

University of São Paulo  
"Luiz de Queiroz" College of Agriculture

Dendrochronology and dendroclimatology of tropical tree species from  
southeastern Peruvian Amazon

**Leif Armando Portal Cahuana**

Thesis presented to obtain the degree of Doctor in  
Science. Area: Forest Resources. Option in: Forest  
Products Technology

Piracicaba  
2022

**Leif Armando Portal Cahuana**  
**Forestry and Environment Engineer**

**Dendrochronology and dendroclimatology of tropical tree species from southeastern  
Peruvian Amazon**

versão revisada de acordo com a Resolução CoPGr 6018 de 2011

Advisor:

Prof. Dr. **MARIO TOMMASIELLO FILHO**

Thesis presented to obtain the degree of Doctor in  
Science. Area: Forest Resources. Option in: Forest  
Products Technology

**Piracicaba**  
**2022**

**Dados Internacionais de Catalogação na Publicação**  
**DIVISÃO DE BIBLIOTECA – DIBD/ESALQ/USP**

Portal Cahuana, Leif Armando

Dendrochronology and dendroclimatology of tropical tree species from southeastern Peruvian Amazon / Leif Armando Portal Cahuana. - - versão revisada de acordo com a Resolução CoPGr 6018 de 2011. - - Piracicaba, 2022.

111 p.

Tese (Doutorado) - - USP/ Escola Superior de Agricultura "Luiz de Queiroz"

1. Madre de Dios 2. Anéis de crescimento 3. El Niño 4. Espécies longevas 5. Florestas tropicais I. Título

## DEDICATION

*This thesis is dedicated to my mother, **Emperatriz Cahuana Aguilar**, for her love and for instilling in me since I was a child to pursue my goals. To my wife, **María Esther Villavicencio Paucarpura**, for her love and unconditional support throughout this process, and finally, to my two sons, **Leif Leonardo** and **Kaiki Adriel**, who were my motivation and strength to move forward in this challenge. Mention to all of them that it is also their achievement.*

## ACKNOWLEDGMENTS

Doctoral studies are complex, and difficult, with happy and sometimes frustrating moments, even more so in a global pandemic process, however, I was always surrounded by people who helped and motivated me throughout this process. First of all, I would like to thank my advisor Mario Tomazello Filho, who motivated me from the first day of this new challenge, being by his side was very important in my comprehensive training, from aspects of teaching, research, directing the laboratory, facilitating development and progress of their advisors, in addition to sharing their friendship, which is the most important thing, being next to the person you admire is fantastic, thank you, Mario.

In Peru, I want to thank everyone involved in the planning and field collection, and thank the Native community of Belgium through its president Mr. Nazareno Aspajo López and Eng. Enrique Pacheco Villanueva for the support with the wood samples, would also like to thank the forestry concession Corporación Forestal Tres Fronteras SRL, through its legal representative, Eng. Federico Ríos Torres, and especially the engineers Erick Grandez Piña and German Payeza Tuesta for their support and availability in collecting the wood samples. , without the samples of more than 166 trees nothing would have been done, thanks to all of them.

In Brazil, I want to thank Dr. Moisés Silveira Lobão for his support in transporting the wood samples from the Brazilian border (Assis Brasil) to the city of Piracicaba in São Paulo with a little more than 3,800 kilometers traveled by the samples from the city of Puerto Maldonado in Peru. I thank the technician of the Wood Anatomy and Identification Laboratory (LAIM) of the Luiz de Queiroz Higher School of Agriculture (ESALQ) Aparecido Candido Siqueira for his invaluable support in sanding the wood, it was several weeks of work where we left tired and with a lot of wood debris on his face and nose and also for his support in obtaining wood samples for X-ray densitometry analysis. Also, all the friends of LAIM were an important part in this objective: Roger Chambi Legoas, Ricardo Ortega Rodríguez, Júlia Lôbo Ribeiro Anciotti Gil, Bruna Hornink, Cláudia Fontana, Gabriel de Assis Pereira, Guilherme Roquette and Alessandra Regina Aguilar Voigt, thank you for all the moments we shared, for your recommendations, observations, support and above all your friendship, my thanks to you, without this motivated human group, talking about the same topic of growth rings in the tropics and sharing our goals and dreams without their friendship I would not have achieved it.

To my friends from the University of Campinas: José Roberto Vieira Aragão, Manolo Trindade Quintilhan, for their friendship, their visits to the laboratory, conversations, motivation and support in this process, to Beto for his training in the R software to study growth rings, to Larry Chañi Paucar for his friendship and for accompanying me on the various trips from the city of Puerto Maldonado to São Paulo, during the voyages in pandemic crossing the border along the Acre River with the wooden suitcases was quite a challenge.

