



Thirty-four years of dendrochronological studies in Perú: A review of advances and challenges

Leif Armando Portal-Cahuana ^{a,*¹}, Claudia Fontana ^{a,2}, Gabriel Assis-Pereira ^{a,3}, Peter Groenendijk ^{b,4}, Fidel A. Roig ^{c,d,5}, Mario Tomazello-Filho ^{a,6}

^a Universidade de São Paulo, Escola Superior de Agricultura Luiz de Queiroz, Department of Forest Resource, Av. Pádua Dias No 11, Piracicaba, São Paulo 13418-900, Brazil

^b Department of Plant Biology, Institute of Biology, University of Campinas – UNICAMP, Campinas, São Paulo 13083-970, Brazil

^c Argentine Institute of Nivology, Glaciology and Environmental Sciences (IANIGLA), CONICET-Universidad Nacional de Cuyo, Mendoza 5500, Argentina

^d Héméra Centro de Observación de la Tierra, Escuela de Ingeniería Forestal, Facultad de Ciencias, Universidad Mayor, Santiago 8580745, Chile

ARTICLE INFO

Keywords:

Climatology
Forest management
Tropical trees
Tree-rings

ABSTRACT

The development of tree-ring chronologies of tropical trees allows to reconstruct the environmental history of the Neotropics on extensive temporal and spatial scales. This article presents a historic, state-of-the-art overview/review of dendrochronological studies in Perú, a megadiverse country in its flora, types of climate and ecosystems. We reviewed all available information on dendrochronological studies by assessing scientific articles in indexed, and non-indexed journals as well university thesis repositories. Dendrochronological studies began in the late 1980s and have botanically involved 20 families, 34 genera and 52 tree species. The most studied families are Fabaceae (16 studies), Meliaceae (12), Rosaceae (06), and Bignoniaceae (04), and the most studied genera were *Cedrela* (13), *Polyplepis* (08) and *Prosopis* (06). The development of chronologies was mainly applied in climatic reconstructions, forest conservation and management. We identify underrepresentation or sampling gaps regarding climatic and geographic complexity. The high tree diversity of Perú constitutes a natural laboratory to develop tree-ring studies to better understand the growth and functioning of tropical tree species, their interaction with climate, and to derive climate reconstructions during the last centuries. This review aims to contribute to the direction of future dendrochronological studies in Perú.

1. Introduction

The study of tree rings has been widely used in temperate regions to understand tree growth and to reconstruct climate. In the tropics, in spite of more than one hundred years of tree-ring studies (Worbes, 2002), for long it was believed that trees did not form annual growth rings, at least to the degree of distinctness as it is observed in most species of temperate climates. From the 1950 s onwards, there has been an increase in tropical tree ring research (Worbes, 2002), in part because

many species form annual growth rings triggered by seasonal variations in climate (Koriba, 1958; Mariaux, 1967; Détienne and Mariaux, 1975; Brienen et al., 2006; Groenendijk et al., 2014). Tree-ring studies have been applied to obtain tree-growth estimates to aid forest management (Détienne et al., 1988; Groenendijk et al., 2017), to assess tree ages and understand forest dynamics (Worbes, 1989; Brienen and Zuidema, 2006; Vlam et al., 2017), to assess climate-change effects on tree growth and physiology (Van der Sleen et al., 2015; Timofeeva et al., 2017), but most studies aim to understand climatic effects on tree growth and to build

* Corresponding author.

E-mail addresses: armantigre@hotmail.com (L.A. Portal-Cahuana), claudiafontanabio@gmail.com (C. Fontana), gabriel_assispereira@hotmail.com (G. Assis-Pereira), peterg@unicamp.br (P. Groenendijk), froig@mendoza-conicet.gob.ar (F.A. Roig), mtomazel@usp.br (M. Tomazello-Filho).

¹ ORCID: 0000-0002-2717-4348.

² ORCID: 0000-0003-2032-5673.

³ ORCID: 0000-0001-5274-0033.

⁴ ORCID: 0000-0003-2752-6195.

⁵ ORCID: 0000-0003-0987-0486.

⁶ ORCID: 0000-0002-9814-0778.

climatic-proxy records to reconstruct the environmental history in different biomes (Brienen et al., 2016; Zuidema et al., 2022). Local temperature and precipitation reconstructions have been built (Esper et al., 2018; Yang et al., 2014), as well as river-flow dynamics and length of flooding (Nolin et al., 2021; Quesada-Román et al., 2020). Several studies have also explored El Niño Southern Oscillation (ENSO) effects on tropical tree growth (Schöngart, 2008; Aragão et al., 2022) and provided ENSO reconstructions beyond meteorological records (*Prosopis pallida* South America (Rodríguez et al., 2005; *Tectona grandis* Asia (D'Arrigo et al., 2006)). El Niño events consist of positive anomalies in sea-surface temperatures in the central and east-central equatorial Pacific (the area off the Pacific coast of South America; Sulca et al., 2018) and are one of the main drivers of interannual tropical climate variability (Zhang et al., 2006). Dendrochronological studies form a key tool to extend reconstructions of ENSO-variability across the tropics (Stahle et al., 1998).

Tropical forests, particularly those in South America, constitute a vital support for the planet, stabilizing the regional and global climate by generating rain, regulating air temperature, subtracting C from the air, among other vital contributions to the planet's life support system. For this reason, tropical dendrochronology is currently in the spotlight, providing answers about the impact of climate change on tree growth (Groenendijk et al., 2015; Islam et al., 2018; van der Sleen et al., 2015), allowing the reconstruction of the climate (Ljungqvist et al., 2020; Granato-Souza et al., 2019; Schofield et al., 2016), understanding the dynamics of forests in the long term (Bergeron et al., 2002; Metsaranta and Lieffers, 2009; Vlam et al., 2017), projecting scenarios for the conservation and use of timber resources (Angoboy et al., 2020; Fu et al., 2020), among other applications. Despite advances in tropical dendrochronology, only a small fraction of tropical tree species have been studied and huge tropical land areas and biomes remain virtually unexplored dendrochronologically (Brienen et al., 2016; Roig, 2000; Schöngart et al., 2017). Therefore, it is important to review the existing studies, analyzing the quality of the species used for dendrochronological studies and identifying areas that are viewed as priority to extend explorations and data generation in the Neotropics (e.g., Zuidema et al., 2022).

Here we present a review on the state-of-the-art of tree-ring studies in Perú. This South-American country stands out for having the second largest area of native tropical forests (and fourth in forest plantation) on the American continent, and for harboring an incredible biodiversity (Pitman et al., 2002; Vásquez et al., 2018; Wittmann et al., 2006), with 84 out of the 117 world life zones are present in the country (Asner et al., 2017a, 2017b; Brack, 2004; Cossío et al., 2014; Oliveira et al., 2007). Perú's proximity to one of the main area of ENSO sea-surface anomalies also positions the country at an ideal spot to allow for multi-century reconstructions of this important driver of tropical climatic variability (Humanes-Fuentes et al., 2020). The country's position, high biodiversity and relatively small size reinforces the great potential of Perú as an ideal country to advance tropical dendrochronological studies.

Our main objectives are to *i.* establish an historical overview of Dendrochronology in Perú; *ii.* identify the species investigated, the characteristics of the constructed chronologies, and the geographic and environmental coverage of these studies; *iii.* analyze the applied dendrochronological approaches; and *iv.* provide suggestions and directions for future dendrochronological studies in Perú. This study thus presents a qualitative and quantitative inventory of the chronologies available for Perú and their spatial and temporal coverage. With it, we hope to reveal the country's potential for dendrochronological studies, and to identify knowledge gaps to be filled for the improvement of dendrochronology in the region.

