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Woody legacies of railroad ties from the Southern Atacama Desert used to strengthen *Nothofagus obliqua* tree-ring chronologies from Northern Patagonia

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During the late Nineteenth and Twentieth centuries there was an intense exploitation of the long-lived *Nothofagus obliqua* forests in the temperate region of South America due to the quality of their hardwood. This exploitation resulted in degradation of this Northern Patagonian ecosystem with severe biodiversity implications. This also has prevented the development of multicentury *N. obliqua* tree-ring width chronologies, with implications for regional environmental and paleoclimatological studies. The large-scale manufacturing of railroad ties distributed across Chile drove part of this exploitation. This study evaluated the use of this cultural material from abandoned tracks preserved in the southern Atacama Desert to strengthen the existing *N. obliqua* tree-ring network in Patagonia. We dated this historical wood using classical crossdating ring-width methods corroborated with wiggle matching of radiocarbon series from railroad tree-rings using the hemispheric ^{14}C curve. Correlation analysis with climate data and paleoclimate field reconstructions shows a clear hydroclimate signal contained in the resulting regional tree-ring record with a consistent spatial pattern across northern Patagonia. The dendrochronological use of railroad ties preserved in the Atacama Desert opens a new avenue for dendroclimatic studies and highlights its heritage importance as a past environmental archive in southwestern South America.

Keywords Railway, Historical wood, Atacama, Patagonia, Historical dendroarchaeology, Cultural heritage

Tree species of the Gondwanan *Nothofagus* genus are one of the most important floristic components of the temperate rainforests in countries of Oceania, and in Chile and Argentina in South America (36°–55°S)[1,2].

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These species inhabit a large variety of environments, changing their abundance as a function of local climate, elevation, soil type, topography and disturbance regimes[2,3]. Several *Nothofagus* species from the temperate forests of South America have been used in tree-ring research including climate reconstructions[4,5], forest dynamics[2,6-9], forest dieback[10,11], climate effects on tree-growth and physiological patterns[12-17], insect outbreaks[18,19], and disturbances such as volcanic eruptions, landslides and fires[20-22]. Concerning climate reconstructions, only three species have been used for this purpose, *N. pumilio* for temperature[4,5], streamflow[23] and precipitation reconstructions[24], *N. betuloides* for temperature[25] and the southern annular mode (SAM) reconstructions, and recently *N. macrocarpa* for soil moisture reconstruction[26]. In this regard, recent findings suggest that the growth of *N. obliqua* trees is sensitive to precipitation and temperature in both Chile and Argentina[16,27]. However, most *N. obliqua* tree-ring chronologies in Chile span no more than 150 years[16] and 300 years in Argentina[27], although evidence indicates that the species' life-span can reach approximately 500 years[28]. This represents a significant potential for developing long-term growth series, which could be valuable for climate reconstructions, forest ecology research, as well as archeological and historical studies.

To date, most climate reconstructions in South America have relied on Andean high-altitude species, such as *Araucaria araucana*, *Austrocedrus chilensis*, *Fitzroya cupressoides* and *N. pumilio*[4,24,29-32]. Additionally, for historical dating, tree-rings of *Pilgerodendron uviferum* has been used in southern Chile[33], *Prosopis* spp. in the Atacama Desert[34] and in the Central Andes[35], among with *Polylepis tarapacana*[36]. However, the potential of *Nothofagus* species remains largely unexplored for these challenges so far. In this scenario, *Nothofagus* species present an untapped opportunity, particularly through the study of historical wood, which could provide valuable records for climate reconstructions and historical dating. This would allow the identification and dating of various historical structures, complementing existing datasets and offering new insights into the climatic and human history of lower-elevation regions, along with other environments where this wood may have been utilized by human communities.

Despite the extensive use of *Nothofagus* tree species for dendrochronological studies, only a few species have precisely dated and well replicated tree-ring width chronologies extending prior to 1700: *N. betuloides* (1489–2008)[37], *N. pumilio* (1546–1990)[5], *N. dombeyi* (1612–2019) and *N. alpina* (1634––2019)[38]. For *N. obliqua*, old-growth forests in the east slope of the Andes have allowed to build a tree-ring width chronology from 1706 to 2013[27]. Regarding the use of relict deadwood to extend *Nothofagus* chronologies in temperate forests, only one attempt has been made with *N. betuloides* yielding very promising results[37]. This fact offers a new avenue to explore and extend current and future *Nothofagus* chronologies taking advantage of the preservation capacity and wood quality of many species from this genus. In this context, *N. obliqua* has exceptional wood mechanical properties and rot resistance, especially when the wood originates from old trees, reason why it has been intensively logged in most of its geographical distribution[28,39-42]. This wood has been widely used in the construction of houses, barns, bridges, beams, poles, and for firewood[43-45], and it was the main species used for the elaboration of railroad ties in the early 1800s[46,47]. To this day, its logging is still legally allowed and it continues to be used for several uses, such as firewood and in construction[41,48]. The valuable and appreciated wood of *N. obliqua* has been used by human communities for a long time. Anthracological studies have found carbonized wood of *N. obliqua* in archaeological sites in southern Chile, showing its use as a raw material in fireplaces, residential structures and funeral rituals[49]. At the same time, ethnographic accounts show the continuity of its use in various structures of the Mapuche people, such as their dwellings[50,51], suggesting an ancient and constant knowledge of the properties of *N. obliqua* wood. All these uses result in diverse wood pieces which can contain old growth patterns and provide an opportunity to extend growth chronologies in ausency of old growth forest in the present.

One of the main uses of *N. obliqua* in the last two centuries was the construction of the railroad across the country. Railroads have been a cornerstone of economic and social development in Chile since their introduction in the nineteenth century[52]. With nearly 9000 kilometers of tracks[47,53], the railway supported the growth of agriculture, mining, and other industries, with the mining and nitrate industry standing out in the north[54], and the forestry industry standing out in the south of the country[52]. By the late Nineteenth Century century, the main user of railroad ties in Chile was the National Railway Company (Empresa de Ferrocarriles del Estado, EFE)[55], which, for example, during the 1960s consumed approximately 1,593,880 units per year of creosote-treated railroad ties, mainly from *N. obliqua* wood, for the line construction[46], (Supplementary material, Fig. S1). However, the use of wood railroad ties has gradually declined and been replaced by concrete structures in the 2000s. Although still utilized in rural areas for various purposes, the production of wooden railroad ties has decreased since the 1970s, mainly due to the reduction of the *N. obliqua* forests near the exploitation sites[46]. This transition from wood to concrete ties has left behind a significant repository of historical *N. obliqua* ties, which not only reflect the forestry practices of the past, but also offer a preserved archive for dendrochronological studies. According to former railroad ties manufacturers' stories in the Panguipulli area (~39°S), within the temperate rainforest region, smooth, knotless and healthy *N. obliqua* trees over 20 meters tall with large diameters (1–2.5 meters) were selected for tie production (Interviews with two former lumberjacks, Panguipulli, May, 2021). These tall and mature trees, referred to as "Pellín" by the Mapuche indigenous people[56], had a significant portion of heartwood which is far more durable than sapwood in *N. obliqua* wood[42]. In contrast, younger *N. obliqua* trees, also called "Hualles"[56], are composed mainly of less durable sapwood. For this reason, railroad construction was one of the main drivers of the extensive exploitation of old-growth forests of this species, contributing significantly to their decline, and also helps explain the current scarcity of old trees alive in the forest.

The historical information that we know about the railroad industry in Chile today, mainly comes from the work of chroniclers, naturalists and historians who documented timber exploitation from the late 16th century onward[39,52]. However, accurate dating techniques have not been applied to provide precise information about the ties construction, provenance and age of the wood used for this purpose in the country. The availability of

N. obliqua old railroad ties constitute a unique opportunity to extend back in time the short and scarce tree-ring width chronologies of this species. Considering that the precise dating offered by tree-ring crossdating methods ensures that each ring can be attributed to a specific year with unmatched accuracy, it can be used for reconstructing detailed past environmental conditions and human activities[57,58]. Moreover, these ties themselves, become a new historical record that offers the possibility of dating and studying from different perspectives the historical dynamics of the construction, maintenance and repairs of the Chilean railroad network. Although there are no specific studies concerning the use of *Nothofagus* historical wood, research with species of the same order Fagales from the Northern Hemisphere, such as *Fagus*, *Quercus*, and *Castanea*, have demonstrated their usefulness in dating historical pieces and ancient structures in different parts of the world, including medieval buildings, shipwrecks, and historical artifacts[59–63]. These studies have highlighted not only the potential of dendrochronology for precise dating but also its ability to reconstruct historical climate conditions and human-forest interactions[64–66]. This global perspective underscores the potential of *Nothofagus* railroad ties to provide valuable insights into historical forestry practices and environmental changes in South America and the world.

