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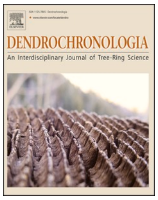

Examining the potential of *Austrocedrus chilensis* tree rings as indicators of past late-spring frost events in central Chile

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ABSTRACT

Austrocedrus chilensis is a South American conifer broadly distributed across the subtropical and extratropical Andes that is widely utilized in tree-ring studies. This species has clear annual growth rings that are sensitive to the moisture supply and has been extensively used to reconstruct the past hydroclimate during the last millennium. Despite a great number of dendrochronological studies based on tree-ring width, little is known about the potential of the species to record intra-annual anomalies and particularly frost rings. In this study, the main traits of *A. chilensis* frost rings were studied and the ability of this endemic Cupressaceae to record spring frosts at five sites across a latitudinal gradient between the Mediterranean and Northern Patagonian Andes was evaluated. The average ages of trees in the study sites varied from 168 to 343 years, with minimum and maximum ages of 33 and 919 years. The results indicated that 85% of the frost rings occurred at the beginning of the earlywood and 15% showed a mid intra-ring position. Regarding the portion of the ring circumference affected by frost damage in cross sections, 59% of the injuries partially affected the entire ring, 30% affected the complete ring circumference, and 11% resulted in a ring fracture. Freezing temperatures that generated frost rings in *A. chilensis* from the upper treeline coincided with events below 0 °C recorded in the agricultural Central Valley of Chile. We estimated the potential time window of the formation of *A. chilensis* frost rings over a two and a half month period from the end of September to mid-November (early spring). Our results indicated that tree age was a determinant factor affecting the ability of trees to record frost rings. The maximum frequency of frost rings occurred at 12 years and the maximum age at which 95% of the total frost injuries occurred within our network was about 120 years. Both the exceptional longevity and the excellent state of preservation of relict wood demonstrates that *A. chilensis* frost rings provide a reliable proxy for monitoring and reconstructing late-spring frost events in central Chile.

1. Introduction

Anatomical traits of the secondary xylem can provide detailed information about abiotic and biotic factors affecting xylogenesis (Wimmer, 2002; Bräuning et al., 2016). Anatomical xylem features, such as cell size, wall thickness, density fluctuations and frost rings are particularly valuable to understanding the response of woody plants to extreme climatic and meteorological events (Schweingruber, 2007). Among the anatomical anomalies recorded in wood structure, frost rings are considered the result of alterations in the xylogenesis process due to the occurrence of abrupt below-freezing episodes during the growing season (Lee et al., 2007). These intra-ring anomalies consist of underlignified, deformed tracheids and bend wood rays, along with the proliferation of parenchyma cells, among other abnormal xylem traits (Lee et al., 2007; Barbosa et al., 2019; Hadad et al., 2019). Frost rings have been studied in several tree species, especially in conifers of the

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Northern Hemisphere (LaMarche and Hirschboeck, 1984; Dy and Payette, 2007; Hadad et al., 2020; Tardif et al., 2020). They are among the most radical trauma caused by extreme temperatures in woody tissue and their characteristics are unequivocal, leaving a permanent imprint within tree rings (Lee et al., 2007; Bräuning et al., 2016).

Late-spring frosts are extremely harmful as they occur at the beginning of the growing season when plants enter labile phenological stages, generating large impacts in agriculture (Rodrigo, 2000; Sharma, 2012; Zohner et al., 2020). Boreal, temperate and Mediterranean regions are prone to late-spring frost events causing severe damage to agricultural crops and woody species (Sangüesa-Barreda et al., 2021; Olano et al., 2021). Although Mediterranean regions represent only 2% of the planet's continental surface, they are crucial for agricultural production (del Pozo et al., 2019). In Chile, the Mediterranean region covers all of central Chile (~30° to 37°S). This area is intensively used for agriculture, horticulture, viticulture and fruit production, where increasing late-spring frost events have become one of the climatic extremes causing serious economic impacts on agricultural production. (Santibáñez et al., 2017; Bravo et al., 2020). In order to retrospectively study the incidence and extent of late-spring frosts, frost-ring chronologies from freeze-sensitive tree species may be used. Much of the frost-ring studies have been conducted using conifers that have demonstrated their reliability in reconstructing extreme weather events (Kern and Popa, 2008; Payette et al., 2010; Waito et al., 2013; Hadad et al., 2020). Tree populations in mountainous open woodlands are suitable for developing frost-ring chronologies because their forming xylem is prone to suffer damage from low temperatures below a threshold that typically triggers frost-rings formation (Panayotov and Yurukov, 2007; Kidd et al., 2014; Gurskaya et al., 2016).