2. Material and methods

The database of dendrochronological studies in Perú was built by collecting information from different sources: scientific articles

electronically indexed in Scopus (www.scopus.com), Web of Science (www.webofscience.com), and Scielo (www.scielo.br); other non-indexed academic articles; and 51 online repositories of Peruvian universities containing undergraduate, master, and doctorate theses. We considered sources of "grey" literature (theses and publications in non-indexed journals) as these may provide important information of new species and study areas. These studies are thus not formally peer reviewed. Yet, there are many difficulties (cultural, financial, linguistic, etc.) for academics in developing countries to publish their studies that are not necessarily related to the quality of the work. Excluding these sources would strongly reduce our sapling size and thus also the representativity of tree-ring studies in Perú.

We used the following keywords: "Dendrochronology", "Dendroecology", "Dendroclimatology", "Growth rings", "Perú" and considered all publications available up to October 2022. All publications were read, analyzed, systematized and we only considered those studies that presented a constructed chronology, regardless of the number of trees used and their intercorrelation level. We systematized information on the study species, botanical family, type of sample (increment core or cross-sectional discs), the number of trees and number of radii sampled, number and percentage of intercorrelated individuals, the period covered by the chronology, total chronology length (years), average of the within-tree intercorrelations (intercor), average of the between tree intercorrelations (Rbar), Expressed Population Signal (EPS), climate type, geolocation, the department in Perú where the study was realized, and in which repository are the samples currently kept. We subsequently used this database to explore the historical panorama, the approaches used, the characteristics of the chronologies, the species investigated, where investigations have been carried out, and the environmental envelope covered by all studies (precipitation and temperature). We also examined studies that applied tree-rings to answer applied questions related to forest management in the country.

Finally, to identify regions in the country where the El Niño Southern Oscillation has the strongest effect on local climate, and thus possibly where trees would best register ENSO variability, we correlated 3-monthly running mean values of the Multivariate El Niño Index (MEI) with the corresponding 3-monthly averages of spatial reconstructions of Temperature (CRU TS 4.05, over the period of 1979–2020; Harris et al., 2020) and Precipitation (CHIRPS reconstruction, 1981–2022; Funk et al., 2015) using the spatial correlation analyses provided by the KNMI Climate Explorer (<https://climexp.knmi.nl>; Trouet and Van Oldenborgh, 2013).

3. Results and discussion

We found a total of 48 publications (Table 1), consisting mostly of grey literature: theses (54 %), articles published in non-indexed journals (8 %) and publications from journals indexed in SCOPUS, Web of Science, and Scielo formed 38 % of the publications reviewed here. Surprisingly, only 23 % of theses' results were published in indexed journals. In this context, scientific information on dendrochronological research in Perú remains mainly in the repositories of Peruvian universities.

3.1. Track record and historic overview

The first report published in Perú on the growth rings of Peruvian forest species was made by Andreas Schwyzer in 1988 (Tomazello et al., 2009), who compiled some unpublished results and indicated possibilities for dendrochronological investigations of three arboreal species (*Chorisia* sp., *Amburana cearensis*, and *Cedrela* sp.) and a shrub species (*Myrciaria dubia*), making the first inferences about applying tree-ring analyses to forest management in the Peruvian Amazon (Schwyzer, 1988). These studies argued the annual nature of the growth rings, with the consequent possibility of developing dating and growth measurement studies with applications in the management of timber species. In

Table 1

Basic information of the dendrochronological studies carried out in Perú. Means of acronyms: species name and family; WOSA = Wood sample type (core, stump) SAIN = Sampled individuals; SrIN = Sampled radii per individual; CRIN = Crossdated individuals; CRPE = Crossdated period; CRLE = Crossdated length; Int = Inter-correlation; CLIM = Climate type (Koppen); Dep = Department. Gray rows are the indexed scientific articles (Scopus, Web of Science).

Species	Botanical family	WOSA	SAIN	SrIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/EPS	CLIM	Dep	Reference
<i>Loxopterygium huasango</i> *	Anacardiaceae	Stump	5	4	3(60 %)	1970-2005	36	0.67	.	BWh	Lambayeque	Rosero (2011)
<i>Loxopterygium huasango</i> *	Anacardiaceae	Stump	4	4	3(75 %)	1956-2003	47	0.51	.	BWh	Lambayeque	Rosero (2011)
<i>Guatteria hyposericia</i>	Annonaceae	Core	17	2	13(76 %)	1979-2015	37	0.42	.	Am	Junín	Zegarra (2018)
<i>Alnus acuminata</i>	Betulaceae	Core	45	2	22(48 %)	1968-2013	46	0.26	.	Cwb	Junín	Requena (2015)
<i>Handroanthus serratifolius</i>	Bignoniaceae	Stump	7	4	7(100 %)	1880-2006	126	0.36	.	Af	Madre de Dios	Jenkins (2009)
<i>Jacaranda copaia</i>	Bignoniaceae	Core	10	4	10 (100 %)	1984-2018	34	0.36	.	Af	Madre de Dios	Portal et al. (2020)
<i>Jacaranda copaia</i>	Bignoniaceae	Core	17	2	13(76 %)	1991-2015	25	0.52	.	Cwb	Junín	Zegarra (2018)
<i>Jacaranda copaia</i>	Bignoniaceae	S/c	25	4	23(92 %)	1952-2019	67	0.49	0.18/0.87	Af	Madre de Dios	Portal (2022)
<i>Bursera graveolens</i> *	Burseraceae	Core	11	.	.	1967-2001	34	0.85	.	BWh	Piura	Rodríguez et al. (2005)
<i>Bursera graveolens</i> *	Burseraceae	Core	19	.	.	1953-2001	48	0.72	.	BWh	Piura	Rodríguez et al. (2005)
<i>Bursera graveolens</i> *	Burseraceae	Core	43	.	.	1964-2001	37	0.74	.	BWh	Piura	Rodríguez et al. (2005)
<i>Bursera graveolens</i> *	Burseraceae	Stump	5	4	4(80 %)	1952-2005	54	0.59	.	BWh	Lambayeque	Rosero (2011)
<i>Bursera graveolens</i> *	Burseraceae	Stump	4	4	3(75 %)	1947-2005	59	0.61	.	BWh	Lambayeque	Rosero (2011)
<i>Cordia alliodora</i>	Cordiaceae	Core	7	.	.	2003-2015	13	0.59	.	Af	Madre de Dios	Mamani (2018)
<i>Cordia alliodora</i>	Cordiaceae	Core	7	4	7(100 %)	2003-2015	13	0.59	.	Af	Madre de Dios	Portal et al. (2021)
<i>Cordia iguaguana</i>	Cordiaceae	Stump	15	3	13(86 %)	1987-2015	28	0.60	.	Aw	Cajamarca	Marcelo-Peña et al. (2019)
<i>Escallonia myrtilloides</i> *	Escalloniaceae	Stump	19	.	11(58 %)	1940-2015	76	0.45	0.54/0.93	Cwb	Junín	Requena et al. (2021)
<i>Escallonia myrtilloides</i> *	Escalloniaceae	Stump	12	.	9(75 %)	1961-2015	56	0.44	0.36/0.87	Cwb	Junín	Requena et al. (2021)
<i>Hura crepitans</i>	Euphorbiaceae	S/c	11	4	11 (100 %)	1744-2018	274	0.43	0.20/0.80	Af	Madre de Dios	Portal (2022)
<i>Amburana cearensis</i>	Fabaceae	Stump	10	2	10 (100 %)	1866-2013	147	0.36	.	Af	Madre de Dios	Portal (2017)
<i>Anadenanthera colubrina</i>	Fabaceae	Stump	12	3	9(75 %)	1950-2009	59	0.41	.	Aw	Cajamarca	Marcelo-Peña et al. (2019)
<i>Apuleia leiocarpa</i>	Fabaceae	Stump	7	2	7(100 %)	1759-2013	255	0.04	.	Af	Madre de Dios	Portal (2017)
Species	Botanical family	WOSA	SAIN	SrIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/EPS	CLIM	Dep	Reference
<i>Cedrelinga cateniformis</i> *	Fabaceae	Core	15	2/3	8(53 %)	1924-2007	83	0.56	.	Af	Loreto	Campos (2009)
<i>Cedrelinga cateniformis</i> *	Fabaceae	Core	20	2/3	14(70 %)	1975-2007	33	0.69	.	Af	Loreto	Campos (2009)
<i>Cedrelinga cateniformis</i>	Fabaceae	Stump	30	2	20(66 %)	1943-2017	75	0.34	.	Af	Madre de Dios	Zavala and Rodríguez (2018)
<i>Cedrelinga cateniformis</i>	Fabaceae	S/c	6	4	6(100 %)	1998-2015	18	0.51	.	Af	Madre de Dios	Reategui (2019)
<i>Dipteryx odorata</i>	Fabaceae	Stump	8	2	8(100 %)	1781-2013	233	0.03	.	Af	Madre de Dios	Portal (2017)
<i>Hymenaea courbaril</i>	Fabaceae	Stump	6	4	6(100 %)	1876-2006	130	0.50	.	Af	Madre de Dios	Jenkins (2009)
<i>Hymenaea courbaril</i>	Fabaceae	Stump	16	3/4	14(87 %)	1845-2008	163	0.34	.	Af	Madre de Dios	Huaman (2011)
<i>Hymenaea oblongifolia</i>	Fabaceae	Stump	8	2	8(100 %)	1778-2013	235	0.32	.	Af	Madre de Dios	Portal (2017)
<i>Myroxylon balsamum</i>	Fabaceae	Stump	10	4	10 (100 %)	1914-2006	92	0.35	.	Af	Madre de Dios	Jenkins (2009)
<i>Myroxylon balsamum</i>	Fabaceae	Stump	10	2	10 (100 %)	1888-2013	126	-0.06	.	Af	Madre de Dios	Portal (2017)