Considering the dry conditions of arid and semi-arid regions in northern Chile (19–32°S), which help preserve wood and provide a unique opportunity to recover well-preserved *N. obliqua* samples from the ties of abandoned railroad tracks in the southern Atacama Desert, our study seeks to bridge the gap between historical forestry practices and modern climate research. The main goals of this study are: (i) to crossdate these historical wood samples with available *N. obliqua* tree-ring width chronologies, (ii) to extend back in time the length of the current *N. obliqua* tree-ring network, and (iii) to assess the climate signal of the new regional *N. obliqua* composite chronology and its potential to be used in climate reconstructions in Chile. Given the scarcity of old *N. obliqua* trees in the temperate rainforests of Chile due to historical overexploitation, the integration of these samples could significantly contribute to strengthening existing tree-ring chronologies, expanding the opportunity of rescue historical information of its geographical distribution, and enhancing climate reconstructions. The use of tree-ring series from railroad ties, particularly from lowland areas of southern Chile, presents a promising new avenue for historical, environmental and climate research, and could serve as a novel example for replication, offering valuable insights in other countries and ecosystems worldwide.

Methods

Study region: the Northern Longitudinal Railway (FCLN)

The study area includes removed, abandoned and/or ruined railway tracks from the Northern Longitudinal Railway Project (Ferrocarril Longitudinal Norte, FCLN) (Fig. 1A,B and 2H), located on the semi-arid southern edge of the Atacama Desert in Chile (Norte Chico, 25–32°S). This region experiences a mean annual precipitation of 150 mm and a mean annual temperature of 15.5 °C (Fig. 1C,D). The semi-arid and desert environment of the transverse valleys in Norte Chico (Fig. 2A) has facilitated the preservation of wooden railroad ties. The FCLN railway line originally spanned approximately from 20° to 32° S, according to the former layout of the tracks (Fig. 1A). The first tracks were privately built in an east-to-west direction by mining companies to extract material from mines and transport them to coastal ports for export. The Copiapó-Caldera line, which began operations in 1851, is an example of these early tracks[54]. These initial tracks were built in an isolated and disconnected manner. The government's FCLN project aimed to connect northern Chile with the capital, Santiago, by integrating privately owned railway branches into a national network[52,54]. Construction began around 1888 but faced 20 years of delays due to financial limitations and political resistance from influential landowners in the Parliament[43,52]. By the early Twentieth century, the FCLN was entirely managed by the National Railway Company (EFE)[54], reaching the northern part of the country where the nitrate and mining industries thrived, particularly in the Tarapacá and Antofagasta regions (19–25°S). This railway system facilitated the transport of both freight and passengers. However, since the mid to late Twentieth century, the railway network gradually declined as tracks were systematically suspended, primarily due to political, technical and economic challenges. Major reasons included decreased mining output, the end of the nitrate industry, annual deficits caused by high operating costs in rugged terrain, reduced goods and products traffic, the low-grade minerals being transported, inadequate infrastructure, and obsolete equipment, but mostly, lack of political-technical will[54]. The competition from the trucking industry, boosted by continued government investment in road infrastructure since 1945, the end of state subsidies during Augusto Pinochet's dictatorship in the 1970s, and the reprivatization of the northern railway system in 1997, among other factors exacerbated the cease of operation of many railway lines[53,54]. This culminated in a widespread crisis for EFE[47], leaving behind a legacy of abandoned infrastructure, including numerous tracks and *N. obliqua* railroad ties. Today, only a few branches of the railway remain active for freight transportation.

Sampling sites for railroad ties were pre-selected using the railroad database from the website www.amigosdeltren.cl to identify abandoned sections of the line. These locations were later verified in the field prior to the sampling. Samples were collected from three locations within the Norte Chico region: Ovalle (OVA), Alcaparrosa (ALC) and Chinchillas (CHI) (Fig. 1).

Sampling, processing and measuring of railroad ties samples

At each site, a minimum of 15 ties were selected from abandoned rail tracks in a well-preserved state that could contain a reasonable number of growth rings (Fig. 2B,C). Depending on the primary cutting elaboration technique the railroad could include more or less annual rings (Fig. 2D). Transverse sections of railroad ties approximately 10–15 cm width were cut using a chainsaw (Fig. 2E). These sections were stored in individual plastic bags, labeled and transported to the laboratory. Broken or shredded samples were glued with soluble wood glue to avoid deterioration during handling. The exposed surface of the samples (transverse plane) was sanded with progressively finer sandpaper (50–800 grit) following standard dendrochronological protocols[67], to maximize the visibility of the rings under 10–50× magnification (Fig. 2F). Prior to sanding, samples with
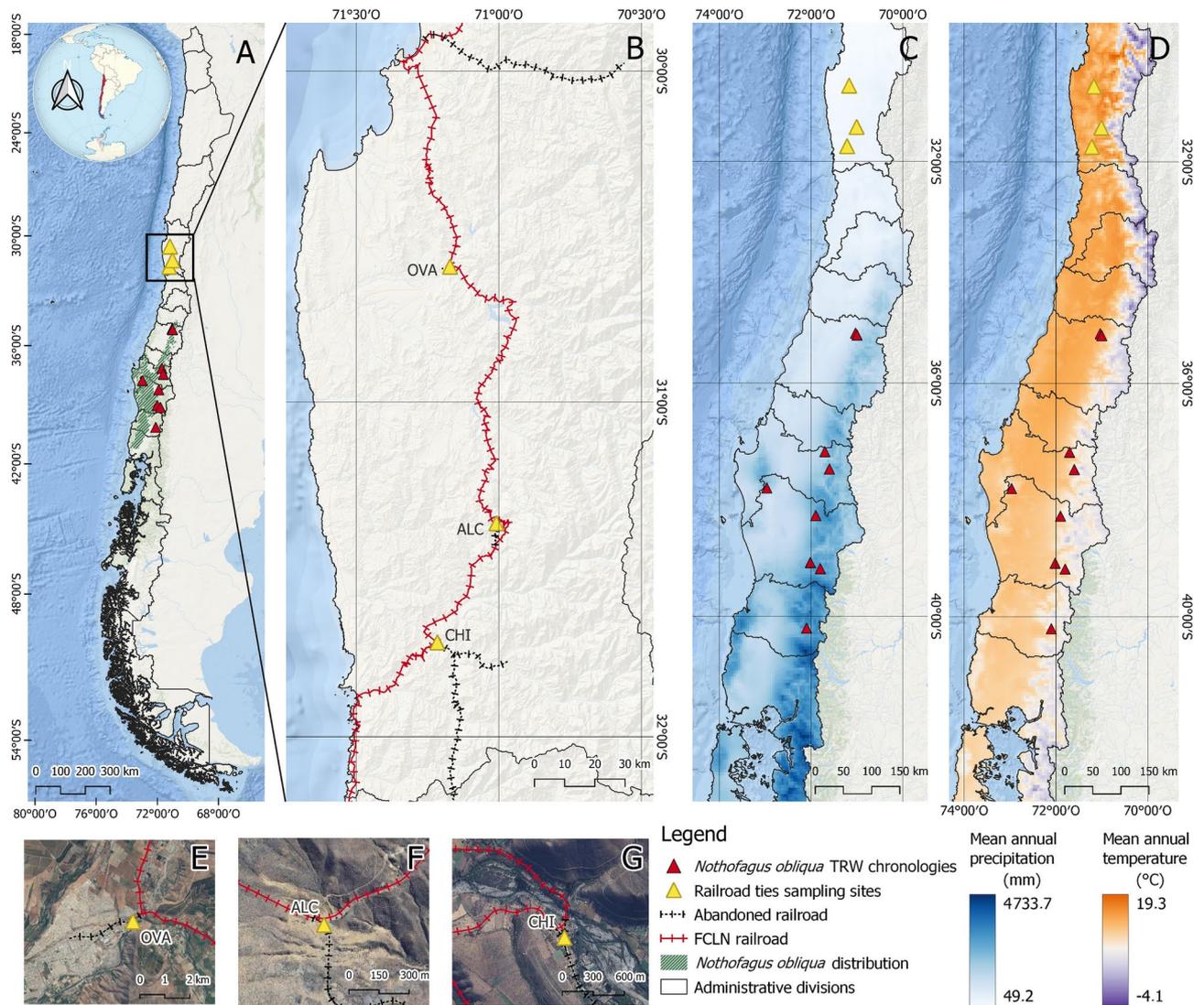
Fig. 1. (**A**) Map of Chile indicating the distribution of *N. obliqua* forests across south-central Chile, the locations of existing *N. obliqua* tree-ring width (TRW) chronologies (red triangles), and the railroad network with the sampling sites located in southern Atacama Desert (yellow triangles), (**B**) map of the Northern Longitudinal Railway Project (FCLN) and the three sampling sites. Red-colored lines represent disused railway tracks, while black lines represent abandoned tracks, (**C**) and (**D**) Precipitation and temperature descriptions of the study regions, (**E**), (**F**) and (**G**) zoom-in of the railroad ties sampling sites. All maps were generated using open-source software QGIS version 3.28.15 (https://qgis.org). Base maps were obtained from Google Satellite (Maps data ©2025 Google, Terrametrics) and ESRI Ocean(*Source* Esri, GEBCO, Garmin, NaturalVue | Esri, GEBCO, IHO-IOC GEBCO, Garmin, NGS), both publicly available for their use.

high creosote content—a toxic substance used for wood preservation[52]—were discarded to prevent handling and mitigate potential health risks associated with this toxic compound[68]. Annual growth rings were first identified as *N. obliqua* wood by comparing wood anatomy cuts from railroad ties with reference samples and their description[69], and then visually dated under a high-resolution stereomicroscope, assuming the first ring as zero in each sample (undated). The ring-width was measured using a microscope coupled to a Velmex Inc. stage measuring system with an accuracy of 0.001 mm. Wherever possible and depending on the difficulty and definition of the growth rings, multiple radii were measured in cross-sections, visually matched for accuracy, and then averaged to create an overall mean series for each individual sample. None of the samples presented bark, but some presented a waney edge indicating the curvature of the last growth ring.

