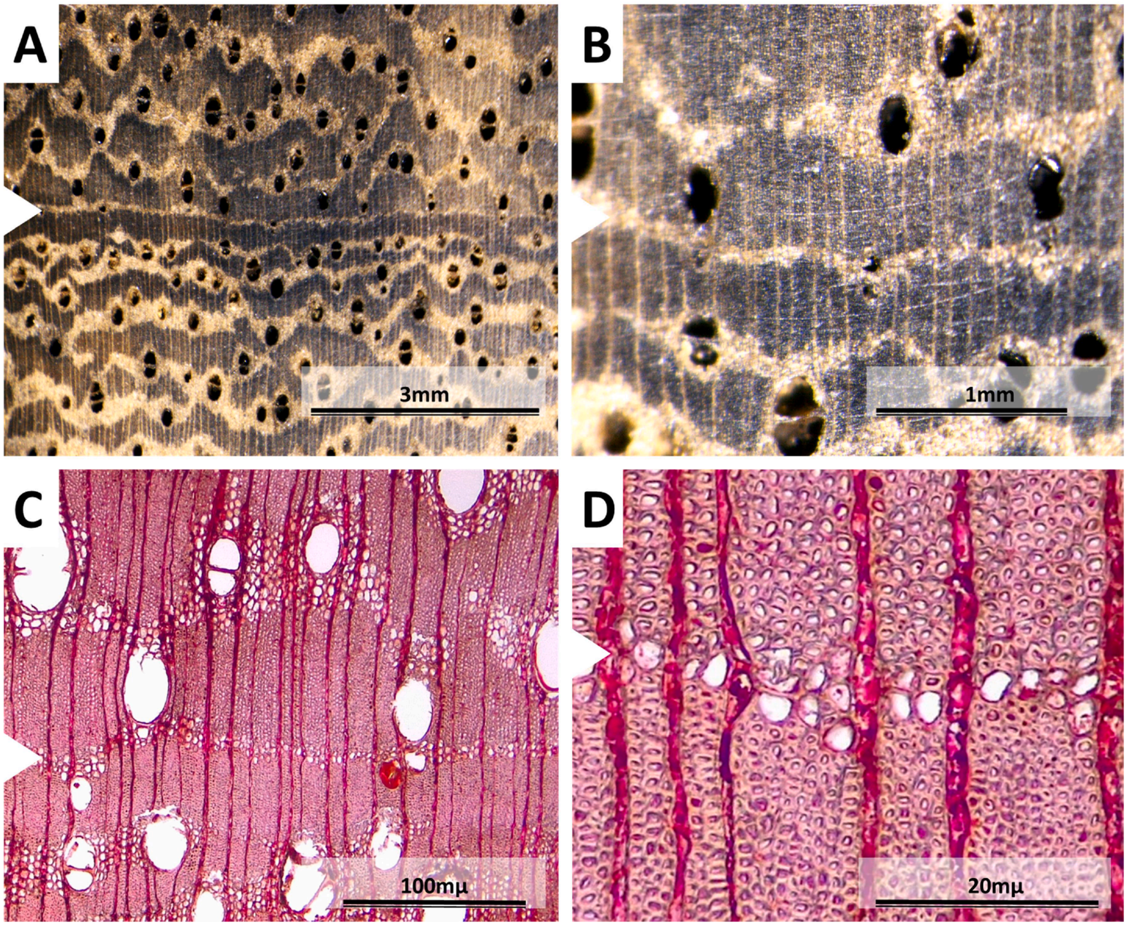

Fig. 2. Growth rings of *Terminalia oblonga*. At the macroscopic level: A) and B) Observation of the growth ring by the change in fiber wall thickness and by a fine marginal parenchyma line. At the microscopic level: C) and D) The fine marginal parenchyma line with 1 to 2 cells is observed, as well as the fiber wall thickness.

South Atlantic, particularly near the South American coast, indicating cooler-than-normal conditions. This pattern suggests a strong regional variability in ocean-atmosphere interactions, where temperature deviations in the Atlantic could influence moisture availability and precipitation regimes in the Amazon Basin.