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Table 1 (continued)

<i>Myroxylon balsamum</i>	Fabaceae	S/c	26	4	24(92 %)	1927-2019	92	0.45	0.21/0.90	Af	Madre de Dios	Portal (2022)
<i>Prosopis pallida</i>	Fabaceae	Stump	54	.	33(66 %)	1965-2001	37	0.41	/0.92	BWh	Piura	López et al. (2006)
<i>Prosopis pallida*</i>	Fabaceae	Stump	10	.	.	1908-2002	94	0.48	/0.85	Cwb	Áncash	López et al. (2006)
<i>Prosopis pallida*</i>	Fabaceae	Stump	5	.	.	1977-2001	24	0.30	/0.68	BWh	Ica	López et al. (2006)
<i>Prosopis pallida*</i>	Fabaceae	Stump	95	.	.	1965-2001	36	0.42	/0.92	BWh	Piura	López et al. (2006)
<i>Prosopis pallida</i>	Fabaceae	Stump	.	.	.	1908-2003	95	0.53	.	Cwb	Áncash	Rodríguez et al. (2005)
<i>Prosopis pallida*</i>	Fabaceae	Stump	10	.	.	1963-2014	51	0.34	/0.84	BWh	Piura	Salazar et al. (2018)
<i>Prosopis pallida*</i>	Fabaceae	Stump	11	.	.	1964-2014	50	0.49	/0.86	BWh	Piura	Salazar et al. (2018)
<i>Prosopis pallida*</i>	Fabaceae	Stump	10	.	.	1970-2014	44	0.44	/0.81	BWh	Piura	Salazar et al. (2018)
<i>Prosopis sp.*</i>	Fabaceae	Stump	10	2	10 (100 %)	1963-2014	51	0.34	.	BWh	Piura	Ancajima (2017)
<i>Prosopis sp.*</i>	Fabaceae	Stump	14	2	11(78 %)	1964-2014	50	0.49	.	BWh	Piura	Ancajima (2017)
<i>Prosopis sp.*</i>	Fabaceae	Stump	10	2	10 (100 %)	1970-2014	44	0.44	.	BWh	Piura	Ancajima (2017)
<i>Prosopis sp.</i>	Fabaceae	S/c	.	.	.	1991-2001	10	.	.	BWh	Piura	Evans and Schrag (2004)
<i>Prosopis sp.</i>	Fabaceae	Stump	12	.	.	1908-2002	95	0.68	.	Cwb	Áncash	Ghezzi and Rodríguez (2015)
<i>Prosopis sp.</i>	Fabaceae	Core	130	.	.	375 y 120 CalBC	63	0.53	.	Cwb	Áncash	Ghezzi and Rodríguez (2015)
<i>Prosopis sp.</i>	Fabaceae	S/c	.	26 y 11	.	.	121	0.54	.	BWh	Áncash	Ortiz (2019)
<i>Tachigali vasquezii</i>	Fabaceae	Core	9	4	9(100 %)	1977-2015	38	0.28	.	Af	Madre de Dios	Portal (2019)
<i>Juglans neotropica</i>	Juglandaceae	Core	18	2/4	.	1805-2009	205	0.47	.	Cwb	Junín	Inga and del Valle (2017)
<i>Juglans neotropica*</i>	Juglandaceae	Core	20	.	15(75 %)	1972-2018	47	0.34	.	Cfb	Amazonas	Egües (2021)
<i>Juglans neotropica*</i>	Juglandaceae	Core	19	.	15(79 %)	1980-2018	39	0.48	.	Cfb	Amazonas	Egües (2021)
<i>Tectona grandis</i>	Lamiaceae	Core	31	4	18(58 %)	1985-2009	25	0.51	.	Cwb	Junín	Zuñiga (2012)
Species	Botanical family	WOSA	SAIN	SraIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/EPS	CLIM	Dep	Reference
<i>Ocotea bofo</i>	Lauraceae	Core	2	4	2(100 %)	1915-2015	101	0.14	.	Af	Madre de Dios	Macedo (2018)
<i>Beilschmiedia tovarensis</i>	Lauraceae	Core	2	4	2(100 %)	1948-2015	68	0.17	.	Af	Madre de Dios	Macedo (2018)
<i>Nectandra reticulata</i>	Lauraceae	Stump	10	2/3	8(80 %)	1909-2011	102	0.70	.	BSh	Huánuco	Navarro and Zevallos (2015)
<i>Ocotea bofo</i>	Lauraceae	Core	2	4	2(100 %)	1915-2015	101	0.14	.	Af	Madre de Dios	Macedo (2018)
<i>Ocotea ovalifolia</i>	Lauraceae	Core	2	4	2(100 %)	1943-2015	73	-0.11	.	Af	Madre de Dios	Macedo (2018)
<i>Ceiba pentandra</i>	Malvaceae	Stump	5	4	5(100 %)	1927-2006	79	0.46	.	Af	Madre de Dios	Jenkins (2009)
<i>Guazuma crinita</i>	Malvaceae	Core	20	4	20 (100 %)	1990-2016	27	0.24	.	Af	Madre de Dios	Dávila (2020)
<i>Cedrela angustifolia</i>	Meliaceae	Core	6	.	2(40 %)	1924-2016	93	0.56	.	Cwb	Junín	Acevedo (2018)
<i>Cedrela fissilis</i>	Meliaceae	Core	20	.	.	1986-2017	32	0.50	.	Af	Madre de Dios	Huamán (2019)
<i>Cedrela fissilis</i>	Meliaceae	Core	20	4	17(85 %)	1986-2017	32	0.50	.	Af	Madre de Dios	Portal et al. (2021)
<i>Cedrela kuelapensis</i>	Meliaceae	Core	12	2	8(66 %)	1974-2015	41	0.47	.	Aw	Cajamarca	Marcelo-Peña et al. (2019)
<i>Cedrela montana</i>	Meliaceae	Core	20	.	.	1920-2010	90	0.33	.	Af	Ucayali	Castañeda et al. (2013)
<i>Cedrela nebulosa</i>	Meliaceae	Core	13	.	.	1883-2015	133	0.47	0.43/0.91	Cwb	Junín	Layne et al. (2018)
<i>Cedrela nebulosa</i>	Meliaceae	Core	13	.	11(81 %)	1960-2016	57	0.49	.	Cwb	Junín	Acevedo (2018)