N. obliqua composite reference tree-ring width chronology

Considering the unknown provenance and temporality of the railroad ties, and in order to ensure a robust basis for cross-dating these series, we developed a composite reference *N. obliqua* tree-ring width chronology. This reference chronology combined eight ring-width chronologies previously developed by Urrutia-Jalabert et al.[16] and two new ring-width chronologies, all from the temperate rainforest region of Chile (35°7'S–39°6'S, Fig. 2G).

Fig. 2. (**A**) The semiarid landscape of Norte Chico region along the railway at the southern Atacama Desert in Chile where railroad ties sampling was carried out, abandoned railroad tracks in (**B**) Ovalle (OVA) and (**C**) Alcaparrosa (ALC), (**D**) illustration of the different orientations of ties manufacturing in a cross-section of a *N. obliqua* trunk with its annual growth rings, (**E**) detail of railroad ties sampling with a chainsaw, (**F**) visualization of *N. obliqua* annual growth rings from a railroad tie wood section, (**G**) Temperate rainforest biome in southern Chile, with Riñihue, Panguipulli and Neltume lakes from left to right, a region which was an epicenter for the manufacture of *N. obliqua* railroad ties, and (**H**) part of the cultural heritage consisting of the abandoned Alcaparrosa tunnel and station infrastructure (notice the water crane manufactured in Bath UK 1906). Pictures A and H from Cristian Campos (https://www.campografia.cl/alcaparrosa/).

The two new chronologies were developed by sampling living trees in remnant forests from the Nahuelbuta National Park in the Coastal Mountain Range (37°47'S–72°59'O, Fig. 1A). At each site (NBT and NBR), tree-cores from 17 and 20 trees, respectively, were collected between 2021 and 2022 using increment borers following standard dendrochronological techniques[67]. In the laboratory, samples were dried, sanded, and dated using the Schulman's convention for the Southern Hemisphere[70], which assigns each ring the calendar year corresponding to the start of radial growth (austral spring). Ring-widths were visually cross-dated, measured, and annually verified using the COFECHA software[71]. Ring-width chronologies were developed using the ARSTAN_41d software, with standardization performed through the application of negative exponential or linear regression curves[72,73]. To check if there was a clear regional tree-growth signal for the complete *N. obliqua* distribution, we assessed the relationship between the 10 chronologies using the Pearson correlation coefficients (see Supplementary material, Fig. S2). Once this was validated, we were able to build a composite *N. obliqua* ring-width chronology, which was used as the reference series to date the railroad ties (Table 1, Fig. 1). This reference chronology was built using the measurements of the 326 samples from the 10 study sites (Table 1). Tree-ring width measurements were detrended using a spline curve with a 50% cutoff, and finally averaged to obtain a regional reference tree-ring width chronology of *N. obliqua* from living trees.

Dating tree-ring series from railroad ties

Once the rings of the railroad tie samples were measured, the exact annual crossdating of the series with the reference chronology was verified at a high-frequency level using COFECHA. We used lagged correlations

ID	Site name	Coordinates	Elevation (m.a.s.l)	First year	Last year	Intercorrelation	N° series	Year >5 series
MEL	Melado	35°9′03″S - 71°00′0″W	1168	1759	2018	0.642	39	1837
TRI	Tricahue	35°7′00″S - 71°2′00″W	954	1804	2018	0.625	31	1860
ARQ	Arquilhue	40°12′00″S - 72°06′00″W	455	1945	2018	0.512	28	1946
LPR	Los Prados	37°30′00″S - 71°36′00″W	668	1932	2018	0.517	33	1934
NAM	Namuncal	39°12′00″S - 71°48′00″W	630	1942	2018	0.535	40	1946
RUC	Rucamanqui	37°12′00″S - 71°42′00″W	987	1953	2018	0.651	45	1956
SPT	San Pablo de Tregua	39°06′00″S - 72°01′00″W	671	1954	2018	0.520	26	1956
VAH	Valle Hermoso	38°18′00″S - 71°54′00″W	696	1908	2018	0.579	40	1919
NBR	Nahuelbuta 1	37°49′35″S - 72°58′00″W	1154	1627	2020	0.588	13	1808
NBT	Nahuelbuta 2	37°49′01″S - 73°00′09″W	1309	1766	2020	0.549	31	1822
COM	Composite reference chronology	–		1627	2020	0.407	326	1759

Table 1. Location and characteristics of the *N. obliqua* tree-ring width chronologies from living trees growing across the species distribution in the temperate rainforest region and the composite reference chronology. Year > 5 shows where the chronology spans more than five series. See also Supplementary material (Fig. S3).

between the measured tree-ring series after detrending with a 32-years spline and removing its temporal persistence by autoregressive modeling[71]. The statistical validation of the comparison between the ring-width series from the railroad ties and the standard reference chronology was conducted using the correlation coefficient and Student's t-value between the high-frequency standardized tree-ring time series. The "t-value" assesses the strength of the association between two tree-ring width series, adjusting the correlation coefficient by sample size[74]. A t-value over 3.5 suggests some degree of match with a small margin of statistical error[74,75], while a t-value exceeding 6.0 indicates a robust and conclusive agreement[76]. Once the floating series were assigned a chronological starting year, a regional *N. obliqua* tree-ring width chronology was developed by combining the series from both living trees with dated railroad ties, thereby strengthening and extending the chronology further back in time. The regional composite chronology was built using the ARSTAN software[72], following the same procedure previously described for the reference chronology.

To verify the tree-ring dating of the *N. obliqua* railroad ties chronology we used annually resolved radiocarbon series following a "Miyake-like" wiggle matching approach[77,78], but using the "bomb-peak" period as the reference event when atmospheric radiocarbon levels almost doubled due to the large number of atmospheric thermonuclear bomb tests detonated in the Northern Hemisphere[79]. For this purpose, we choose the previously ring-width dated ALC002 *N. obliqua* railroad tie sample (which covered the period 1640–1981) and selected six consecutive annual rings corresponding to years around the bomb-peak period (1963–1968; with Schulman's convention[70] annual rings 1962–1967). Then, the ^{14}C content of each of the 6 years were determined and the sequence wiggle-matched against the single-year-resolution reference curve of the ^{14}C content in tree-rings from the Southern Hemisphere zone 1-2 developed by Hua et al.[78,80,81]. To determine its exact calendar year, we used a classical Chi-squared (χ^2) fit of the ^{14}C 6 years railroad tie sequence to the ^{14}C reference curve in conjunction with 10,000 Monte-Carlo simulations to obtain a goodness of fit and a realistic range of possible solutions[77]. Besides being the largest tree-ring sample, the ALC002 presents the most recent annual ring of all the tie series and presents in one of its corners a classical waney edge indicating a bark edge[78]. The ALC002 sample preparation for ^{14}C content determination was done by cutting each of the six selected dated annual rings under a binocular microscope using sterile ceramic knives over an acrylic table, polished with diamond tools to remove the surface that was in contact with extraction and sanding tools, stored in falcon tubes and sent to DirectAMS, Washington, USA. All ^{14}C determinations were carried out over the α-cellulose extracted from wood samples to avoid translocation between growth rings[82] and following standard procedures[83].

Climatic signal in the regional composite *N. obliqua* chronology

To assess the spatial and temporal relationship between the regional composite *N. obliqua* tree-ring width chronology (comprising both living trees and historical railroad ties) and the climate variability, we analyzed its correlation with various climatic datasets and paleoclimatic reconstructions. This assessment was conducted using both internationally validated climate products and long-term hydroclimate reconstructions (all published in scientific journals), allowing us to explore *N. obliqua* sensitive to past and present climate variability.

To assess the climatic signal in the tree-ring width chronology and its spatial representation, we generated correlation maps for 3, 6 and 12-months windows between the standard chronology and the high resolution 0.25° × 0.25° latitude-longitude gridded precipitation and maximum temperature data from ERA5[84] for the period 1950–2020. These time windows were chosen based on the observation that *N. obliqua* exhibited significant correlations with climate variability across multiple seasonal combinations. For the period prior to 1950, and to validate the climate signal of the chronology including railroad ties, we compared our chronology with longer climate datasets extending back to 1901, such as the CRU TS4.08 precipitation dataset (0.5° × 0.5° latitude-longitude)[85]. Correlation analyses were performed using this dataset for the period 1901–1950 to verify the consistency of *N. obliqua*'s response to precipitation across different climate products. To further ensure coherence, we conducted correlation analyses for the period 1950–2020, allowing for direct comparison with

ERA5 data, and for the entire common period covered by CRU TS4.08 and the *N. obliqua* chronology (1901–2020).