Correlations with El Niño

Regressions between the El Niño phenomenon indices and the radial growth of *T. oblonga* showed a positive effect of the El Niño 1 + 2 index on growth in seasonally flooded forests, with a significantly steeper slope compared to other regions analyzed (Fig. 7A). On the other hand, regression analyses for the El Niño 3, 3.4, and 4 indices did not show significant differences in slopes, with weak and similar effects observed in all cases, and low correlations between these indices and the species' growth (Fig. 7B, C, and D). Notably, the El Niño 1 + 2 index was the only one to exhibit a notable relationship, suggesting that this region of the Pacific has a more direct impact on the climatic conditions that favor the growth of *T. oblonga*.

Teleconnections between growth and climate

The highest correlations were observed with the Atlantic Multidecadal Oscillation (AMO) and the Western Hemisphere Warm Pool (WHWP) indices (Fig. 8). Significant positive correlations with the AMO were detected in September and October of the previous year, as well as in July, August, and September of the current year, suggesting that phases of warmer Atlantic sea surface temperatures favor *T. oblonga* growth. The WHWP showed even stronger correlations, particularly in July and August, reinforcing its influence on tree growth during these months.

In contrast, the Pacific Decadal Oscillation (PDO) from September to June ($r = 0.19$, $p = 0.08$) and the Tropical Southern Atlantic (TSA) from September to March ($r = 0.24$, $p = 0.06$) exhibited notable but inconsistent correlations, failing to reach statistical significance in most cases. The Pacific North American (PNA) index showed significant correlations only in July ($r = 0.28$, $p = 0.03$), indicating a weaker but still relevant climatic influence.

These findings suggest that *T. oblonga* growth is more sensitive to Atlantic climate variability, particularly to AMO and WHWP warming phases, rather than to Pacific decadal oscillations. The stronger correlations during the growing season indicate that temperature and moisture transport from the tropical Atlantic play a key role in determining radial growth patterns in seasonally flooded Amazonian forests.

Discussion

This study provides a detailed insight into the dendrochronological potential of *Terminalia oblonga* in the eastern Amazon of Peru, identifying this species as the most promising for building chronologies in seasonally flooded tropical forests of the Madre de Dios Department. The selection of *T. oblonga* is based on its favorable anatomical structure and its abundance in the study area, which allowed the development of a master chronology with high intercorrelation and sensitivity. The question posed in the introduction, regarding the viability of *T. oblonga* for dendrochronological studies and its response to climatic variations and phenomena such as El Niño, has been addressed through a thorough analysis of the growth rings and their correlation with climatic