Late-spring frost damage in trees results from the interaction between two meteorological drivers (Vitasse et al., 2018; Ma et al., 2019): (1) warmer spring temperatures that promote xylogenesis and resumption, and (2) late-spring freezing temperatures that damage immature wood cells. Provided the observed warming of the climate, plants have been exposed to longer growing seasons (Schwartz et al., 2006) and, consequently, crops and forests face a higher risk of damages associated with late-spring frosts as their growing season starts earlier (Vitasse et al., 2018).

In South America, all of the frost-ring studies to date have been developed in northern Patagonia using *Araucaria araucana* (Molina) K. Koch (pehuén) along the forest steppe ecotone (Villalba and Roig, 1986; Hadad et al., 2012, 2019; Arco Molina et al., 2016) and tree-ring widths of *Nothofagus pumilio* (Poepp. & Endl.) Krasser (lenga) (Sangüesa-Barreda et al., 2019). Further north, in the Mediterranean region of central Chile, *Austrocedrus chilensis* (D. Don) Pic. Serm. & Bizzarri (ciprés de la cordillera) (Cupressaceae) emerges as an excellent candidate to study late-spring frosts as it grows throughout the entire region, usually from 800 to 2200 m a.s.l., therefore showing freeze-sensitive tree rings (Rojas-Badilla et al., 2017). This species can also reach up to ~1500 years in age (Le Quesne et al., 2014). Due to the decrease in temperature with the rise in elevation by a rate of 0.6 °C per 100 m in the Andes of central Chile (Iribarren Anacona et al., 2014), the occurrence of late-spring frosts in the lowlands could easily overcome the minimum temperature threshold that produce frost rings in the mountainous forest sites. However, frost-rings formation and its relationships with late-spring frost occurrence have not yet been studied in the upper elevation woodlands of *A. chilensis*.

In this study, tree-ring material from five upper treeline populations of *A. chilensis* in the subtropical Andes of Central Chile were examined. Frost rings on the cores of living trees and cross sections from relict wood were identified and both their intra-ring position and the severity were recorded to assess their correspondence with minimum temperature records in the study area. Finally, we developed a probabilistic model to assess the ages of trees when frost rings occurred.

2. Materials and methods

2.1. Study area

The study area extends along a latitudinal gradient in the Mediterranean region of central Chile from the boundary with the semi-arid climate of the north and the temperate climate of the south (33°–39° S; Fig. 1) (Kottek et al., 2006; Christie et al., 2011). Mean annual precipitation ranged from 300 mm in Santiago (33.5º S) to 1200 mm in Temuco (38.8° S) (Quintana and Aceituno, 2012). Precipitation arises from frontal systems from the Pacific Ocean, which precipitate as snow in the Andes (Masiokas et al., 2013). More than 70% of the total annual precipitation occurs in the winter (May-August), resulting in a dry season from late spring to early autumn (October to April). The Rengo Metrological Station (310 m a.s.l.; 34°24'S) represents the typical conditions of the Central Valley of Chile, with a mean annual precipitation of 520 mm, and mean minimum temperatures of 4 °C in the winter (June-August), 8 °C in the spring (September-November), and 12 °C in the summer (December-February).

2.2. Study species

Austrocedrus chilensis woodlands in central Chile constitute a Mediterranean-type ecosystem between the southern border of the Atacama Desert in the north and the deciduous–evergreen temperate forests in the south (Donoso, 1982), reaching up to 1500 m a.s.l. in the Andes as a discontinuous treeline (Armesto et al., 2007). *Austrocedrus chilensis* is an endemic conifer tree species that typically grows in xeric rocky habitats (Villagrán et al., 1998) from 32°39′ S to 43°30′ S in Chile and 36°30′ S to 43°35' S in the northern semiarid Patagonian steppe of Argentina (Donoso, 1993). Throughout its distribution area, isolated populations occur on steep slopes at elevations from 900 to 2200 m a.s.l., where it can reach more than 1500 years old (Le Quesne et al., 2006, 2014). In contrast, at its southern limit, which occurs at 400 and 800 m a.s.l., it can reach ages of five to six centuries (Villalba et al., 1998). *Austrocedrus chilensis* possesses clear annual rings (Roig, 1992) and its dead wood remains in fact for centuries before decaying, allowing for century to millennial long tree-ring chronologies to be developed (Le Quesne et al., 2006).