To further extend the assessment, we used the 0.5° × 0.5° gridded South American Drought Atlas (SADA)[31], which spans South America from 12°S to south, covering a period from 1400 to the present. The SADA is a tree-ring based field reconstruction (0.5° × 0.5°) of austral summer (December–February) soil moisture, using the self-calibrated Palmer Drought Severity Index (scPDSI) as a target metric, developed using more than 300 tree-ring width chronologies from over 10 tree species as predictors, not including *N. obliqua*. Therefore, our regional composite chronology was completely independent from this reconstruction. However, given that our chronology reaches an EPS > 0.8 only from 1740 onward, we restricted the use of the SADA dataset and further analyses to the period 1740–2020, ensuring that all analyses were conducted with robust population signals. The Expressed Population Signal (EPS) statistic measures the common variability within a chronology which is dependent upon sample depth[86,87]. When the EPS value drops below a predetermined level (often 0.85), the chronology begins to reflect individual tree-level signals rather than a coherent stand-level signal[87]. Nevertheless, it can still be reliably dated and used in archaeological studies[87]. Also, some studies argue that an EPS >0.8 is sufficient to represent a strong population signal[88–91]. Based on this criterion, we truncated the composite chronology at 1740, ensuring that all subsequent analyses were based on data with EPS > 0.8.

Following this approach, we performed correlation analyses between our chronology and the precipitation reconstruction for Northern Patagonia[92] for the periods 1900–1988, 1800–1988 and 1740–1988. Additionally, we examined its relationship with streamflow reconstructions located in different parts of the geographical distribution of *N. obliqua*, including the northern area represented by the Maule river[93], south-central area using the Biobío[94] and Imperial rivers[95], and the Puelo river representing the southern area of the species distribution[96]. The streamflow reconstructions from these rivers were correlated with the *N. obliqua* chronology for the periods 1900–2000, 1800–2000 and 1740–2000.

Finally, we assessed the correspondence between historical extreme climate events documented in historical records and our chronology. For this purpose, we followed the methods and techniques of historical climatology, which involve the search and compilation of information from periods preceding or parallel to instrumental records[97–99]. We consulted various historical sources, including chronicles, archival documents, newspapers and magazines, obtained from libraries, archives and museums in major cities of central-southern Chile (Santiago, Temuco, Valdivia, Puerto Montt), covering the period from the arrival of European colonizers to the present. This information was systematized and classified into years of drought (dry years) and high-rainfall (wet years). The search covered central-southern Chile from 1619 onward; however, for this study, we only considered climatic events between 1740 and 1920, given the EPS constraints and the availability of precise instrumental data in more recent years.

Results

Composite reference tree-ring width chronology

The composite reference *N. obliqua* ring-width chronology from living trees had a total of 326 series with an intercorrelation of $r = 0.407$ ($p < 0.01$) (Table 1). The span of this chronology ranged from 1627 to 2020, though the low number of old trees allowed a well replicated chronology since 1759 (n > 5 tree-ring width series), but reaching an EPS > 0.85 since 1780, with a marginal decline in the period 1805–1830. Moreover, the intercorrelation values between the five ring-width series that covered the period 1760–1809 was r = 0.51 ($p < 0.05$) (with series from NBR and MEL site), demonstrating the coherence of the growth patterns in the composite chronology even with a low number of ring-width series. The two new chronologies developed in the Nahuelbuta Mountain Range (codes NBT and NBR) included the oldest living trees of *N. obliqua* reported to date (Supplementary material, Fig. S3), playing a crucial role for strengthening the composite chronology of the species.

Tree-ring dating of railroad ties

In total, 26 out of the 45 railroad ties series were dated: 12 from the ALC site and 14 from the OVA site. The high creosote impregnation of the CHI site samples hindered the accurate identification of the growth rings, preventing the dating of these samples. The temporal extension of the wooden pieces ranged from 23 to 345 years (Table 2, Fig. 3). Specifically, six samples were under 50 years old, nine were between 50 and 100 years, five ranged between 100 and 150 years, four were between 150 and 250 years, and only two were more than 300 years (ALC002 and ALC020) (Fig. 3). The samples covered different time periods, with the oldest starting in 1534 (ALC020) and the most recent ending in 1981 (ALC002) (Table 2, Fig. 3). Railroad ties series' correlations with the reference chronology ranged from 0.175 to 0.532, and t-values ranged from 2.09 to 6.38 (Table 2). Only 7 out of 26 tree-ring series were cross-dated with the reference chronology before 1780, and still obtained good statistics in several samples (Table 2, Fig. 4). Each tree-ring series from railroad ties was cross-dated and plotted against the reference chronology (Fig. 4).

The samples from railroad ties came from wood pieces of similar size, however, they exhibited a wide variation in the number of rings, resulting in growth series of different time lengths. This variability is attributed to differences in tree growth rates and variations in the wood-cutting orientation during the railroad tie manufacturing process (Fig. 2D). In most cases, this variation can be explained by the young age effect, where younger trees tend to exhibit wider rings mainly due to higher growth rates[100], as observed in samples where the railroad tie was crafted from the youngest sections of the wood. This age-related growth pattern is well documented for *N. obliqua,* a pioneer species characterized by fast growth during its early establishment stages[48,101]. Thus, samples with a low number of years (e.g. OVA004 with 23 years) displayed higher growth rates (i.e. wider rings) compared to samples of similar size but with a significantly higher number of rings (i.e. narrower rings), indicating slower growth rates (e.g. ALC002 with 345 years), likely obtained from old trees.

Only one rotten sample was found (ALC017) in the total sampling. Furthermore, no particular growth patterns were found with respect to each site, probably due to the mixed origin of the wood used in the manufacturing process. Future studies comparing growth patterns from different sites could help determine whether local growth patterns can be used to identify the provenance of the historical *N. obliqua* wood pieces.

Verification of dating by ^{14}C wiggle matching

A total of six radiocarbon measurements were carried out on the ALC002 series, which was the largest tree-ring series analyzed in this study (period 1640–1981). The wiggle-match of the 6-year radiocarbon series from ALC002 against the annually resolved tree-ring ^{14}C reference curve from the SH 1–2 region[80], corroborated the exactitude of the ALC002 cross-dating by classical ring-width patterns. The lowest χ^2 value of the wiggle-matching indicated that the 1962–1967 calendar period assigned by cross-dating was perfectly dated and corresponded to the same ^{14}C period in the calendar years of the Hua et al.[80] reference ^{14}C curve (Fig. 5).

N. obliqua regional chronology and its climate signal

After verifying the ties dating through cross-dating with the composite reference chronology and radiocarbon analysis, a regional ring-width chronology was constructed using all the growth series. By cross-dating both the undated series and the living tree-rings chronologies, it was possible to extend and strengthen the *N. obliqua* regional chronology, particularly in the oldest period (1600s) and especially since the Eighteenth Century. This improvement enhanced the correlation and increased the number of samples during this period, reaching between 10 and 18 series (Fig. 6). The final regional chronology spans from 1534 to 2020, comprising 353 ring-width series with an intercorrelation of 0.404 ($p < 0.01$). The EPS dropped below 0.85 in the earlier centuries of the chronology (prior to 1865) due to a decreasing sample size. However, since 1740 it remained above 0.80 indicating that these sections of the chronologies still contained a strong population signal.

Among the spatial climate analysis, the new regional tree-ring width chronology showed significant positive correlations with late spring - early summer (November–January) precipitation (r values from 0.23 to 0.53) and significant negative correlations with maximum temperature (r values from -0.23 to -0.46) during the period 1950–2020 ($p < 0.05$, Fig. 7A,B). Similarly, significant correlations were found for 6 months (southern hemisphere spring-summer) and 12 months windows (winter–winter and spring–spring) for both variables (Fig. S4). The highest correlations were found in the temperate rainforest region from northern Patagonia, encompassing the Andes and the lowlands to the west in Chile, and extending toward the eastern Patagonia steppe in Argentina following the Arid Diagonal climatic pattern[102]. The spatial correlation patterns between the regional chronology and the SADA from 1740 to 2020, when EPS > 0.80, displayed the highest significant positive correlations (r values from -0.49 to 0.42) across the *N. obliqua* distribution in the temperate forest biome in Chile, and also extending to the desert steppe at the leeward of the Andes in Argentina (Fig. 7C).

Regarding the relationship between the regional chronology, historical precipitation records and climate reconstructions, our results indicate that the new regional chronology of *N. obliqua* successfully records some historical drought events from central-south Chile (Fig. 8A). For example, documented droughts such as the megadrought of 1770–1782[103–105] coincide with a decline in tree-ring width (Fig. 8A). Drought years that also coincided with a decline in tree-ring width were 1791–1792 and 1800–1803[106], as well as of 1869–1876 (a period of relative dryness interspersed with normal years)[104,106–108], and of 1907–1917 (except for 1914, a wet year)[106,108]. Apparently, wet years were not particularly reflected in the tree-ring chronology (Fig. 8A).