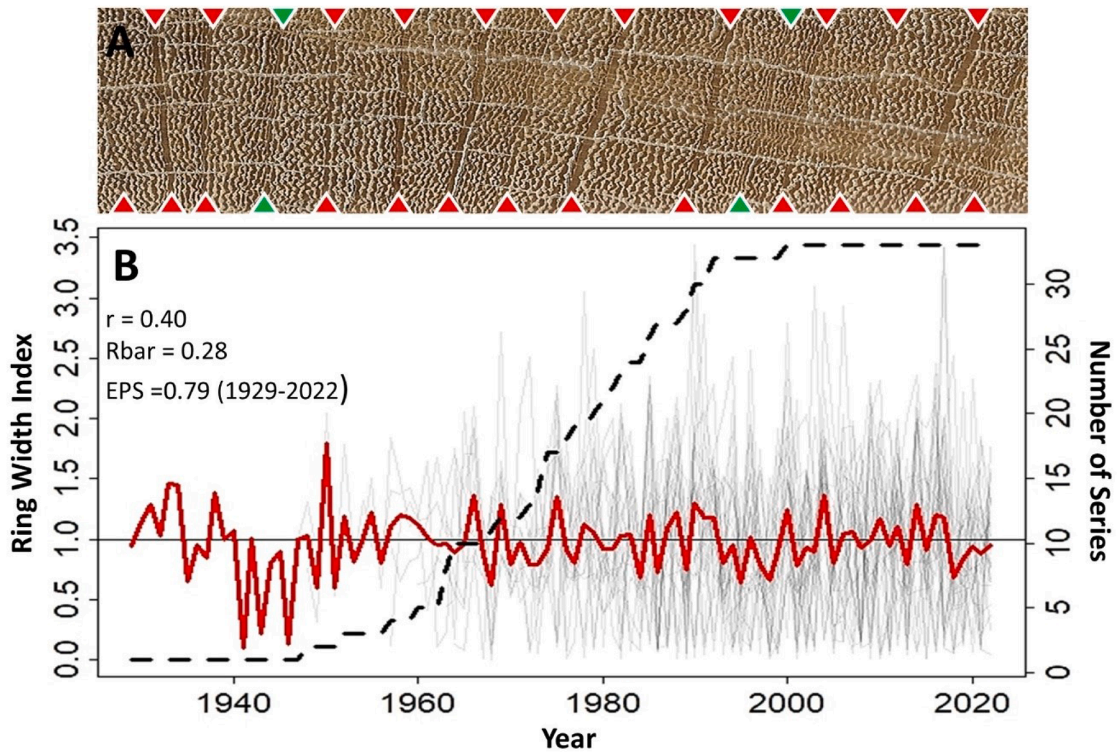

Fig. 3. Master chronology (1929–2022) of the growth ring width indices of *Terminalia oblonga*. (A) Microscopic visualization of *T. oblonga* growth rings. Red triangles indicate true rings, and green triangles indicate false rings. (B) The red line represents the master chronology, the gray solid lines indicate individual average time series, and the black dashed line shows the number of radial cores used for index calculation. Mean sensitivity and series intercorrelation were calculated with COFECHA; r = series intercorrelation, Rbar = mean correlation coefficient, and EPS = expressed population signal calculated with ARSTAN.

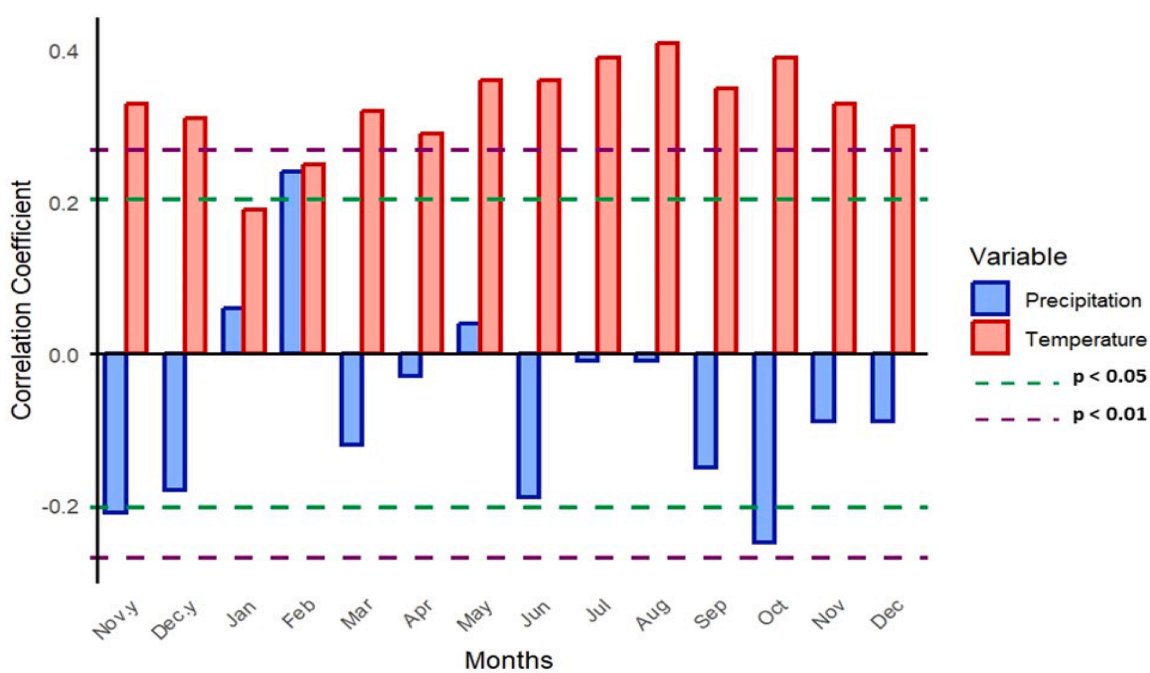

Fig. 4. Climatic Sensitivity of the *Terminalia oblonga* Chronology in Relation to Mean Monthly Precipitation and Air Temperature. Bars that surpass the green dotted lines indicate statistical significance at $p < 0.05$, while those crossing the purple lines represent significance at $p < 0.01$.

variables.