2.3. Field and laboratory work

We sampled five old-growth *A. chilensis* woodlands covering 4° of latitude in the Mediterranean Andes between 2.020 and 1.030 m a.s.l. (Fig. 1; Table 1; Fig. S1). The wood material used for this research was collected during several field campaigns following standard dendroclimatological criteria to develop hydroclimate reconstructions (Fritts, 1976; Stokes and Smiley, 1996). Long-lived living trees growing in rocky escarpments and relict wood from dead trees were selected to develop multi-century registries. In addition, two 5 mm cores were collected with increment borers at heights less than 1 m above ground from living trees greater than 0.2 m in diameter. Cross sections of relict wood were gathered using a chainsaw from fallen and partially buried well-preserved dead trunks. Cores and cross sections were polished using increasingly finer sandpaper up to 800 grains cm^{-2} until wood cells were clearly distinguishable in transverse sections under magnification. All tree-ring series were visually dated and ring widths were measured under a Nikon SMZ800N microscope with a measuring stage (Velmex Inc., Bloomfield NY, USA) to the nearest 0.001 mm. The COFECHA program (Holmes, 1983) was used to quantitatively identify cross-dating errors due to partially absent rings, false rings or incorrect measurements.

Using the complete cross sections of *A. chilensis,* we identified frost rings and classified the types of damage according to the intra-ring position and the affected proportion of the tree-ring circumference (Schweingruber, 2007). Moreover, we determined two types of frost

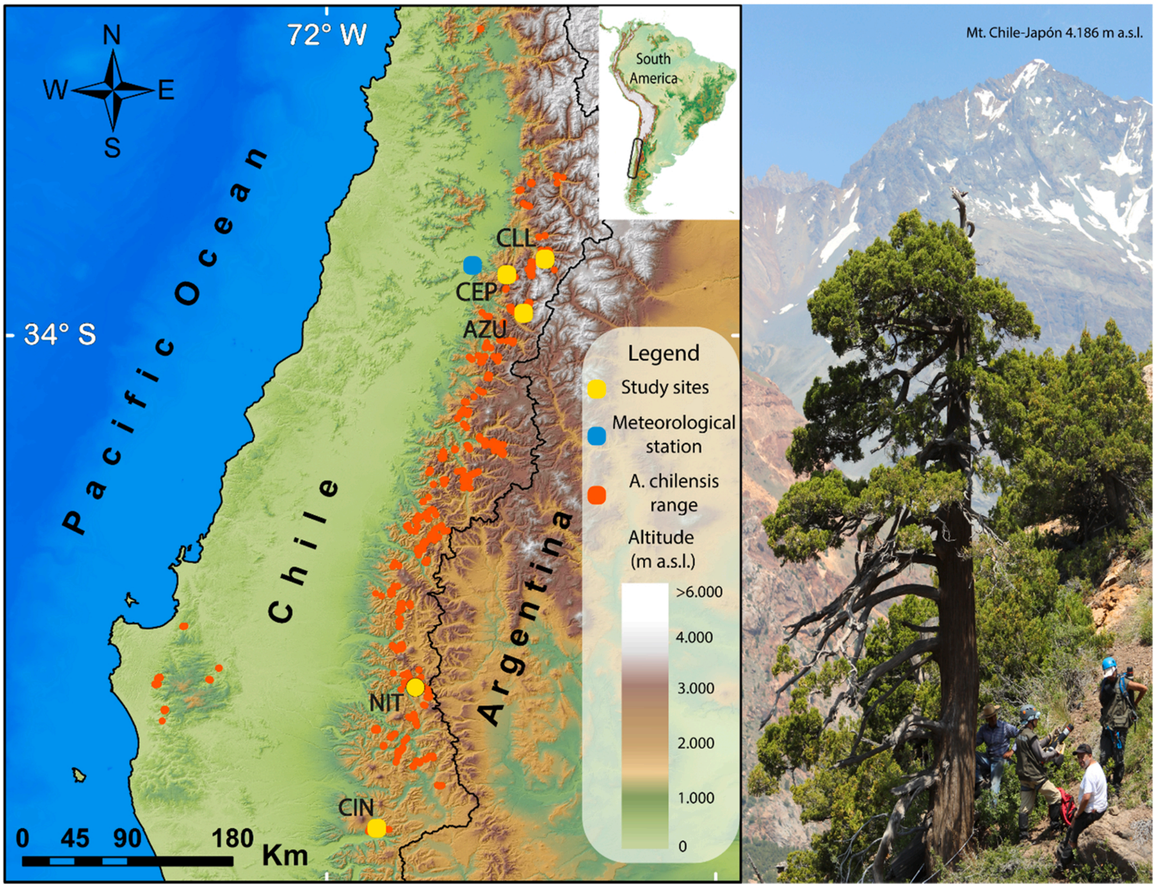

Fig. 1. Map indicating the distribution range of *Austrocedrus chilensis*, and location of the study sites and the Rengo Meteorological Station. The image on the right corresponds to a sampled *A. chilensis* individual in the Andes of central Chile.

Table 1
Characteristics of the sampling sites and the sampled trees, arranged from north to south in the Mediterranean Andes (CLL, CEP, AZU) and the Temperate Andes (NIT, CIN) of Chile. The number of tree rings with the position within the earlywood of frost rings identified on cross sections with pith, as shown in Fig. 2, and the severity of damage in frost rings along the complete cross sections are shown.