The correlation analysis between the regional chronology and precipitation data from the CRU TS4.08 dataset for the period 1901–2020 yielded an r value of 0.45 ($p < 0.05$), being stronger in the second half of the century (1950–2020, $r = 0.46$, $p < 0.05$), compared to the early Twentieth century (1901–1950, $r = 0.42$, $p < 0.05$) (Fig. 8B). Regarding the Northern Patagonia precipitation reconstruction from Villalba et al.[92], which overlaps with our regional composite chronology from 1740 to 1988, it showed significant correlation values across periods: $r = 0.25$ (1740-1988, $p < 0.05$), $r = 0.31$ (1800–1988, $p < 0.05$), and $r = 0.51$ (1900–1988, $p < 0.05$) (Fig. 8B).

Finally, correlation analyses with the available streamflow reconstructions within the *N. obliqua* distribution range—encompassing the Maule[93], Biobío[94], Imperial[95], and Puelo[96] rivers—, yielded varying results. The Maule river streamflow reconstruction displayed the highest correlation values (Fig. 8C), with $r = 0.22$ ($p < 0.05$) for the entire period (1740–2000), $r = 0.28$ ($p < 0.05$) for 1800-2000, and $r = 0.46$ ($p < 0.05$) for 1900–2000 (Fig. 8C). In contrast, correlations with the Biobío and Puelo streamflow reconstructions were more moderate, with $r = 0.16$ ($p < 0.05$) and $r = 0.15$ ($p < 0.05$), respectively, for 1740–2000, and $r = 0.35$ ($p < 0.05$) and $r = 0.31$ ($p < 0.05$), respectively for 1900–2000. Correlations with the Imperial River streamflow reconstruction were not significant for the evaluated periods.

Discussion

Dendroarchaeological potential of historical *N. obliqua* wood

To the best of our knowledge, this study represents the first initiative dating tree-rings from railroad ties. The historical expansion of railways across Chile contributed significantly to the country's connectivity and economic development in the Nineteenth Century and Twentieth century, while also led to the degradation of *N. obliqua* forests in Northern Patagonia[39,52,54]. This exploitation impacted regional biodiversity with some effects persisting to this day in an ecosystem type that remains underrepresented in Chilean protected areas[110,111]. Additionally, it has reduced the availability of old-growth *N. obliqua* forests and ancient trees, hindering the development of multi-century *N. obliqua* tree-ring width chronologies, with implications for long-term ecological, environmental and paleoclimatological studies in the region[28,112]. By integrating traditional crossdating ring-width methods with wiggle matching of radiocarbon series from railroad ties, this study successfully dated wood samples from these historical artifacts, significantly extending the regional *N. obliqua* tree-ring chronology in Northern Patagonia back to AD 1534. This newly extended chronology, comprising 353

Seq.	ID	N° rings	r*	t-value*	Dating
1	ALC001	143	0.323	4.05	1680–1822
2	ALC002	345	0.175	3.30	1640–1981
3	ALC004	56	0.429	3.49	1640–1695
4	ALC006	71	0.255	2.19	1792–1862
5	ALC009	73	0.271	2.37	1875–1947
6	ALC010	128	0.247	2.86	1818–1945
7	ALC012	131	0.259	3.04	1640–1770
8	ALC013	105	0.532	6.38	1825–1929
9	ALC014	178	0.408	5.94	1764–1941
10	ALC017	37	0.359	2.40	1868–1904
11	ALC018	84	0.398	3.93	1779–1862
12	ALC020	328	0.189	3.48	1534–1861
13	OVA001	75	0.238	2.09	1693–1767
14	OVA002	242	0.264	4.23	1656–1897
15	OVA003	58	0.401	3.28	1915–1972
16	OVA004	23	0.439	2.24	1816–1838
17	OVA005	73	0.348	3.13	1718–1790
18	OVA006	99	0.338	3.54	1839–1937
19	OVA009	110	0.272	2.93	1749–1858
20	OVA010	205	0.331	4.99	1633–1837
21	OVA012	168	0.339	4.64	1607–1774
22	OVA013	42	0.371	2.53	1920–1961
23	OVA016	40	0.345	2.26	1731–1770
24	OVA017	49	0.405	3.03	1646–1694
25	OVA019	81	0.386	3.72	1710–1790
26	OVA021	35	0.512	3.42	1666–1700

Table 2. Characteristics of the *N. obliqua* tree-ring series from railroad ties and corresponding dating statistics. All statistics were calculated from the detrended tree-ring series using a flexible cubic smoothing spline with a 50% wavelength cutoff at 32 years and its temporal persistence removed by autoregressive modeling. ID, sample code; N° rings, number of annual rings; *r*, correlation coefficient with the reference chronology; t-value according to Baillie & Pilcher[74]; Dating, calendar period covered by the sample. *All values are significant at $p < 0.05$.

growth series, enhances previously underrepresented periods, providing a more robust temporal framework. Furthermore, this chronology now constitutes the strongest reference series for dating *N. obliqua* wood, widely used in construction of houses, bridges, and various artifacts and infrastructure[44,47,49], being a valuable new resource for studying past human wood-use technologies and historical environmental conditions.

The dating of railroad ties tree-ring series from southern Atacama Desert, using reference chronologies located further south within the species' distribution in Northern Patagonia, resulted in the longest *N. obliqua* tree-ring record to date, and one of the longest for the genus worldwide. This underscores the regional environmental signal contained in *N. obliqua* tree-ring data, as evidenced by correlations with climate variables (Figs. 7 and 8). Although the obtained intercorrelation was slightly lower than those reported for other regional tree-ring chronologies of angiosperms in southern South America, such as *N. pumilio*[113,114], this outcome may be partially explained by the heterogeneous spatial distribution of individual chronologies into the wide environmental amplitude were *N. obliqua* grows[44], and the likely low-elevation origin of the railroad ties, were higher interspecific competition, combined with greater accessibility for human communities, has historically led to more intensive logging[44]. These factors can introduce greater growth variability, potentially weakening the climate-growth relationship compared to tree-ring chronologies from less disturbed or higher-elevation sites, such as *N. pumilio*[113–115]. Individually, the longest railroad ties tree-ring series showed relatively low correlations with the reference chronology, however we confirmed the dates by identifying the globally recognizable ^{14}C bomb peak, a signal produced by the massive detonation of nuclear tests during the 1960s[79].

Despite the cessation of passenger transport on the railway lines in the study region between 1975 and 1977, freight transport continued until 1987–1992[54]. The last year recorded in our railroad tie chronology was 1981, indicating that the line was actively maintained and repaired at least until then. This finding underscores that the southern Atacama railway network may contain historical wood suitable for tree-ring studies, spanning from its construction in the late Nineteenth Century century through the early 1980s, offering a valuable resource for historical dendroarchaeology and environmental research (Fig. 2H). While historical dendroarchaeology has been widely applied in various regions of the world—such as North America, Europe and Asia—to date buildings, wooden artifacts, and cultural heritage sites[61,116–119], examples from South America remain scarce.
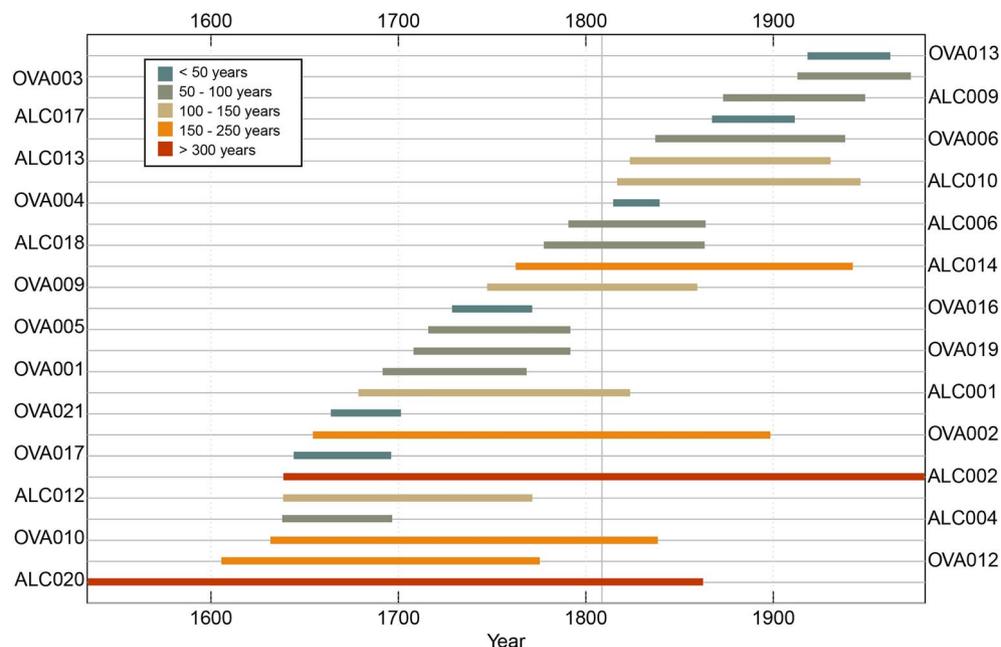
Fig. 3. Temporal extension of railroad ties tree-ring width series arranged chronologically. Horizontal bars represent the extension of each series. Vertical lines show the year since when the composite reference *N. obliqua* chronology from living trees has > 5 and > 10 series, respectively.