Marking of the growth rings

The marking of the growth rings of *T. oblonga*, observed in this research, confirms the clear delimitation by the change in the thickness of fiber walls and the presence of a thin marginal parenchyma line, which is consistent with what was noted by León (2007), who highlighted these same anatomical features in the species. Similarly, Marcelo-Peña et al. (2020) observed that the combination of fiber

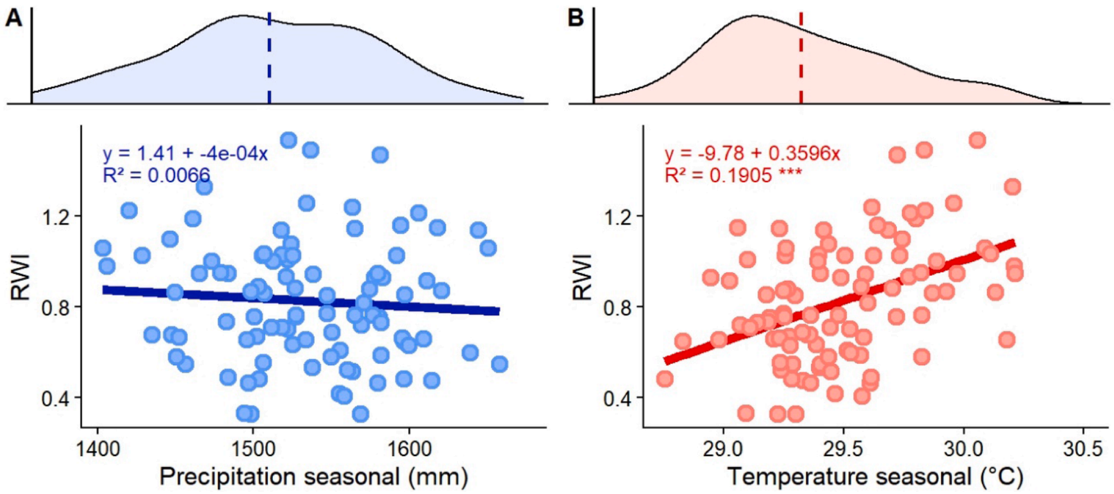

Fig. 5. Relationship Between the Growth of *Terminalia oblonga* and Climatic Variables. (A) Linear regression between the ring-width index (RWI) and seasonal precipitation (blue, left panel), showing a weak negative correlation. (B) Linear regression between the ring-width index (RWI) and seasonal maximum temperature (red, right panel), indicating a significant positive correlation. The density plots above each graph illustrate the distribution of seasonal precipitation (A) and seasonal maximum temperature (B), with dashed vertical lines marking the mean values. Regression equations, R^2 values, and statistical significance levels (p-values) are provided in each graph. Asterisks indicate significance levels: *** $= p < 0.001$. The analysis covers an annual growth cycle using climatic data collected between 1929 and 2022.