Site	Cipresillos	El Cepillo	Azufre	Nitrao	Cabeza de Indio
Code	CLL	CEP	AZU	NIT	CIN
Altitude (m a.s.l.)	1500–1990	1603–2023	1619–1750	1030–1490	1367–1710
Latitude (S)	34°26'24	34°32'49	34°48'55	37°41'52	38°46'26
Longitude (W)	70°18'41	70°34'2	70°29'37	71°17'55	71°34'46
Aspect	SW	N-NW	S	N	N
Period (years)	879–2012	439–2013	1172–2013	1339–2005	1740–2016
Average tree age (years)	343	302	283	238	168
Age range (years)	121–761	49–919	115–531	77–521	33–273
N° of examined series (trees)	118 (68)	135 (80)	96 (52)	109 (66)	51 (36)
N° of series (trees) with frost rings	20 (20)	57 (53)	56 (41)	53 (33)	27 (17)
N° of cross sections with frost rings	12	27	21	13	4
Position within the earlywood					
Start	54	288	101	58	14
Middle	11	41	35	5	0
Severity in cross sections					
Partial	49	171	85	42	11
Complete circumference	10	130	22	18	2
Fracture	6	27	29	4	1

injuries, bearing in mind whether they occurred at the beginning or in the middle part of the earlywood. In regards to the portion of the circumference of the ring affected by frost damage, we considered three types: partial, along the entire ring contour, and with separation of the wood tissue along the frost injury (fracture).

In the tree-ring samples with pith, the zero cambial age was determined as that of the pith. In samples that did not present pith, but rather a full arch formed by the most inner available tree rings (wood cores or cross-sections without pith), the number of missing rings to the pith was estimated using the geometric method developed by Duncan (1989) in order to determine the cambial age. A total of 509 series were studied in search of frost rings, 293 series from living individuals and 216 series from relict wood.

2.4. *Exploring frost rings according to tree ages*

To obtain a diagnostic of the frequency distribution of frost-ring formation as a function of cambial age, the Cullen and Frey graph (Cullen and Frey, 1999) was calculated for every study site, as well as for all study sites combined using the fitdistrplus package (Delignette-Muller and Dutang, 2015) in the R environment (Core Team, 2018). We used the cardidates package (Rolinski et al., 2007) in the R environment (Core Team, 2018) to obtain distribution traits and diagnostic statistics to decide which function fit our data best. Then, for the best fitted models, at every study site and for all study sites combined, we also used the cardidates package to calculate the Akaike information criterion (AIC) so as to obtain basic statistics, such as the coefficient of determination (R^2), the age of maximum fitted frequency of frost rings, and the age of 95% frequency for the real and best fitted models. Finally, using a 40-year old record of daily minimum temperatures from the Rengo Meteorological Station, we explored the extreme spring frost events recorded in the lowlands. In addition, we compared the observed sequence of frost rings in El Cepillo site with a record of minimum temperatures from the Rengo Meteorological Station (Fig. 1) to establish a link between frost-ring formation and late-spring frost occurrence. Tree-ring series from El Cepillo, which is near the Rengo Meteorological Station, showed a good replication of young and mature trees from which frost rings were identified.

3. Results

3.1. *Frost rings in Austrocedrus chilensis*

In this study, a total of 509 tree-ring series obtained from 302 individual trees were analyzed, among which 213 series from 164 trees exhibited frost-ring registries (Table 1). The study site with the longest frost-ring record was El Cepillo, ranging from the 7th to the 20th century (Fig. S1). The average tree age per site was close to 310 years in the northern sites (CLL, CEP, AZU) and 200 years in the southern sites (Table 1). We identified 607 frost rings in the tree rings of 77 complete cross sections, among which 84.8% of the injuries were located at the beginning of the earlywood, while 15.2% were located in the middle part of the earlywood (Fig. 2, Table 1). According to the portion of the ring circumference affected by frost damage, 59% of the injuries partially affected the ring contour, 30% occurred throughout the ring, and 11% of the injuries resulted in fracture (separation) of the woody tissue. It should be noted that frost damage causing wood fractures occurred in the first 55 years.

3.2. *Relationship between earlywood frost rings and late-spring frosts*

At the El Cepillo site, the frost rings recorded in two young trees were compared with recent late spring frost episodes at the Rengo Meteorological Station in the Central Valley of Chile. Temperature extremes that generated frost damage in *A. chilensis* individuals at the upper treeline coincided with events below 0 °C recorded at the weather station (Figs.1, 3). Using the adiabatic air cooling rate (ca. 0.6 °C / 100 m), it was estimated that frost rings occurred in *A. chilensis* populations in the Mediterranean Andes of Chile at temperatures of ≤ −9 °C.