In historical archeology, tree-ring research has been used to date a whaling shipwreck from North America discovered on the Atlantic Patagonia coast and to determine the provenance of its wood materials[76]. Similarly, dendrochronology using *Pilgerodendron uviferum* has been employed to corroborate the years of the construction and, similarly to our results with railroad ties, allowed to identify periods of maintenance not recorded in historical documents associated to heritage churches on Chiloé Island in southern Chile[33]. Additionally, studies have examined tree-growth patterns in archaeological wood from *Prosopis tamarugo* and *Prosopis alba* from pre-Hispanic periods in the Atacama Desert[34,35], and dated archaeological sites in the Central Andes back to the 13th century using *Polylepis tarapacana* tree-rings [36]. Nevertheless, the use of historical wood from railroad ties represents an innovative approach in dendroarchaeology studies in South America and beyond, especially since old trees were historically selected for the manufacture of ties due to their wood properties[42]. It should be noted that Domínguez-Delmás et al.[120] proposed the potential use of various wooden structures, including railroad ties, for dendroarchaeological studies in Spain's Iberian Peninsula. This suggests that abandoned railway infrastructure in other regions may serve as valuable sources for similar research, and our study could help foster international research synergies in this field. Previous tree-ring research related to railways has primarily focused on reconstructing disturbance histories and tree ages in a railroad logging camp in Oregon[121], or tracing the history and provnance of timbers used in constructing the Terminal Warehouse connected to the railway lines of New York[118]. Given that the *Nothofagus* genus is widely distributed across Chile, Argentina, Australia, New Zealand, New Guinea and New Caledonia[122], and that *N. obliqua* railroad ties from Chile were exported to several countries including Germany and South Africa[123,124] (Fig. S1), this study opens new avenues for tree-ring research using this historical railway wood in the Global South and beyond. Furthermore, additional species such as oak (*Quercus* spp.), which was widely used for railroad ties[125–127] and has been extensively studied in dendrochronology[64–66], could provide valuable new tree-ring records for this field. By extending tree-ring chronologies from railroad ties, future studies could focus on a variety of research topics, including paleoclimatic records, international historical timber markets, wood properties and species selection for railway ties, the extent of forest exploitation driven by this demand, the current status of remaining old-growth forest, and growth rates comparisons between historical and contemporary individuals of these species.

Dendroclimatic potential of *N. obliqua* chronologies
Utilizing historical wood samples can significantly extend and enhance existing tree-ring chronologies for environmental and climate studies[128,129]. This is especially important in regions where old-growth forests and ancient trees are scarce due to severe historical human disturbance, as is the case with *N. obliqua* forests. Our resulting composite chronology spans multiple centuries and reveals a clear hydroclimate signal across Northern Patagonia (Figs. 7 and 8). Also, significant correlations between the chronology and hydroclimatic reconstructions remark this attribute (Fig. 8).

Spatial correlations between the new regional composite *N. obliqua* chronology and gridded climate data (ERA5) showed significant positive patterns with precipitation and negative patterns with maximum temperature. These correlations were stronger than those reported by Urrutia-Jalabert et al.[16] for specific site chronologies and weather stations, potentially due to a large number of samples that the new chronology has involved. The
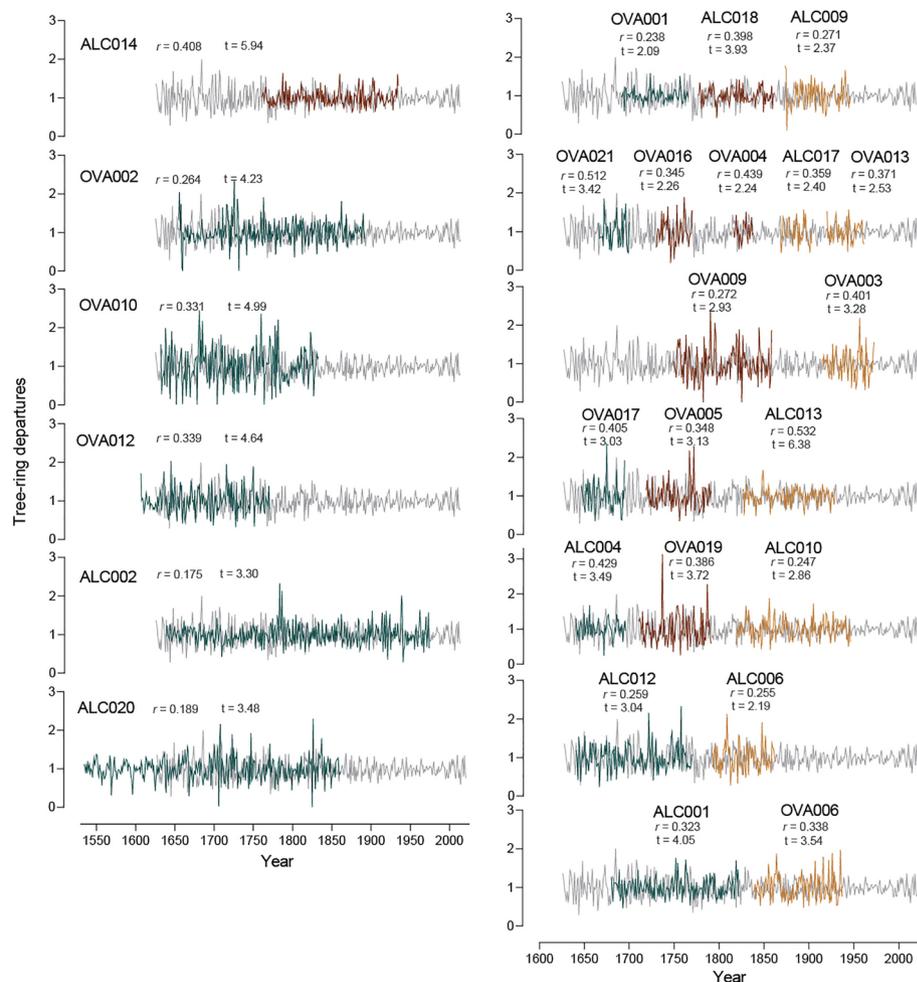
Fig. 4. Residual version of the living trees composite chronology (gray) and the railroad ties superimposed on it (each one named with individual codes). Colors in the time series represent the start period of the first ring for each railroad tie series (dark green = from 1533 to 1700, brown = from 1701 to 1800, and orange = from 1801 to 1915). r = correlations coefficients, and t = t-value statistics for the common period of railroad series and the reference chronology.

precipitation correlation map revealed a strong climate signal across the core of *N. obliqua*'s distribution, as well as in other *Nothofagus* species known for their sensitivity to hydroclimate variability[3,12,13,15]. The correlation map with maximum temperatures highlighted the detrimental effect of warmer summers on *N. obliqua* radial growth, consistent with previous findings for specific site chronologies[16]. The negative effect of spring-summer temperatures on growth has also been reported for other *Nothofagus* species in the area[12,13,15,113]. The strong and significant correlation patterns between our new regional *N. obliqua* chronology and a completely independent paleoclimate reconstruction of soil moisture (scPDSI) represented by the SADA[31], spanning the last 280 years, confirm the consistent hydroclimate signal contained in this tree-ring record. All the spatial correlation patterns between our regional *N. obliqua* chronology and ERA5 precipitation and temperature (period 1950–2020), along with the SADA (period 1740–2020), consistently capture climate variability within the *N. obliqua* distribution area and extend across Northern Patagonia (Fig. 7).