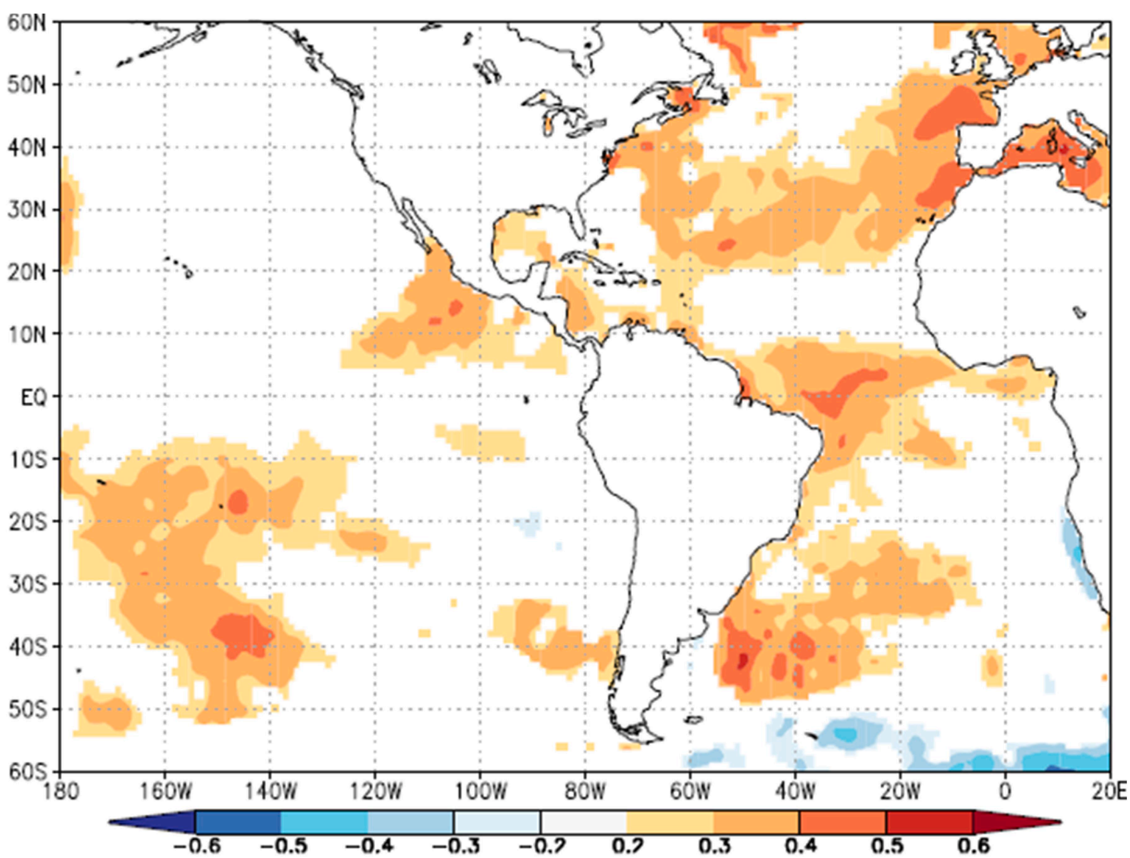

Fig. 6. Spatial correlations between monthly sea surface temperatures (SST) in grid cells of the Atlantic and Pacific Oceans and the ring width index chronology of *Terminalia oblonga* during the period 1960–2022. Moving averages corresponding to the 7-month growing season were used. The results presented correspond to the months with the most significant correlations.

thickening and marginal parenchyma in *T. oblonga* is a key element for its distinction. These findings, along with the evidence presented by Beltrán (2011) regarding the visibility of growth rings in the species with the naked eye, support its dendrochronological potential, particularly in areas where seasonal conditions such as flooding influence growth patterns. The consistency of these results with previous studies strengthens the use of *T. oblonga* in the reconstruction of climatic time series, as its anatomy is well-suited for identifying annual rings and