Five earlywood frost rings recorded in 1972, 1979, 1981, 1991 and 2003 in young *A. chilensis* trees in El Cepillo coincided with sub-zero temperature events recorded in the spring at the Rengo Meteorological Station (Fig. 3). The first four studied events showed that minimum daily temperatures ranging between −8 and −12 °C occurred between September and the second half of October. In 2003, temperatures reached −10 °C in the first days of September, with no observed records exceeding the −8 °C threshold in the following days. Three occurrences of minimum temperatures below −12 °C were recorded in early September (September 1, 1974 and September 3, 1986 and 1996).

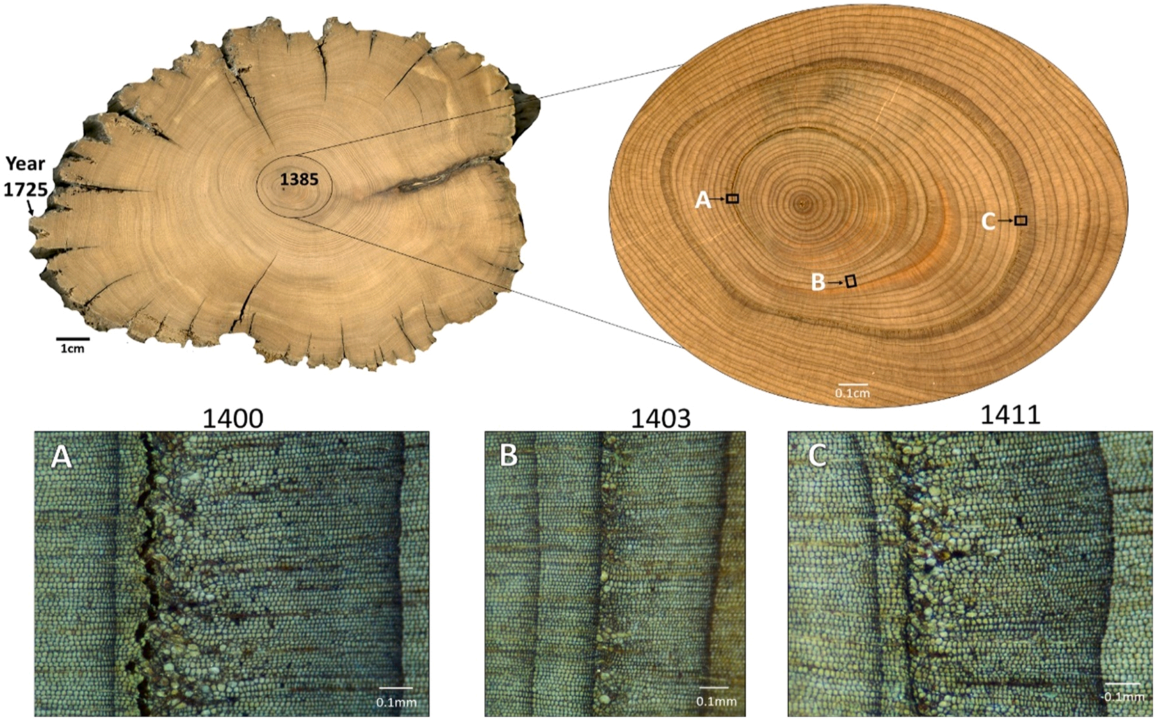

Fig. 2. Cross section with pith in the year 1385 showing three types of frost rings observed by the time the tree was 15, 18 and 26 years old (calendar years 1400, 1403 and 1411, respectively): (a) freeze-damaged cells at the beginning of xylogenesis during the year 1400 with a fracture across a section of the whole ring circumference, (b) freeze-damaged cells at the beginning of xylogenesis during the year 1403 partially reordered, and (c) freeze-damaged cells at the beginning of xylogenesis during the year 1411 across the entire ring circumference.