To confirm the accuracy of the new *N. obliqua* chronology as a potential predictor for climate reconstruction, we examined the coincidence of extreme events identified on historical documents and validated climate reconstructions. Our historical analysis, combined with the comparison between the regional chronology and various precipitation and streamflow reconstructions (Fig. 8), reveal significant insights into temporal climate variability. On the one hand, and consistent with the positive relationship between *N. obliqua* tree growth and precipitation[16] [and this study], our composite chronology effectively captured all the documented dry periods through a decline in ring-width (1764–1784, 1791–1792, 1800–1803, 1869–1876, 1907–1917, Fig. 8A). The latter period has been described as a prolonged dry decade, with 1914 being an exception as a wet year[106,108], a pattern that is distinctly reflected in our tree-ring chronology (Fig. 8A). Unlike droughts, wet years were not clearly recorded in tree-rings, due to the decreasing sensitivity of tree growth to rainfall above a certain threshold, as documented by Villalba et al.[92].
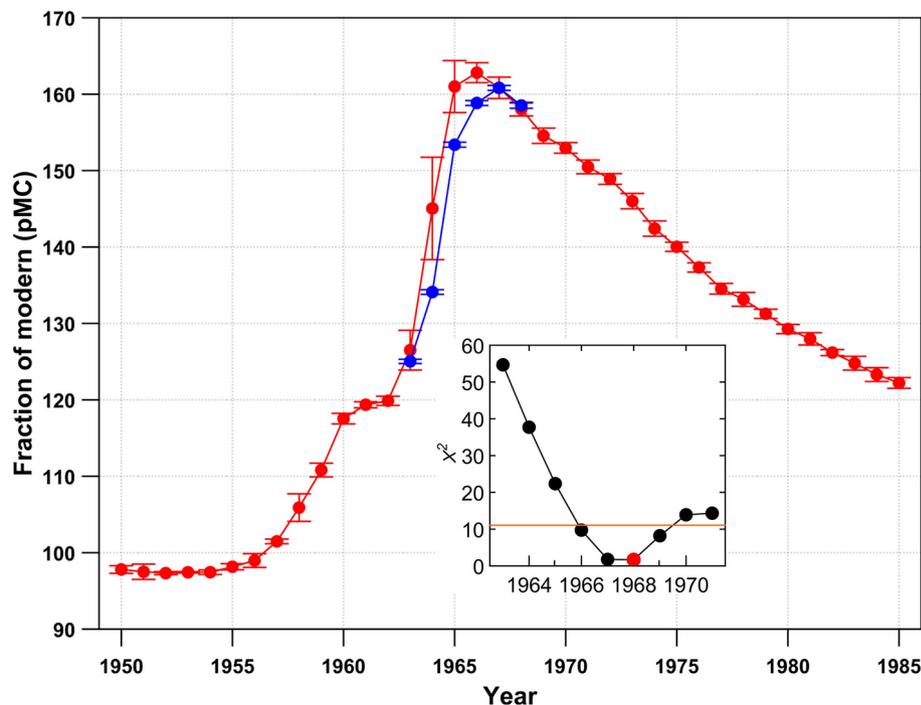
Fig. 5. ^{14}C wiggle matching of the *N. obliqua* ALC002 tree-ring sample using as a reference curve the series of the ^{14}C content in annual rings from the Southern Hemisphere zone 1-2 developed by Hua et al.[80] (curve in red). Six consecutive years (blue) of the *N. obliqua* ALC002 series wiggle-matched to the exact calendar year during the bomb peak period. Inset plot: output of the Chi-square ($χ^2$) Monte-Carlo test at 95% probability (horizontal orange line), t-statistic= 11.07; df = 6, the red dot indicates the lowest $χ^2$ value ($χ^2 = 1.7$; maximum probability) indicating the calendar year of the most recent year of the ^{14}C *N. obliqua* series.

On the other hand, our analyses relating the regional composite chronology with hydroclimate reconstructions, further support these findings. A stronger relationship was observed between our tree-ring chronology and the northernmost studied river (Maule, Fig. 8C). The Maule River watershed is located within the north Mediterranean-temperate transition zone, where *N. obliqua* thrives at its northern distribution limit[93]. This streamflow reconstruction better reflects periods of water scarcity[93], aligning with the drought signals in our chronology. The correlation decreases for southern rivers, possibly due to increased precipitation and reduced dependence on groundwater storage, which may buffer tree growth against short-term droughts[130,131].

These findings highlight the potential of combining tree-ring width chronologies from living *N. obliqua* trees with historical wood from railroad ties to enhance the temporal coverage and improve data resolution for future climate reconstructions. This approach could significantly improve dendroclimatic studies using a species that has not been employed for this purpose before. Future research integrating this extended dataset could refine our understanding of long-term climate variability in the region and improve hydroclimatic reconstructions for southern South America, and at the same time could provide a new paleoclimatic time series to compare the climate variability between Andean and low-elevation areas.