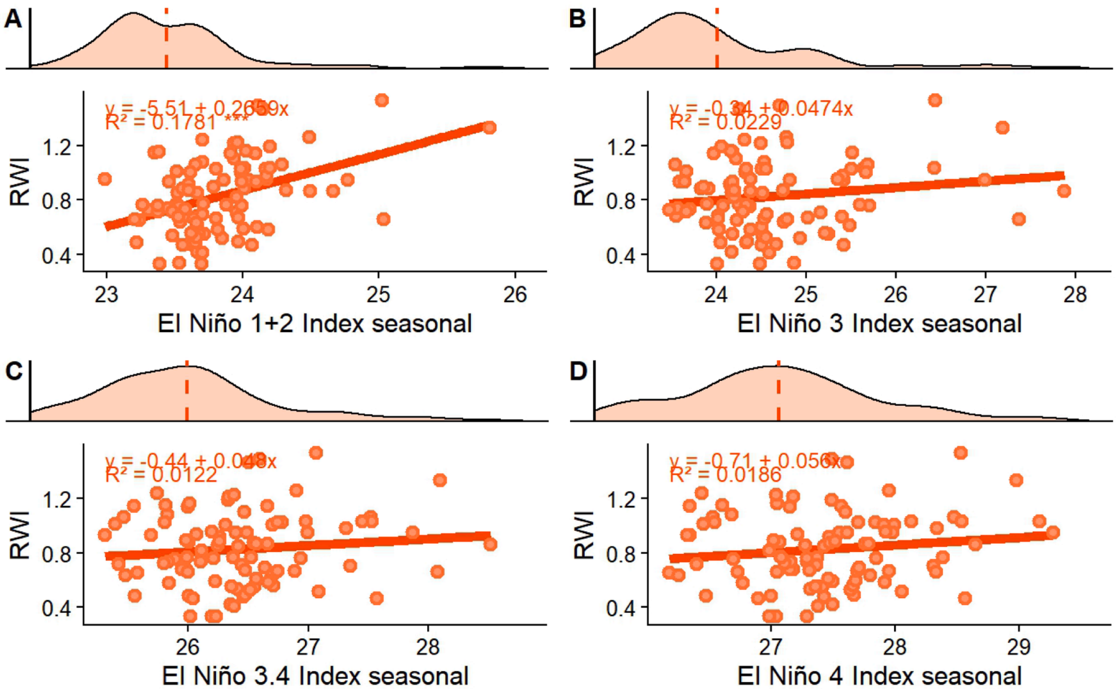

Fig. 7. Relationship between *Terminalia oblonga* growth and El Niño indices. (A) Linear regression between the ring-width index (RWI) and the El Niño 1 + 2 index, showing the strongest positive correlation with tree growth. (B–D) Linear regressions for El Niño 3, 3.4, and 4 indices, which exhibit weaker correlations with *T. oblonga* growth. The density plots above each graph illustrate the distribution of seasonal ENSO index values, with vertical dashed lines marking the mean SST anomaly for each region. Regression equations, R^2 values, and statistical significance levels (p-values) are provided in each graph. Asterisks indicate significance levels: *** = $p < 0.001$. The analysis covers the period from November of the previous year to June of the current year, using climate data from 1929 to 2022.

its response to environmental fluctuations is a relevant indicator for future research.

Furthermore, the results of this research on *T. oblonga* are in line with previous studies that have documented the formation of annual growth rings in species from the Amazonian floodplain forests. Schöngart et al. (2002) explain that seasonal flooding triggers leaf fall and a cambial dormancy lasting around two months, which contributes to the formation of annual rings in many species, including both deciduous and evergreen trees, as also demonstrated by Schöngart et al. (2007). Similarly, Schöngart et al. (2005) documented that prolonged flooding induces the formation of clearly defined annual rings in *Macrolobium acaciifolium*, providing the foundation for dendrochronological studies in floodable areas. This is consistent with Dezzeo et al. (2003), who found that species such as *Campsiandra laurifolia* and *Pouteria orinocoensis* in floodplain forests form distinct annual rings due to environmental conditions. In the case of *T. oblonga*, the formation of clearly defined rings can be attributed to these cycles of seasonal flooding, further reinforcing its potential for dendrochronological studies in the Amazon.

Chronology and synchronization of growth rings

This study represents a significant milestone, as it establishes the first chronology for *T. oblonga* in the eastern Amazon of Peru and provides a solid foundation for dendrochronological research in the region. The 94-year chronology (1929–2022) marks an important advancement, as previous reviews of dendrochronology in Peru reported no established chronologies for species from the Combretaceae family (Portal-Cahuana et al., 2023a).

The dendrochronological potential of *T. oblonga* was confirmed through a detailed anatomical characterization and a comparative evaluation of twenty forest species. The selection of *T. oblonga* was based on its well-defined growth rings, distinctive wood structure, and abundance in the study area, making it one of the most promising species for dendroclimatic studies in the Amazon. These results enhance our understanding of the species' growth dynamics and reinforce its suitability for long-term climate reconstructions and sustainable forest management.

To assess the reliability of the constructed chronology, we analyzed the intercorrelation of growth series, obtaining a value of 0.40, which exceeds the COFECHA threshold of 0.32, confirming strong synchronization among samples. Additionally, the Expressed Population Signal (EPS) reached an average value of 0.79, indicating that the growth signal accurately represents environmental variability.

These values confirm the high dendrochronological potential of *T. oblonga*, as an EPS above 0.75 is generally considered reliable for climate reconstructions (Brienen et al., 2016; Marcelo-Peña et al., 2020). The strong intercorrelation and EPS values suggest that *T. oblonga* can reliably capture climate variability over time, supporting its inclusion in long-term dendroclimatic studies in the Amazon.

Previous studies have shown that other species of the *Terminalia* genus, such as *T. amazonica, T. catappa, T. guyanensis, T. quintalata*, and *T. superba*, all from the Combretaceae family, form clearly defined annual growth rings, validating their suitability for dendrochronological analysis, as reported by Brienen et al. (2016), Marcelo-Peña et al. (2020), Schöngart et al. (2017), and Worbes (2002). In the case of *T. oblonga*, this study confirms those findings, providing new evidence of its dendrochronological potential with the construction of the first chronology for the species in the little-explored department of Madre de Dios in southeastern Peru.