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Table 1 (continued)

<i>Cedrela odorata</i>	Meliaceae	Core	9	2/4	.	1890-2012	123	0.41	.	Cwb	Junín	Inga and del Valle (2017)
<i>Cedrela odorata</i>	Meliaceae	Stump	5	4	5(100 %)	1942-2006	64	0.47	.	Af	Madre de Dios	Jenkins (2009)
<i>Cedrela odorata</i>	Meliaceae	S/c	46	2/4	27(58 %)	1803-2009	213	0.45	.	Cwb	Junín	Pereyra (2011)
<i>Cedrela odorata</i>	Meliaceae	Stump	15	4/5	11(73 %)	1825-2006	181	0.49	.	Af	Madre de Dios	Schipper (2011)
<i>Cedrela odorata</i>	Meliaceae	S/c	56	4	52(93 %)	1787-2018	231	0.94	0.22/0.94	Af	Madre de Dios	Portal (2022)
<i>Cedrela sp.</i>	Meliaceae	Core	21	.	12(57 %)	1900-2016	117	0.41	.	Cwb	Junín	Acevedo, (2018)
<i>Swietenia macrophylla*</i>	Meliaceae	Core	7	2	5(71 %)	1926-2005	80	0.46	.	Af	Madre de Dios	Rosero (2009)
<i>Swietenia macrophylla*</i>	Meliaceae	Core	13	2	8(61 %)	1884-2005	122	0.41	.	Af	Madre de Dios	Rosero (2009)
<i>Swietenia macrophylla</i>	Meliaceae	S/c	47	4	34(72 %)	1781-2018	237	0.46	0.20/0.90	Af	Madre de Dios	Portal (2022)
<i>Pinus muricata</i>	Pinaceae	Core	35	3/4	34(97 %)	1991-2011	10	0.51	.	Aw	Cajamarca	Domínguez (2014)
<i>Pinus patula</i>	Pinaceae	Core	35	3/4	34(97 %)	1991-2011	10	0.51	.	Aw	Cajamarca	Domínguez (2014)
<i>Pinus patula</i>	Pinaceae	Core	35	3/4	34(97 %)	1991-2011	10	0.51	.	Aw	Cajamarca	Ortega (2014)
<i>Pinus radiata</i>	Pinaceae	Stump	7	3	7(100 %)	1977-2004	27	0.68	.	Aw	Cajamarca	Melo (2010)
<i>Drypetes sp.</i>	Putranjivaceae	S/c	24	4	22(92 %)	1888-2019	131	0.45	0.19/0.89	Af	Madre de Dios	Portal (2022)
Species	Botanical family	WOSA	SAIN	SraIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/EPS	CLIM	Dep	Reference
<i>Podocarpus glomeratus</i>	Podoarpaceae	Core	80	1/2	.	1925-2013	88	.	.	Cwb	Apurimac	Villacorta et al. (2016)
<i>Polylepis flavipila</i>	Rosaceae	Stump	35	.	.	1951-2016	65	.	.	ET	Lima	Camel et al. (2019)
<i>Polylepis microphylla</i>	Rosaceae	Stump	26	.	.	1965-2018	54	0.56	/0.85	BSK	Cusco	Rodríguez-Morata et al. (2022)
<i>Polylepis pepei</i>	Rosaceae	Stump	17	3/4	.	1870-2006	137	0.65	/0.89	BSk	Cusco	Jomelli et al. (2012)
<i>Polylepis rodolfo-vasquezii</i>	Rosaceae	S/c	50	.	39(78 %)	1859-2015	157	0.51	0.32/0.95	Cwb	Junín	Requena et al. (2020)
<i>Polylepis rodolfo-vasquezii*</i>	Rosaceae	S/c	50	2	40(80 %)	1881-2016	135	0.58	0.31/0.82	Cwb	Junín	Vidal (2020)
<i>Polylepis rodolfo-vasquezii*</i>	Rosaceae	S/c	169	2	121 (72 %)	1921-2016	95	0.52	0.29/0.89	Cwb	Junín	Vidal (2020)
<i>Polylepis rugulosa</i>	Rosaceae	Stump	23	3/4	.	1940-2005	66	0.51	/0.90	BWk	Arequipa	Jomelli et al. (2012)
<i>Polylepis subsericans</i>	Rosaceae	Stump	15	3/4	.	1892-2006	115	0.64	/0.90	Cwb	Cusco	Jomelli et al. (2012)
<i>Polylepis tarapacana</i>	Rosaceae	Stump	43	.	30(70 %)	1602-2015	414	.	0.36/0.92	BWk	Tacna	Crispín et al. (2022)
<i>Esenbeckia cornuta</i>	Rutaceae	Stump	15	3	14(93 %)	1993-2014	21	0.56	.	Aw	Cajamarca	Marcelo-Peña et al. (2019)
<i>Zanthoxylum rhoifolium</i>	Rutaceae	Core	10	4	10 (100 %)	1985-2017	32	0.42	.	Af	Madre de Dios	Colina (2019)
<i>Pourouma minor</i>	Urticaceae	Core	17	2	12(70 %)	1988-2015	28	0.37	.	Cwb	Junín	Zegarra (2018)

(*) Species were studied by the same author at different sites.

the late 1980 s, the first attempts to apply dendroclimatology in Perú were carried out by the University of Piura in collaboration with the Geophysical Institute of Perú and the University of Colorado in the United States. The goal of these studies was to detect El Niño-Southern Oscillation events from signals revealed by tree rings (Rodríguez et al., 2005; UC, 2016). Despite the start in the 1980 s, the first dendrochronology laboratory in Perú was installed in 2001 at the University of Piura (Rodríguez et al., 2005). The first chronology validated with dendrochronological parameters in Perú was carried out 17 years ago, where the incidence of El NIÑO events was related to the growth of forests on the north coast of the country (Rodríguez et al., 2005). Since 2004, the number of publications has increased considerably, as observed in Fig. 1a.