The bike rides and walks throughout this process were very helpful to oxygenate me both in Brazil and Peru and with Guilherme Roquette we got to know several cycling routes in the city and surroundings of Piracicaba, getting to know different places and landscapes that remained imprinted on the retina of my eyes, I also thank my friend Javier Navio Chipa for these moments of sports in Peru and friendship in the final part of the doctorate.

To all my family: Lucy, Esther, Bertin, Rolando, Zinthia and Gina, who throughout this was were aware of my progress and always gave me their love when I returned after each trip, they were a fundamental pillar in this achievement.

To the members of my thesis jury Dr. Fidel Roig (IANIGLA), Dr. Peter Groenendijk (UNICAMP) and Dr. Gabriel de Assis Pereira (USP), who helped me and made recommendations since the qualification of the

doctoral project and who help me get this result. I would especially like to thank Dr. Fidel Roig for everything he taught in this world of tropical tree growth rings, his teachings were crucial to continuing this line of research and Dr. Peter Groenendijk who was practically like a co-advisor in this thesis of doctorate, to all of them a thousand thanks.

Finally, thank the National Scholarship and Educational Credit Program (PRONABEC) of the Ministry of Education of Peru, for the scholarship for doctoral studies (Jefatural Resolution No. 1537-2019-MINEDU/VMGI-PRONABEC-OBE), this financing was important for achieving my doctorate.

## SUMMARY

RESUMO.....	8
ABSTRACT.....	9
RESUMEN.....	10
1. GENERAL INTRODUCTION.....	11
1.1. Outline of the thesis .....	13
1.2. Graplllll abstract.....	14
References.....	15
2. THIRTY-FOUR YEARS OF DENDROCHRONOLOGICAL STUDIES IN PERU: A REVIEW OF ADVANCES AND CHALLENGES .....	19
Abstract .....	19
2.1. Introduction.....	19
2.2. Material and Methods .....	20
2.3. Results and Discussion.....	21
2.4. Conclusions.....	32
References.....	32
3. POTENTIAL FOR TREE-RING ANALYSIS OF 34 TREE SPECIES FROM THE PERUVIAN AMAZON.....	41
Abstract .....	41
3.1. Introduction.....	41
3.2. Materials and Methodology .....	43
3.3. Results.....	46
References.....	55
Appendix. Supplementary material.....	59
4. LONG TERM RING WIDTH CHRONOLOGIES OF SIX SPECIES AND THEIR ASSOCIATIONS WITH CLIMATE AND ATMOSPHERIC VARIABLES IN SOUTHWESTERN AMAZON.....	79
Abstract .....	79
4.1. Introduction.....	79
4.2. Methodology .....	81
4.3. Results.....	84
4.4. Discussion .....	91
References.....	94

Appendix. Supplementary material .....	104
5. FINAL CONSIDERATIONS.....	111



## RESUMO

### **Dendrocronologia e dendroclimatologia de espécies arbóreas tropicais do sudeste da Amazônia peruana**

As florestas tropicais da América do Sul possuem uma alta biodiversidade, porém sua extensão e suas próprias características tornam sua conservação muito complicada, isso acontece em todos os países que a compõem e o Peru não é alheio a essa realidade, por isso são necessárias pesquisas voltadas para a conservação de suas florestas e que auxilia o manejo florestal sustentável, minimizando seus impactos, com informações técnicas e científicas de acordo com sua realidade. O estudo dos anéis de crescimento por meio da dendrocronologia é uma importante ferramenta para auxiliar com informações que auxiliam no manejo florestal de forma rápida e econômica. É por isso que o objetivo principal é analisar as espécies tropicais da floresta amazônica no sudeste do Peru para estudos dendrocronológicos e dendroclimáticos, para os quais foi realizado primeiro uma história da arte da dendrocronologia no Peru, a fim de ter uma ideia clara dos avanços e dos desafios dessa ciência no país, então foi analisado o potencial dos anéis de crescimento de 34 espécies florestais para estudos dendrocronológicos na região de Madre de Dios (MDD), região de tríplice fronteira com clima sazonal, realizado a partir de uma amostragem por espécie, então, por fim, foi estudada a dendrocronologia de seis espécies de MDD, onde foram coletadas um total de 181 árvores das seis espécies e 04 amostras para cada árvore. De maneira geral, o procedimento consistiu em secar as amostras em temperatura ambiente, em seguida lixar-polir e por fim digitalizar as seções transversais para medir os anéis de crescimento, caracterizar e construir as cronologias das espécies estudadas. Os resultados obtidos são: há um artigo de revisão que mostra o estado da arte da dendrocronologia no Peru e, entre outras coisas, são levantados desafios futuros. Sobre o potencial dos anéis de crescimento de 34 espécies, 82% apresentaram anéis muito visíveis e moderadamente visíveis (28). Com relação ao estudo dendrocronológico das seis espécies, foram obtidas estatísticas aceitáveis e foi possível construir três cronologias de mais de 200 anos, as espécies foram influenciadas pelo clima local (precipitação) na estação chuvosa e com as anomalias do mar de TSM temperatura dos oceanos Pacífico e Atlântico, destacando a influência do fenômeno El Niño no crescimento das espécies. Esses resultados destacam a necessidade de entender como as espécies florestais estão lidando com as mudanças climáticas nas florestas tropicais. Esse conhecimento é fundamental para aplicá-lo ao manejo florestal e à conservação das florestas tropicais.