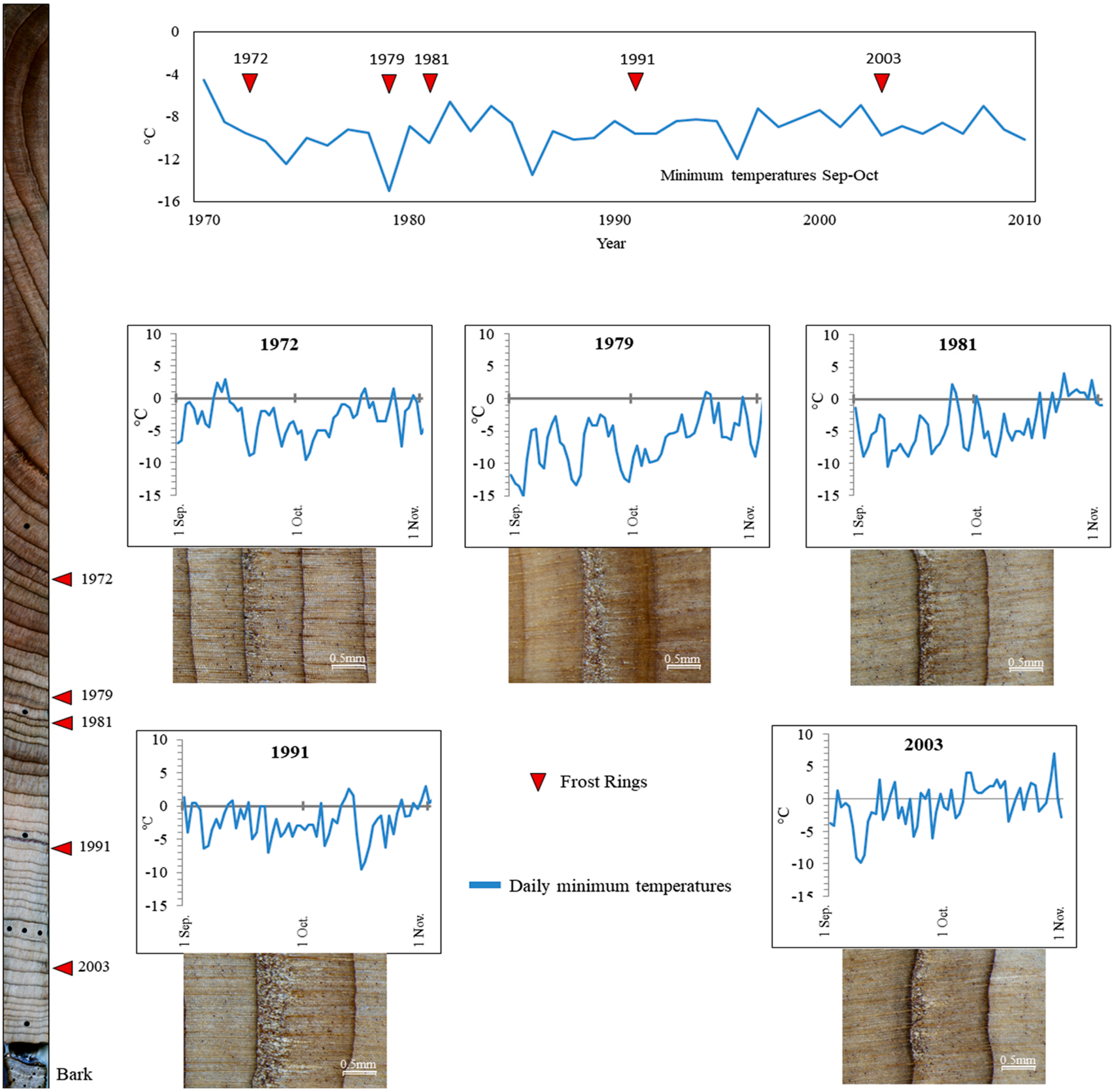

Fig. 3. Example of a core sample of *A. chilensis* from a live tree growing at 2000 m a.s.l. at the El Cepillo site. For the years 1972, 1979, 1981, 1991 and 2003 frost rings are shown, as well as the corresponding late spring (September-October) daily minimum temperature series for each of the five events. Temperature data was recorded at the Rengo Meteorological Station and extrapolated using the adiabatic air-cooling rate. The upper graph indicates the absolute late-spring (September-October) minimum temperatures for the period 1970–2010.

3.3. *Distribution of earlywood frost rings according to cambial age*

In this study, 961 frost rings (607 in cross sections and 354 in cores) were identified from a total of 143,197 tree rings examined. The tree-ring series with frost rings showed a wide time range, from the year 650 to the present, with fewer and younger samples towards the south. The period with the highest frost-ring replication was between 1700 and 1850; the 20th century was not covered in samples taken from three sites (CLL, AZU, NIT; Fig. S1).

The distribution of frost rings in this study (<1 m in height), as a function of age, showed a clear tendency for damage to occur in younger individuals. As longevity increased, the ability of *A. chilensis* to record damage drastically decreased (Fig. 4). The highest frequency occurred in specimens under 50 years of age, with a maximum of ca. 12 years of age. Interestingly, the northern sites recorded maximum frequencies at ages close to 20 years, while at the southern sites ages with maximum frequencies were between 6 and 9 years old. The Cullen and Frey graphs (Fig. S2) indicated that the observed frost-ring frequencies, for every study site and for all study sites combined, were related to cambial ages following a function of the beta family, and more specifically according to a Weibull function, as the AIC and R^2 values indicated (Table. S1). The maximum longevity at which the majority (95%) of *A. chilensis* individuals presented frost rings was estimated to be around 115 and 129 years, according to the current distribution, as well as the one fitted by the Weibull distribution (Table S1). Furthermore, some frost rings were also recorded in older trees, up to 350 years old (Fig. 4).