Several teaching and research initiatives on growth rings organized

at Peruvian universities were fundamental for the development of dendrochronology in the country. For instance, the inclusion in 2007 of a dendrochronology course as part of the Forests and Forest Resources Management Master's degree in of the La Molina National Agrarian University. This course focused on the basic aspects and fundamentals of dendrochronology, such as, sample collection, data processing and interpretation. The course was taught for several years in collaboration with the Escola Superior de Agricultura Luiz de Queiroz of the São Paulo University in Brazil and resulted in master's theses that evaluated the potential of Peruvian species for dendrochronological studies (Campos, 2009; Melo, 2010; Becerra, 2011; Huaman, 2011; Schipper, 2011). Another institution that taught courses related to dendrochronology was the University of Piura, where mainly undergraduate theses on dendrochronology were produced (Ancajima, 2017; Córdova, 2003;

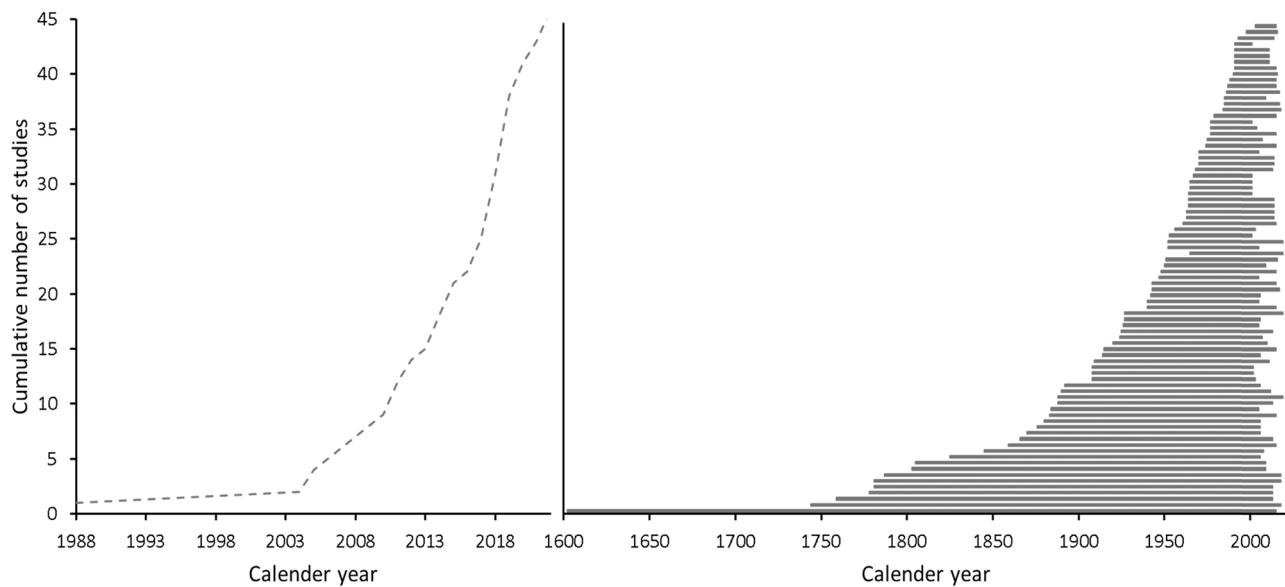


Fig. 1. Cumulative number of dendrochronological studies in Perú (left panel) and the temporal coverage of these chronologies (right panel).

Flores, 1994; Martínez, 2002; Ortiz, 2019), the National University of Centro Perú, where undergraduate theses were also generated (Beltrán, 2011; Inga, 2011; Pereyra, 2011; Ramírez, 2018; Valencia, 2011), and more recently also the Continental University, the National Amazon University of Madre de Dios and the National University of Jaén have also organized courses, often in collaboration with researchers from Brazil, Argentina, and Colombia.

3.2. Taxonomic coverage

In total, the reviewed studies included 20 botanical families, 34 genera and 52 species. Among all families studied, four comprised the largest number of investigations, being: Fabaceae (16 studies), Meliaceae (12), Rosaceae (06), and Bignoniacae (04) (Information on popular names and uses of the species in the Appendix Section, Table S1). It is worth noting that Fabaceae is the most studied family, with 16 investigations covering 11 species. In general, Fabaceae species are known to have distinct growth rings by the presence of a marginal parenchyma band (InsideWoods, 2004). In addition, Fabaceae is a family with a wide distribution, occurring in a diversity of habitats, having several genera and species (Lewis et al., 2005), and showing locally abundant populations (Caiafa and Martins, 2010). These particular conditions expand sampling possibilities in large areas of the Neotropics. In relation to the most considered genera in this survey, it is mentioned *Cedrela* (13), *Polylepis* (07) and *Prosopis* (06), with 48 studies. The genus *Cedrela* is one of the most studied in South America and Perú is considered the center of the diversity of the genus, with 10 of the existing 17 species present in the country (Pennington and Styles, 2010), of which four species endemic (*C. kuelapensis*, *C. molinensis*, *C. longipetiolata*, and *C. weberbaueri*) (SERFOR, 2020). *Cedrela* species form well distinct rings marked by semiring porosity and the presence of a marginal parenchyma, whose annual formation has been proven by studies of cambial activity (Marcati et al., 2006), X-ray densitometry (Albuquerque et al., 2016), carbon isotopes (^{13}C) (Anholeto, 2013), oxygen isotopes (^{18}O) (Brienen et al., 2012) and ^{14}C dating validation (Baker et al., 2017; Hammerschlag et al., 2019; Santos et al., 2021, 2020). The species *Cedrela odorata* has a potential longevity of 308 years (Tomazello et al., 2009), thus allowing for multi-century climatic reconstructions. The dendrochronological potential and wide distribution of *Cedrela* give this genus an important role to extend tree ring studies in the country. Growth information from tree-rings also serves as an important input for the management and protection of this species (Brienen et al., 2006),

which is intensely exploited for the high quality of its wood. Data on growth and longevity are also crucial to protect other threatened or endemic tree species, which constitute almost 10 % of the tree flora of Perú (Quesada-Román et al., 2022; Vásquez et al., 2018).

3.3. Chronology characteristics

The chronologies reviewed varied in their temporal coverage between 10 and 414 years (Table 1). Among the species with the highest longevity, *Polylepis tarapacana* (414 years), *Hura crepitans* (274 years), *Apuleia leiocarpa* (255 years), *Hymenaea oblongifolia* (235 years), *Dipteryx odorata* (233 years), *Cedrela odorata* (213 years), and *Juglans neotropica* (205 years) stand out (Table 1). These results corroborate other studies that demonstrate the longevity potential of tropical trees, average of maximum observed ages of 207 years (Brienen et al., 2016), 186 years (Locosselli et al., 2020) and 214 (Groenendijk et al., 2014) being reported. Details of the type and number of samples used in dendrochronology in Perú are provided in Appendix Figs. S1 and S2.

The highest intercorrelations of the 51 species studied in dendrochronology is in the northern coast portion of Perú (Fig. 2), where the correlations range between 0.34 and 0.85. This region is strongly affected by the El Niño phenomenon (Guzman et al., 2020; Sulca et al., 2018; Takahashi, 2004), which through its positive warm phase (dry, El Niño) and the negative phase (wet, La Niña) produce rainfall anomalies along the northern coast of Perú and southern Ecuador, impacting the groundwater recharges, the natural regeneration and expansion of the seasonally dry tropical forests (Pécastaing, 2020).

As water availability is the limiting factor in these arid and semi-arid ecosystems, ENSO triggers an extraordinary response in plant productivity tree and shrub recruitment, and expansion of woody cover (Holmgren et al., 2006). For example, the growth reaction of *Prosopis pallida* in northern Perú (Piura) was of significant increase to the precipitation that occurred in ENSO years (Holmgren et al., 2006). Correlations with precipitation are higher in drier sites, while correlation with temperature are lower in the more humid sites (Fig. 2). We also identified areas in Perú where climate is sensitive to the El Niño Southern Oscillation (Appendix Section, Fig. S4). These results give an idea of areas with important potential for dendroclimatic reconstructions in the country, which in recent years has been one of the main activities in Latin America along with the search for potential tree species for this purpose (Sánchez-Calderón et al., 2022).