Spatial correlation with SST

The results regarding the correlation between the *T. oblonga* chronology and sea surface temperatures (SST) show patterns consistent with previous studies. Significant positive correlations were observed in the tropical and subtropical Atlantic, as well as in the equatorial and southern Pacific, similar to those reported by . However, this study

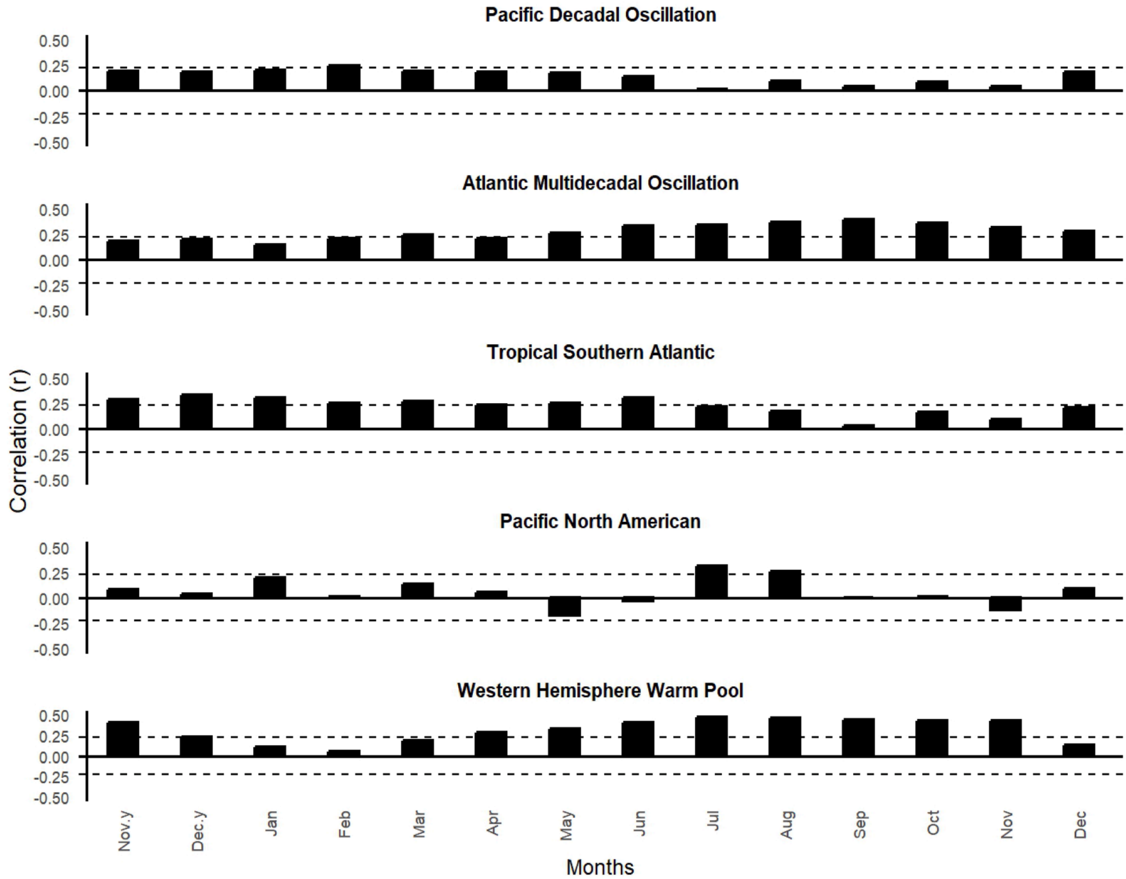

Fig. 8. Pearson correlations between large-scale atmospheric circulation indices and the master chronology of *T. oblonga* in a seasonally flooded low terrace forest in Madre de Dios. The black bars represent Pearson correlation coefficients (r) between the ring-width index (RWI) and the climatic indices: Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO), Tropical Southern Atlantic (TSA), Pacific North American (PNA), and Western Hemisphere Warm Pool (WHWP). Dotted lines serve as a visual reference but do not strictly define statistical significance ($p < 0.05$). Note: Months labeled with (.y) on the x-axis refer to the previous year, indicating a possible lag effect between climate variability and tree growth.

extends the correlation to the entire growing season. Barbosa et al. (2018) also found positive correlations in the southern Atlantic and Pacific, but not in the northern Pacific, suggesting a different sensitivity of *T. oblonga*.