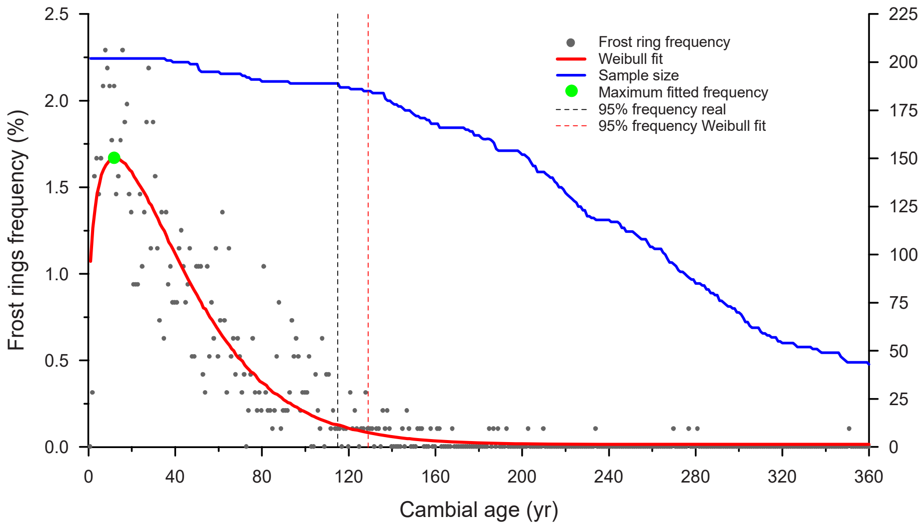

Fig. 4. Frequency distribution of *Austrocedrus chilensis* frost rings and cross section samples with pith of all the study sites as a function of the cambial age of occurrence. Red line indicates the fitted Weibull distribution of the frequency of frost-rings determined using the cardidates R package (Rolinski et al., 2007). Frequency of frost-rings, radii sample size, maximum fitted frequency and the 95% cumulative frequency for real data and Weibull fitted distribution, as a function of cambial age, are shown.

Among the complete set of samples studied, only 10 cross sections showed frost rings at cambial ages more than 120 years old, which corresponded to small trees with an average diameter of 25 cm. Of these, four cross sections showed quite eccentric growth, with the center displaced towards the edge, and three were Krummholz specimens with creeping trunks located at the upper tree limit. In addition, one sample showed a frost ring at a cambial age of 200 years, immediately after a fire scar with characteristic wood discoloration.

4. Discussion

4.1. Earlywood frost rings in Austrocedrus chilensis

Distinctive earlywood frost rings attributable to frost injuries in the xylem of *A. chilensis* were detected in five sites at the upper treeline over a vast area in the Andes of central Chile. Considering that 85% of the frost rings found occurred at the beginning of the earlywood, it is likely that most frost rings occurred early in the growing season associated with late-spring frost occurrences. This is consistent with findings from various species of Pinaceae from the Northern Hemisphere (Rhoads, 1923, 2010; Kidd et al., 2014; Gurskaya et al., 2016), as well as with *A. araucana* (Arco Molina et al., 2016; Hadad et al., 2019, 2020) and species of Cupressaceae (Villalba and Roig, 1986) from southern South America.

In this study, the low proportion of *A. chilensis* tree rings showing frost rings (ca. 0.67%) was less than the 1% previously reported by Rojas-Badilla et al. (2017). These rates are also lower than those estimated for Pinaceae in southern Europe (Panayotov et al., 2012; Di Filippo et al., 2021) and in *A. araucana* in southern South America, with < 0.8% of injured tree rings (Hadad et al., 2012). The highest rates of frost-ring formation were observed in boreal conifers, where 4–40% of the rings may be damaged by extreme sub-zero temperature events (Payette et al., 2010; Waito et al., 2013). When considering the total number of tree-ring series of *A. chilensis* studied (ca. 500), more than 40% of the analyzed samples showed frost rings, i.e. in four of the five studied sites. These numbers are similar to those (40–47%) found in Macedonian pine (*Pinus peuce* Griseb.) in sites of the upper treeline in Bulgaria (Panayotov and Yurukov, 2007).