The level of intercorrelation between species varies, indicating

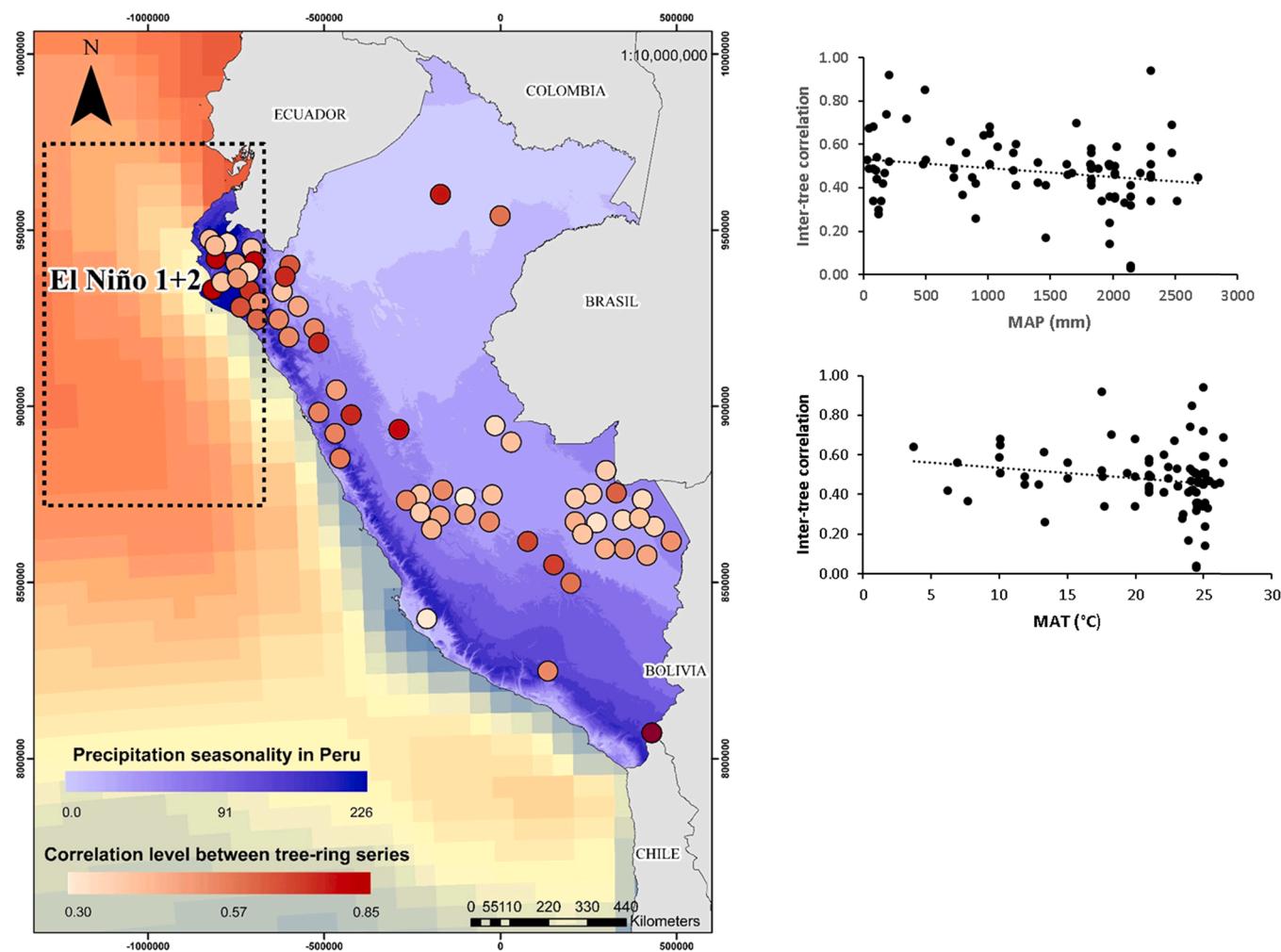


Fig. 2. Map of Perú showing the intercorrelation value between tree-ring time series (circles) and rainfall seasonality (background gradation color calculated WorldClim data; Fick and Hijmans, 2017). The dotted line rectangle shows the area of influence of the El Niño 1 + 2 phenomenon on the north coast of Perú. Right, graphs of the intercorrelation of the studies of the growth rings vs precipitation (above) and vs temperature (below).

species with highly synchronous growth over time and species in which this synchronism is low or non-existent (Table 1). Among the highest mean values of inter-tree correlation, *Bursera graveolens* (mean $r = 0.70$), and the genera *Polylepis* ($r = 0.57$) and *Cedrela* ($r = 0.50$) species stand out. These last two genera are noteworthy due to the potential longevity of their species (*Polylepis* = 414 years; *Cedrela* = 308 years) (Table 1). In general, inter-series correlations decrease with increasing rainfall (Fig. 2) and the lowest correlations are linked to the climate of humid tropical forest (Af). In these biomes we highlight species of the Lauraceae and Fabaceae families that showed low growth synchronicity, for example, *Apuleia leiocarpa*, which is one with the longest observed longevity (255 years), but from low to null synchronism ($r = 0.04$) (Table 1). Although the cambial activity studies indicate that *A. leiocarpa* forms annual rings (Brandes et al., 2015), the low reported synchronism can additionally be induced when considering samples taken in the sector of the buttresses of the stem or the low sample size analyzed in the only reference study for this species (Portal, 2017).

3.4. Spatial distribution of the chronologies

In general, the chronologies are widely distributed throughout the country in different geographical coverages (Fig. 2). However, it is possible to identify regions with a higher concentration of studies and also unexplored spots (Fig. 2). It should be noted that a gap is observed

in the regions where there is a greater water deficit. Precisely these regions subject to hydrological stress, with consecutive months of precipitation below 60 mm, are important for dendroclimatic studies of seasonally dry forests (Worbes, 1999). In several areas there is still no development of dendrochronologies: northwest (Tumbes, La Libertad, Lambayeque), north (San Martín), central (Pasco), southwest (Ica, Ayacucho, Huancavelica), southeast (Moquegua, Puno). Therefore, studies should be increased in these departments to expand the frontiers of dendrochronological knowledge in Perú. Details of the number of papers by departments of the country (Appendix Section, Fig. S3).

3.5. Environmental envelope

The climatic type that includes the highest percentage (39.1 %) of dendrochronological studies correspond to the tropical rainforest (type Af; Fig. 3). The total area covered by these forests in Perú amounts to 69 million ha (ca. 60 % of the country), distributed in coastal, highland, and tropical rainforest regions. These forests cover the largest extension of the forested area of the country (94 %), which implies that, from a geographical coverage perspective, these forests area underrepresented in dendrochronological studies. Part of these tropical forests are subjected to commercial exploitation of native timber species, so there is a great availability of wood disc samples for dendrochronological development.