Implications and future directions

The lack of precise documentation regarding the origin of the trees, felling dates, and the initial installation and maintenance of railway lines poses challenges that must be addressed. Our findings emphasize the importance of continuing research on these historical structures, as they represent a valuable data source for dendrochronological and environmental studies. *N. obliqua* from other historical infrastructures such as beams, bridges, tunnels and warehouses, could potentially provide even longer environmental records and historical information about other human activities in the past. Also, developing new *N. obliqua* chronologies from remaining relict old-growth forests in protected areas, would greatly improve the cross-dating of historical wood samples. The absence of the inner trunk arc in most analyzed wood samples—likely due to rooting—suggests that the original trees were significantly older than the rings we were able to date. Given the lack of information regarding the provenance of the railroad ties, future studies are encouraged to incorporate genetic analyses and advanced techniques such as isotopic signatures and chemical fingerprints[132] to better determine the origin of the wood, facilitating a more precise identification of the source forests. Loader et al.[133] suggest that the use of oxygen isotope chronologies could improve the dating quality of wood samples by refining the accuracy of complacent ring sequences in master chronologies. However, the contamination of the railroad ties with creosote and other compounds[46] may present challenges for this approach. Creosote—an oily preservative derived from tar, petroleum or wood tar— was widely used in railroad manufacturing to increase durability and to protect the wood from rot, fungi and insect infestations[46]. Additionally, compounds soluble in organic solvents such as pentachlorophenol, and
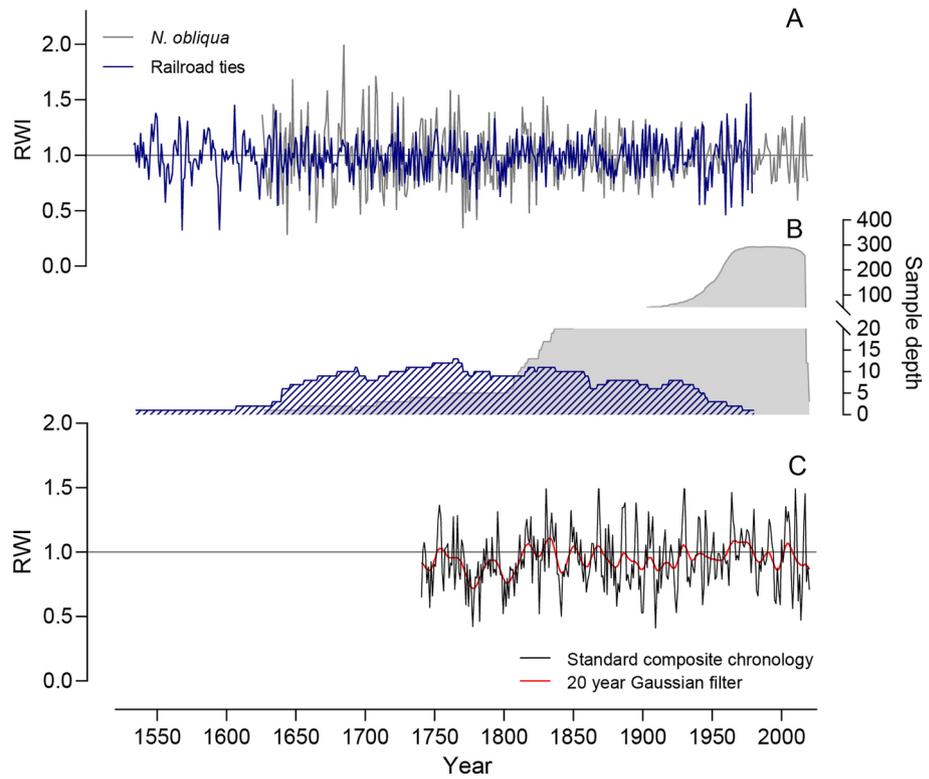
Fig. 6. (**A**) Comparison between the residual versions of the living-trees (gray) and railroad-ties (blue) *N. obliqua* chronologies, (**B**) sample depth of each chronology, (**C**) standard version of the *N. obliqua* regional chronology composed by tree-ring series from living trees growing in the temperate forests of southern Chile and railroad ties series collected in the southern Atacama Desert. The chronology was plotted from the year when EPS > 0.80. The red line represents a 20-year Gaussian filter.
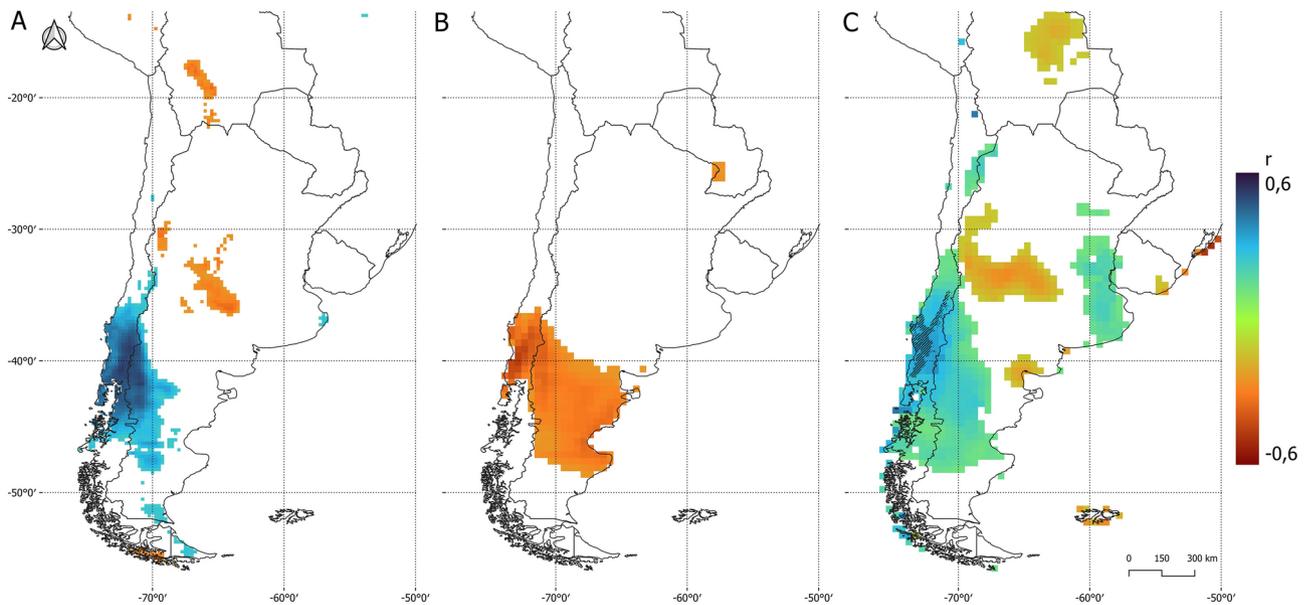
Fig. 7. Spatial correlation maps between the regional *N. obliqua* tree-ring width chronology composed by tree-ring series from living trees and railroad ties, and: (**A**) late spring - early summer (November–January) ERA5 precipitation during the 1950–2020 period, (**B**) mean late spring - early summer (November–January) ERA5 maximum temperature during the 1950–2020 period, and (**C**) Austral summer self-calibrated Palmer Drought Severity Index (scPDSI) field reconstruction indicated by the South American Drought Atlas (SADA) for the 1740–2020 period. The black dashed lines in panel C indicate the approximate *N. obliqua* forest distribution in Chile. Only significant correlation values ($p < 0.05$) are shown.
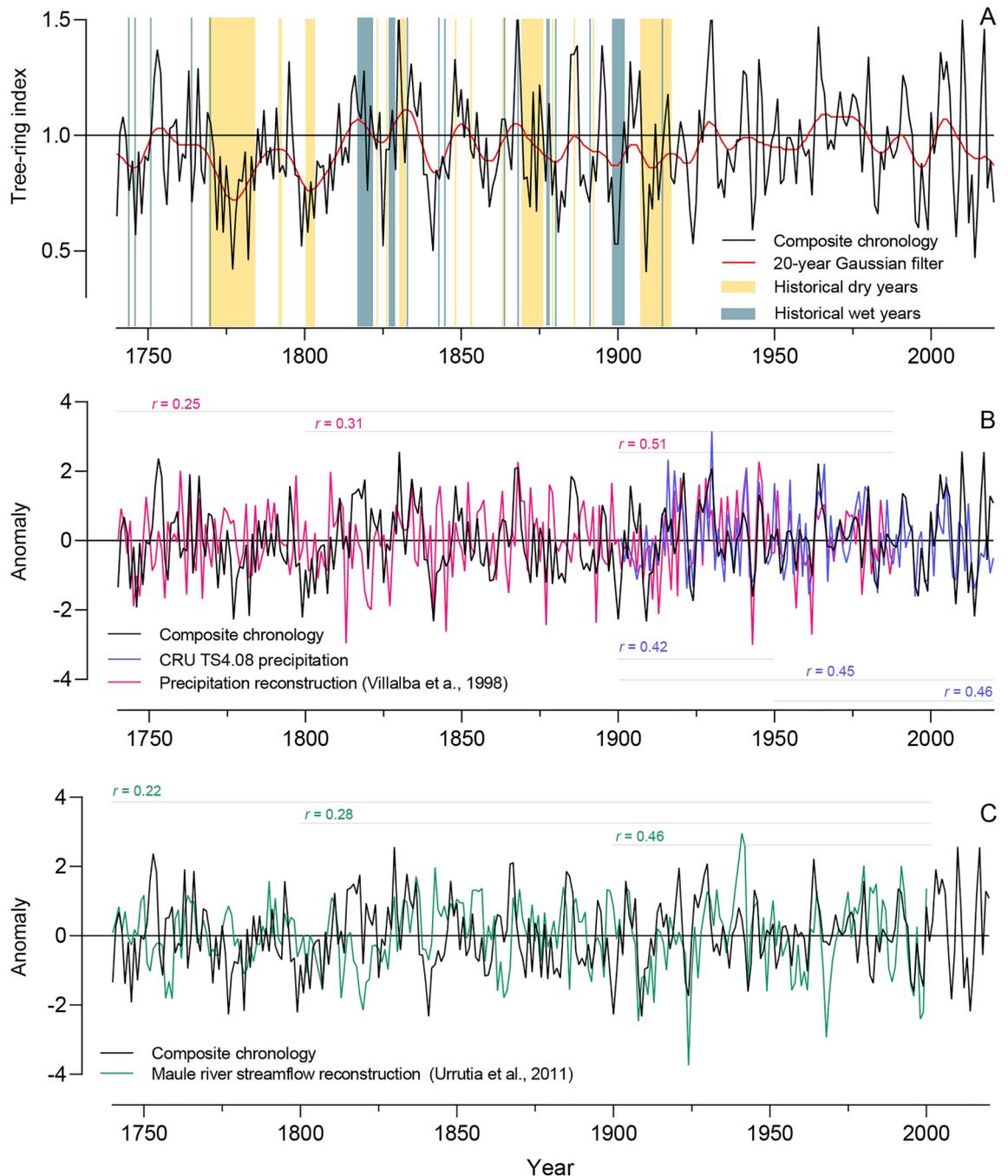
Fig. 8. Comparison of the regional composite chronology with historical precipitation records and climate reconstructions. (**A**) Standard composite chronology (black line) smoothed with a 20-years Gaussian filter (red line), alongside historically identified dry years (yellow bars) and wet years (blue bars), according to Ortlieb[98], Steiger et al.[103], Vicuña Mackenna [104], Taulis[106], Camus & Jaksic[107], "El Diario Austral de Temuco" newspaper[108], Carvallo Goyeneche[109]. Comparison of the composite chronology with: (**B**) precipitation from the CRU TS4.08 dataset (1901–2020) (blue line) and the precipitation reconstruction for Northern Patagonia (1740–1988) (magenta line) by Villalba et al.[92]; (**C**) Maule River streamflow reconstruction (green line) from Urrutia et al.[93]. In both panels, significant correlation values (r (p < 0.05)) are shown for three different periods.

soluble salts such as zinc chloride or fluoride, copper sulfate, among others, were also extensively used in Chile during the 60s and 70s for wood preservation[46]. Once installed, many railroad ties may have been exposed to heavy mining load in northern Chile[52], which could have introduced additional sources of contamination. The living trees used for railroad ties were likely not exposed to contaminants before processing[46].

The railroad ties, previously central to the country's railway infrastructure, now offer an important resource for environmental and earth science research, and can contribute valuable information for archeological,

historical and socio-ecological studies. This places the railway's significance as an essential part of Chile's cultural heritage. The remaining past railway infrastructure, including abandoned railroad tracks in the Atacama Desert, are key for future tree-rings studies across south-central Chile, and constitute a unique archive for the study and the understanding of the historical relationship between humans and the forest.

Final remarks

The results obtained through traditional crossdating methods, strongly developed in dendrochronology field, corroborated by radiocarbon wiggle matching using the bomb-peak, and the presence of well-preserved tree-ring samples over 300 years old, underscore the scientific importance of this tree-ring heritage. The strengthened *N. obliqua* chronology developed here is not only valuable for climate reconstructions but also for socio-environmental studies on the forests of southern Chile and the human impacts on them, being one of the only vestiges to contain long-standing information about the growth of the trees in the past. However, the preservation of Chile's railway heritage is currently at risk, threatened by the theft of railroad ties and the looting and disappearance of stations. This underscores the urgent need for protection measures to safeguard this historical legacy.

The abandoned railway network in parts of the Atacama Desert not only tells the history of Chilean industrialization processes and economic development, but also contributes significantly to socio-environmental research in ecology, anthropology, archaeology, history, heritage studies and geography. Preserving Chilean railway infrastructure contributes to safeguarding national cultural heritage and documenting the historical role of British engineering and mining companies in the region. Integrating railway history with tree-ring research offers an opportunity to connect Chile's industrial past with contemporary efforts toward sustainability. The abandoned railroad ties in the Atacama Desert emerge as a witness of the human impact on earth at regional and global scales, reflecting the exploitation of native forests in Patagonia and the massive detonation of nuclear bombs in the Northern Hemisphere.

Data availability

The data generated during the current study are available from the corresponding author on reasonable request.

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Author contributions

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Competing interests

The authors declare no competing interests.

Additional information

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