Additionally, Locosselli et al. (2016) observed non-significant positive correlations with El Niño, while this study highlights negative correlations in the South Atlantic, where lower SST negatively affect the growth of *T. oblonga*. observed strong correlations in the tropical Pacific, partially aligning with this analysis. The studies by Layme-Huaman et al. (2018) and Requena et al. (2020) also emphasize the influence of Pacific and tropical Atlantic SST on the growth of species, which aligns with the patterns observed in *T. oblonga*, influenced by oceanic thermal variations.

Influence of the El Niño phenomenon

The results of this research show that the El Niño 1 + 2 index has a significant positive effect on the radial growth of *T. oblonga* in seasonally flooded forests, while the El Niño 3, 3.4, and 4 indices show weak correlations. This suggests that the eastern Pacific region has a more direct impact on the climatic conditions that favor the species' growth, which is consistent with previous studies, such as those by Köhl et al. (2022) and Morales et al. (2020), who demonstrated that climatic variations related to El Niño influence the growth dynamics of tropical tree species. Wigneron et al. (2020) also observed how extreme El Niño events impact the ability of tropical forests to recover, affecting their long-term productivity.

The variability in the response to the El Niño phenomenon among the different indices suggests that local factors, such as edaphic and climatic characteristics, also play an important role in the sensitivity of species. According to studies by Batista and Schöngart (2018), trees in floodplains often develop adaptations that allow them to better take advantage of changes in water availability, which could explain the greater sensitivity of *T. oblonga* to the El Niño 1 + 2 index.

Teleconnection

The results of our research show significant correlations between the AMO (Atlantic Multidecadal Oscillation) y WHWP (Western Hemisphere Warm Pool) indices and the growth of *T. oblonga*, especially during the months of July, August, and September. This finding is consistent with previous studies that have identified the key role of the AMO in modulating climatic phenomena such as droughts and precipitation variability (Aragão et al., 2018; Marengo et al., 2021), where a warmer North Atlantic tends to decrease precipitation in tropical regions, which could influence tree growth. In particular, Marengo et al. (2021) highlight that the AMO has been associated with ocean warming and anomalous precipitation patterns in recent drought events, which aligns with our observations of a positive correlation during these months. The WHWP, which reached its highest values in July and August, has also been linked to the intensification of tropical storms and climate variability in the Caribbean region, suggesting that its influence may be tied to changes in water availability, affecting the growth of *T. oblonga*.

In contrast, our analysis showed that the PDO (Pacific Decadal

Oscillation) and TSA (Tropical Southern Atlantic) indices do not present consistent correlations over time. This is consistent with what was noted by, who found that the PDO only correlates positively at the end of the growing season, and with Marengo et al. (2021), who identified that the impact of the PDO and ONI (Oceanic Niño Index) on precipitation is generally low and more dependent on the phase they are in. The significant correlation in July for the PNA index (Pacific North American Pattern), although isolated, reflects what has been observed in previous studies (Barbosa et al., 2018), where South Atlantic anomalies have a more consistent influence on the growth of tropical species than those of the North Pacific.

This study confirms the high dendrochronological potential of *Terminalia oblonga* in the seasonally flooded forests of the eastern Amazon in Peru. The 94-year chronology (1929–2022) precisely constructed through cross-dating techniques provides a valuable tool for future research on forest dynamics in response to climatic phenomena such as El Niño. The results show a significant relationship between the growth of *T. oblonga* and climatic variables, particularly with the El Niño 1 + 2 index, suggesting that climatic variability in the eastern Pacific influences the species' growth. The clear presence of annual rings in *T. oblonga* reinforces its utility for climate reconstruction studies, offering new perspectives on the sustainable management of tropical forests. This work not only expands the field of tropical dendrochronology research but also emphasizes the importance of deepening our understanding of the interaction between climate change and forest ecosystems, an area that still has much to explore.

CRediT authorship contribution statement

Miguel Angel Ranilla-Huamantuco: Resources, Methodology, Investigation, Formal analysis. **John Canales-Ramirez:** Methodology, Investigation. **Robert Finfan Farfan-Huanca:** Methodology, Investigation. **Jorge Luis Ranilla-Huamantuco:** Methodology, Investigation. **Javier Navio-Chipa:** Methodology, Investigation. **José Guilherme Roquette:** Validation, Software, Methodology, Investigation. **Mario Tomazello-Filho:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Leif Armando Portal-Cahuana:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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