The subtropical highland climate (type Cwb) is the second type of

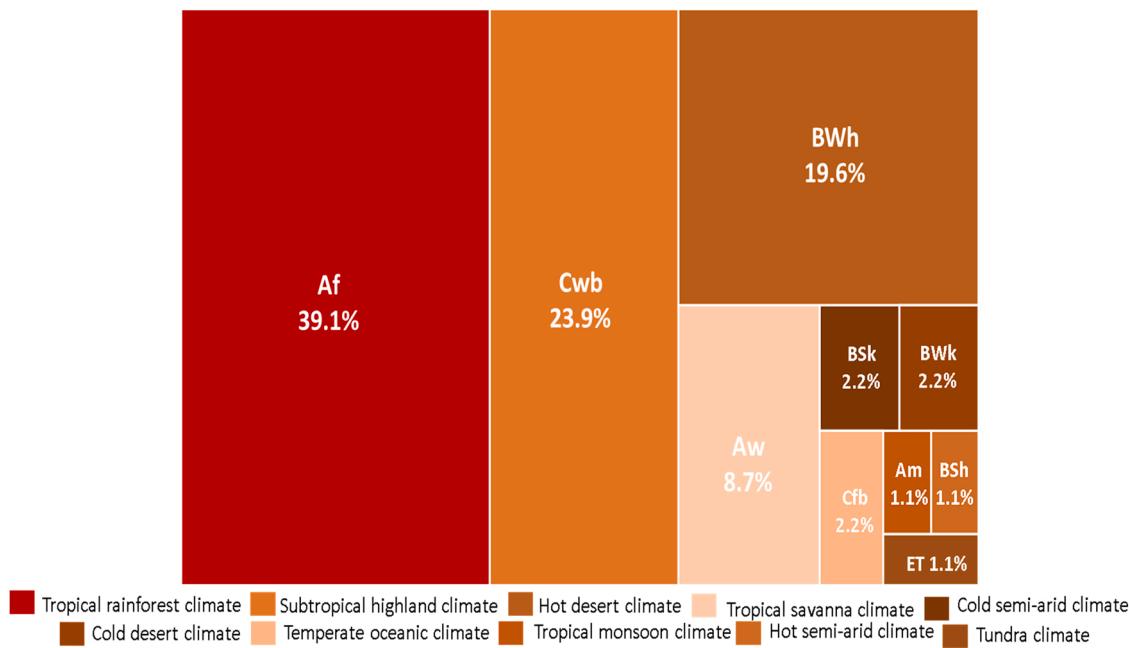


Fig. 3. Distribution of dendrochronological studies carried out in Perú in relation to the Köppen climate-type classification (Köppen, 1948).

climate with the largest number of studies (23.9 %), followed by warm desert climate (type BWh) with 19.6 % and tropical savanna climate (type Aw) with 8.7 % (Fig. 3). Subtropical highland climate and warm desert climate types are found along the country's coast. These are regions under strong influence of the El Niño Southern Oscillation phenomenon (ENSO) (Rodríguez et al., 2005). Trees growing under such climate types generally show high dendrochronological potential (Aragão et al., 2019), allowing reconstructions of ENSO events. Considering the studies carried out to date and the diversity of climatic types in Perú, there is a need to increase efforts in the expansion of chronologies towards climatic areas that are dendrochronologically underrepresented.

We identified that there is a greater concentration of dendrochronological studies in forest areas where trees are commercially exploited. In these areas, access roads and the logistic support by forestry companies (forestry concessions) facilitates obtaining (entire cross-

sectional) samples. Such collaborations, however, somewhat limits the discovery of new species for dendrochronology studies, as logging companies generally exploit a limited set of species with commercial. In other departments where forest exploitation is not carried out, what limits dendrochronological studies is, among others, the access to forested areas (lack of roads) and the logistics involved, the almost mandatory use of non-destructive sampling (borers), which provides more limited samples to work with and crossdate.

The distribution of dendrochronological studies in Perú covers almost all climatic types, although with differences in representation. In terms of mean annual precipitation (MAP, mm yr⁻¹) there is an acceptable number of studies above 1000 mm yr⁻¹, that is, the wettest portion of the Peruvian climate (the density curve of the network -grey line- above the density curve that represents the climatic envelope of Perú, orange line; Fig. 4), however, below this level of precipitation,

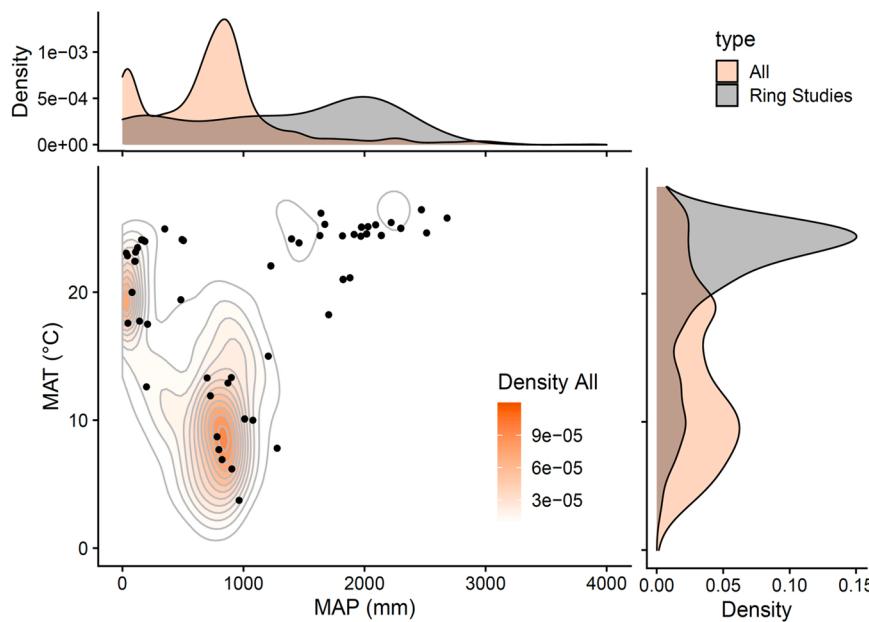


Fig. 4. Tree-ring studies (black dots and grey density plots) considered in this review related to the precipitation (MAP) and temperature (MAT) envelope for Perú (Density All/ orange area). The upper panel shows MAP density plots and the right one the density plots corresponding to MAT; the central panel shows a 2D density plot of the combined envelopes. Black dots represent individual chronologies (i.e., site × species combinations) and orange-color intensity the density distribution of the total envelope.

studies are scarcer (Fig. 4). In relation to the mean annual temperature (MAT, °C), the largest number of tree ring studies has been carried out in the warmest part of the Peruvian climate (areas with MAT above 20 °C). The analysis shows that tree ring studies have focused preferentially on warmer, wetter climates (climate type Aw discussed above), suggesting that future studies should be expanded to cooler/drier areas.

3.6. Approaches and applications of tree-ring studies

The approaches of the studies varied, with chronologies mainly applied on the potential of species for climate-growth and climate reconstructions, and on the use of tree rings for forest management and conservation. In several studies validation of the results was also performed with complementary analysis using stable isotopes (e.g., *Inga* and *del Valle*, 2017) and radiocarbon dating (e.g., Cintra et al., 2019). Recently, the first investigations on climatic reconstructions have been carried out in the country: using growth rings of *Cedrela nebulosa*, *Cedrela odorata* and *Juglans neotropica* trees, the hydroclimatic variability of two centuries in the Andes Amazonia was reconstructed (Humanes-Fuentes et al., 2020). The $\delta^{18}\text{O}$ stable isotopes in *Macrolobium acaciifolium* tree rings provided evidence of precipitation decreases during the dry season of the Amazon in the last 40 years (Cintra et al., 2022).