One third of the frost rings observed in this study were visible along the entire tree-ring circumference, whereas ca. 59% of them affected solely a portion of the tree circumference. These results may be contrasted with those shown by Gurskaya and Shiyatov (2006) in subarctic conifers of the Southern Urals, where the majority of frost rings occurred on the entire ring circumference. This imposes restrictions for sampling if based merely on wood cores obtained with increment borers. Gurskaya and Shiyatov (2006) suggested increasing the number of sampled cores and considering different orientations with perpendicular radii near the stem base to ensure detection of frost rings. Site topography and growth form of *A. chilensis* trees in the Mediterranean Andes often prevents obtaining wood cores in different orientations at the stem base. It is therefore advisable to obtain at least two perpendicular cores covering most of the tree diameter at the lowest possible height above ground to increase the probability of recording frost rings. Provided that all *A. chilensis* samples in this study were taken below one meter, it remains to be determined if frost rings also appear higher along the stem (younger cambial age), as has been found in boreal Pinaceae (Fayle, 1981; Waito et al., 2013; Hadad et al., 2020). This would provide more continuous records of late-spring frost events. Remarkably, 11% of the total frost rings produced a fracture of the ring, which could indicate an eventually greater severity of these events, an aspect that should be further investigated. No frost rings were detected in the latewood of *A. chilensis,* nor were two frost rings found in the same year, such as those described by Gurskaya and Shiyatov (2006) and Barbosa et al. (2019).

4.2. Relationship between temperature records and frost rings

The coincidence between frost-ring years identified in tree rings of young trees from El Cepillo and sub-freezing temperature records from the Rengo Meteorological Station demonstrates that *A. chilensis* tree rings constitute a reliable proxy for detecting late-spring frost occurrences and their recurrence in the long-term. *A. chilensis* individuals in three of the studied sites showed frost rings in the year 1845 (Fig. S3), which was historically considered a very cold year (Vicuña Mackenna, 1877). Among the five abrupt sub-freezing temperature events linked with frost rings detected in young *A. chilensis* trees, crop losses with severe economic and social impacts occurred in 1991 and 2003 in the study area (Bravo et al., 2020). The frosts that occurred on October 15th and 16th in 1991 caused great damage to vineyards, cherries, pome fruits and kiwis. In addition, the frosts that occurred on September 8th and 9th in 2003, in combination with intense rainfall in mid-November, produced a total loss of cherries, stone fruits and blueberries in the northern portion of the study area (Aldunce and González, 2009).

4.3. Distribution of earlywood frost rings according to cambial age

Different investigations analyzing abiotic factors affecting susceptibility to low temperatures and frost occurrence in trees have identified altitude as a relevant factor (Panayotov et al., 2012; Gurskaya et al., 2016). Additionally, the maximum cambial age at which *A. araucana* produces frost rings has been found to be higher in dry environments and lower in humid environments (Arco Molina et al., 2016). In this sense, northern sites are the most xeric within the distribution range for the species, which also coincide with the upper altitudinal limit (ca. 2000 m a.s.l.). Trees in these sites recorded freezing damage at older ages than in the southern, lower and moister sites. In any case, a greater number of sites should be investigated to further evaluate the role that elevation, latitude and local water availability play in relation to the age at which trees showed maximum frequencies of frost rings.

The Weibull frequency distribution model for all sites combined indicated that the cambial age of *A. chilensis* individuals at which 95% of frost rings occurred is around 120 years, which is considerably older than the previously found data in the literature. Considering different studies in Northern Hemisphere conifers, the cambial age at which most frost damage has been recorded in tree rings is $\leq$ 40 years and in individuals with diameters $\leq$ 6 cm (Waito et al., 2013; Kidd et al., 2014; Gurskaya et al., 2016; Hadad et al., 2020). A similar pattern was observed in *A. araucana* (Hadad et al., 2019) from the northern Patagonia, where 75% of the frost rings occurred in the tree's first 40 years of life.

5. Conclusions

This study supports the potential of *A. chilensis* tree rings as indicators of past late-spring frosts in southern South America and aims to encourage the use of this species to develop an extended network of frost-ring chronologies in the study area. The findings indicate that *A. chilensis* frost rings mostly occur in trees less than 120 years old, over a wide latitudinal range across the Andes in central Chile. This indicates that a good representation of young trees and of the central portion of relict wood is essential to obtain a robust long-term reconstruction of spring frost occurrence, including the most recent events. This will allow a better understanding of the long-term variability and changes in the occurrence of extreme climatic events in a region that lacks a long-term instrumental record of this valuable information, with wide application in relevant productive sectors, such as agriculture and fruticulture in this Mediterranean climate. Under the current scenario of increasing temperatures across central Chile, the earlier onset of cambial activity in woody plants in the spring is occurring, thus the risk of spring frost occurrence is expected to increase. Multicentury *A. chilensis* frost-ring records obtained from both living trees and dead relict wood, emerges as a valuable proxy with great potential to assess the occurrence and evolution of late-spring frosts to contextualize the present climate variability in central Chile with a long-term perspective.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2022.125962.

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