Palavras-chave: Madre de Dios, Anéis de crescimento, El Niño, Espécies longevas, Florestas tropicais

## ABSTRACT

### **Dendrochronology and dendroclimatology of trees of tropical tree species from southeastern Peruvian Amazon**

The tropical forests of South America have high biodiversity, however their extension and their characteristics make their conservation very complicated, this happens in all the countries that comprise it and Peru is no stranger to this reality, so research is required oriented to the conservation of its forests and that helps sustainable forest management, minimizing its impacts, with technical and scientific information according to its reality. The study of growth rings through dendrochronology is an important tool to help with information that helps manage forests quickly and economically. That is why the main objective is to analyze the tropical species of the Amazon rainforest in Southeast Peru for dendrochronological and dendroclimatic studies, for which a history of the art of dendrochronology in Peru was first carried out, to have a clear idea of the advances and the challenges of this science in the country, then the potential of the growth rings of 34 forest species was analyzed for dendrochronological studies in the Madre de Dios region (MDD), a tri-border region with seasonal climate, carried out from a sample by species, then, finally, the dendrochronology of six MDD species was studied, where a total of 181 trees of the six species and 04 samples for each tree were collected. In general, the procedure was to dry the samples at room temperature, then sanded-polished and finally scanned the cross-sections to measure the growth rings, be characterized and build the chronologies of the species studied. The results obtained are: there is a review article that shows the state of the art of dendrochronology in Peru and, among other things, future challenges are raised. About the potential of the growth rings of 34 species, 82 % presented very visible and moderately visible rings (28). Regarding the dendrochronological study of the six species, acceptable statistics were obtained and it was possible to build three chronologies of more than 200 years, the species were influenced by the local climate (precipitation) in the rainy season and the anomalies of the SST sea temperature of the Pacific and Atlantic oceans, highlighting the influence of the El Niño phenomenon on the growth of species. These results highlight the need to understand how forest species are coping with climate change in tropical forests. This knowledge is key to applying it to forest management and the conservation of tropical forests.

Keywords: Madre de Dios, Growth rings, El Niño, Long-lived species, Tropical forests

## RESUMEN

### **Dendrocronología y dendroclimatología de especies arbóreas tropicales del sudeste de la Amazonía peruana**

Los bosques tropicales de América del Sur, presentan una alta biodiversidad sin embargo su extensión y sus características propias hacen que su conservación sea muy complicada, esto sucede en todos los países que la conforman y el Perú no es ajena a esta realidad, por lo que se requiere investigaciones orientadas a la conservación de sus bosques y que ayude al manejo forestal sostenible, minimizando sus impactos, con información técnica y científica acorde a su realidad. El estudio de los anillos de crecimiento a través de la dendrocronología es una herramienta importante para auxiliar con informaciones que ayuden al manejo de los bosques de una manera rápida y económica. Es por ello que se plantea como objetivo principal analizar las especies tropicales de la selva Amazónica del Sureste del Perú para estudios dendrocronológicos y dendroclimáticos, para ello primero se realizó una historia del arte de la dendrocronología del Perú, para tener una clara idea de los avances y de los retos de esta ciencia en el país, luego se analizó el potencial de los anillos de crecimiento de 34 especies forestales para estudios dendrocronológicos en la región de Madre de Dios (MDD), región trifronteriza con clima estacional, realizado a partir de una muestra por especie, seguidamente, finalmente se estudió la dendrocronología de seis especies de MDD, donde se colectaron en total 181 árboles de las seis especie y 04 muestras por cada árbol. De manera general el procedimiento fue secar las muestras a temperatura ambiente, posteriormente, lijados-pulidos y finalmente escaneados las secciones transversales para medir los anillos de crecimiento, ser caracterizados y construir las cronologías de las especies estudiadas. Los resultados que se tienen es: se cuenta con un artículo de revisión que muestra el estado del arte de la dendrocronología en el Perú y entre otras cosas se plantean los retos futuros. Sobre el potencial de los anillos de crecimiento de 34 especies, el 82 % presentaron anillos muy visibles y moderadamente visibles (28). Referente al estudio dendrocronológico de las seis especies, se consiguieron estadísticos aceptables y se logró construir tres cronologías de más de 200 años, las especies tuvieron influencia del clima local (precipitación) en la estación lluviosa y con las anomalías de la temperatura del mar SST del océano Pacífico y Atlántico, destacando la influencia del fenómeno El Niño en el crecimiento de las especies. Estos resultados ponen de manifiesto la necesidad de comprender como las especies forestales están afrontando el cambio climático en los bosques tropicales. Este conocimiento es clave para aplicarlo al manejo forestal y a la conservación de los bosques tropicales.