Two studies stand out on the potential of growth-ring analyses of several tree species. The first one was carried out in the Amazon forest in Central Perú (Satipo and Chanchamayo provinces), evaluating the potential of 80 forest species from 28 botanical families they found that 30 % of the studied species presented dendrochronological potential (Beltrán and Valencia, 2013). The second is a study carried out in four departments of Perú (Cajamarca, Junín, and Ucayali), evaluating the potential of 183 forest species from 45 botanical families they found that 23 % of the studied species presented easily distinguishable ring boundaries and 33 % showed moderately distinguishable boundaries (Marcelo-Peña et al., 2020). These studies are significant contributions to the study of growth rings in the country, forming the basis for other dendrochronological studies in Perú.

Many of the chronologies built had the intent to detect effects of ENSO on tree growth variability. ENSO events are ocean-atmospheric phenomenon that occur in the tropical Pacific region and have strong effects on the climate of the northern and central coastal regions of Perú. Two coastal departments, Tumbes and La Libertad did not register ENSO related research in scientific journals, but show a strong effect of ENSO on their climate variability (Appendix Section, Fig. S4), highlighting unexplored potential areas of research. Both regions present dry forests, that probably will have trees very responsive to climate (e.g., Aragão et al., 2022). Tumbes province is also home to the largest extension of mangroves in the country, these are crucial coastal forests and several studies have already shown the potential of tree-ring studies in mangroves (Maxwell et al., 2018; Menezes et al., 2013).

3.7. Forest management and the applications of dendrochronology

Growth rates of trees vary strongly between species, affecting the age that trees attain minimum cutting diameters set by forest legislation (Schöngart et al., 2017). Also, growth rates of trees of the same species can vary strongly between sites, but this variability is often ignored in the timber management of tropical forests (Ligot et al., 2019). Tree-ring analyses can be used to obtain accurate tree growth data and can thus be applied as a practical tool to correctly managing production forests (e.g., Groenendijk et al., 2017). So far, few studies in Perú have applied tree rings for this purpose despite the use of several commercially important species in many of the reviewed studies (e.g., *Apuleia*, *Cedrela*, *Cedrelinga*, *Handroanthus*, *Hymenaea*, *Swietenia*, etc.). The installation and monitoring of permanent sampling plots “PPM” is mandatory in the Peruvian forest and wildlife legislation (Ley Forestal y de Fauna Silvestre N° 3, 2976, 2015), but forest management can profit largely from the

inclusion of dendrochronological methodologies, as the growth data is obtained quickly and covers the lifespan of trees. For species that show visible growth rings, tree-ring derived growth data can thus complement plot derived data (such as recruitment and mortality). Economic stimuli, such as discounts on exploitation fees, could be granted to forest concessions holders that provide woody material to universities or research institutions for dendrochronological studies.

3.8. ^{14}C Carbon and stable isotopes

Tree ring chronologies can be validated using the decay of the radioactive carbon ^{14}C . In the tropics, the atmospheric ^{14}C peak caused by above ground nuclear tests (the bomb-peak curve, Worbes and Junk, 1989) is often used to check the correct dating of the tree rings (e.g. Groenendijk et al., 2014). Few studies on Peruvian species have applied this method, such as, for example, *Cedrela odorata* and *Juglans neotropica* in the Junín and Ucayali departments (Inga and del Valle, 2017) and *C. odorata* in the Madre de Dios department (Ballantyne et al., 2011). In both studies, the annuity of the growth rings of these species was demonstrated by ^{14}C . Studies combining ring-width chronologies with stable isotope analyses (e.g., of the ^{13}C carbon isotope, or ^{18}O oxygen isotope) are scarce in Perú. These studies can be used to enhance climatic reconstructions (Brienen et al., 2012) or allow for reconstructions in the absence of growth synchrony in tree-ring widths (van der Sleen et al., 2015b), to assess effects of atmospheric and climatic changes on tree growth (van der Sleen et al., 2015a), or to better understand the growth and physiology of tropical trees (Brienen et al., 2022). In Perú, these analyses were performed focused on climatic signals, and only for three species: *Prosopis* sp., ($\delta^{18}\text{O}$) in the north of the country (Piura) (Evans and Schrag, 2004), *Cedrela odorata* ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) in the northern Loreto department, *Macrolobium acaciifolium* ($\delta^{18}\text{O}$) in the Amazonian Loreto floodplains (Cintra et al., 2019, 2022) and *Cedrela odorata* ($\delta^{18}\text{O}$) in the south east of the Peruvian Amazon (Madre de Dios) (Ballantyne et al., 2011). Due to the multiplicity of applications that isotope studies allow, these studies should be more widely applied to Peruvian climate and vegetation types.

3.9. Recommendations

Armed with a broad view of the state of the art of dendrochronology in Perú, some considerations and recommendations can be summarized, which can contribute to filling the identified knowledge gaps and to recognize the emerging scientific opportunities from applying dendrochronological studies in Perú. We recommend:

1. Working with logging companies as part of their commitments to improve forest-management information;
2. Improving collaborations with international laboratories that work with other dendro-analyses proxies, e.g., stable isotopes (carbon and oxygen), X-ray densitometry, wood chemistry, validation by ^{14}C radiocarbon dating, etc.;
3. Focusing on expanding climate reconstruction, with a focus on climatic / ENSO-sensitive areas (e.g., Piura and Tumbes departments) and on long-lived species *Polyepis tarapacana* and *Hura crepitans*;
4. Exploring the potential of sampling and working with historical buildings and archaeological sites to expand the chronologies beyond extant tree ages;
5. Filling sampling gaps in underrepresented parts of the environmental envelope (e.g., around a MAP of 900 mm yr⁻¹ and 8–10 °C MAT) and in regions lacking dendrochronological studies: Tumbes and Puno departments.

4. Conclusions

As a country mega-diverse in tree species and along its environmental gradients, Perú is positioned to become an important center for

the development of dendrochronological studies, allowing the exploration of important questions related to the ecology and evolution of tropical forests (Marcelo-Peña et al., 2020). Due to its position near the tropical Pacific Ocean, the Peruvian forests are also strategic for understanding and reconstruction of the El Niño Southern Oscillation temporal dynamics through tree ring research.

The number of dendrochronological studies in Perú has been increased rapidly over the last years, especially considering the short history of these studies in the country: the first explorative studies occurred a little over 30 years ago and the first validated chronology was published only 17 years ago. Currently, chronologies have been developed for 52 tree species from 20 botanical families, from a variety of phytophysiognomic and climatic types. In this sense, teaching the discipline in research institutes and universities has been the key to the emergence of new research groups to further consolidate dendrochronological studies in the country. However, there are still challenges to strengthen dendrochronological research in Perú, including the financing of research programs, the implementation of other methodologies (e.g., stable isotopes), and the possibilities of collaboration and exchange programs.

Broadly, knowledge about tree growth and climate sensitivity of tropical trees is urgently needed to improve forest management practices, the design of conservation policies, and derivation of paleoclimatic information. The high degree of endemism in the country's flora, amplitude of biomes and climatic conditions of Perú hinders the implementation of these topics, while dendrochronology is positioned as a relevant contributor to help solve these important issues.

Declaration of Competing Interest

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

Data Availability

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

Acknowledgments

The present study was this study was made possible by the support financed by the Programa Nacional de Becas y Crédito Educativo, Perú (PRONABEC) of the Ministerio de Educación del Perú and the São Paulo Research Foundation (NSF-FAPESP project PIRE-CREATE 2017/50085-3, FAPESP grants 2018/01847-0 and 2019/27110-7). This work was carried out with the support of CAPES - Financing Code 001.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.dendro.2023.126058](https://doi.org/10.1016/j.dendro.2023.126058).

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