Palabras claves: Madre de Dios, Anillos de crecimientos, El Niño, Especies longevas, Bosques tropicales

## 1. GENERAL INTRODUCTION

Tropical forests are the refuges of biodiversity, presenting innumerable direct and indirect ecosystem services, and providing benefits for the well-being of humanity (Aguirre et al., 2021; Edwards et al., 2019; Lakerveld et al., 2015) also, Tropical forests play an important role in the climate system where evaporation and condensation are engines of global atmospheric circulation, contributing to the cycle of carbon, water, etc. (Malhi et al., 2008; Marengo et al., 2018). Tropical and subtropical terrestrial ecosystems play an important role throughout the world as carbon sinks because they absorb more carbon than they emit. It is currently estimated that terrestrial ecosystems sequester approximately 30% of global CO<sub>2</sub> annually, where gross absorptions and emissions in tropical forests are four times higher than in temperate and boreal forests combined (Fan et al., 2019; Xu et al., 2021) and to mitigate global climate change the management of these carbon sinks is an important tool (Chisholm et al., 2013).

However, these tropical forests are fragile, small changes in their function and structure could have consequences on global biodiversity, carbon cycle and climate (Malhi et al., 2002), research shows that they are having variations in precipitation and temperature, for example, it is reported that since 1980 the Amazon basin has warmed 0.5 °C and that during the dry season it presents stronger warming over the southeast of the Amazon (Jiménez-Muñoz et al., 2016) it is exacerbated in tropical forests due to synergies and interactions with other threats such as anthropogenic activities that result in fragmentation in their ecosystems, as a consequence of the process of the economic integration of the Amazon, based mainly on the use of renewable natural resources and not renewable sources, such as logging, deforestation, mining, shifting cultivation, etc. (Malhi et al., 2002; Marengo et al., 2018; Nobre et al., 2016; Qin et al., 2017). In addition to all these risks suffered by tropical forests, there are external events that have direct and indirect consequences on Amazonian ecosystems such as the El Niño Southern Oscillation (ENSO) phenomenon in the tropical Pacific, as well as surface temperature anomalies of the Sea (SST) of the Pacific and Atlantic oceans, inducing dry or flood anomalies (Sulca et al., 2018) and a series of climatic, anthropogenic and climatic anomaly combinations that affect tropical forests in diversity, distribution, composition, structure and its resilience (Deb et al., 2018; Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016).

One way to evaluate the influence of local climate and global environmental variables in tropical forests is through the growth rings of trees, these studies in tropical forests have existed for more than 120 years where the annuality of the growth rings of tropical species (Worbes, 2002), using it to know the growth past, to know what the relationships of growth with the environment are and to reconstruct the climate (Mariaux, 1967; Détienne, 1989; Layme et al., 2018; Aragão et al., 2022). However, these studies of tree growth rings are still scarce in tropical forests, given that there are more than 40,000 species of tropical trees in the world (Slik et al., 2015) and South America, for example, reports 6,727 tree species (Cardoso et al., 2017) but studies show that only 220 to 230 species of tropical trees have been confirmed in all continents and climatic zones with annual formation and growth (Brienen et al., 2016; Schöngart et al., 2017) that is, we only know 0.6% of the tropical species that form confirmed annual growth rings, although in recent decades the study of growth rings in tropical forests has spread rapidly, there is a knowledge gap very wide and in need of narrowing it.

Therefore, it is necessary to carry out more studies of tropical tree species that mark growth rings and/or those that do not, since this information will help researchers and help them save time and money (Groenendijk et al., 2014). Some studies have analyzed tropical tree species in the world, showing the potential of the anatomy of growth rings (distinction, type of marking, etc.), in addition to seeking to build chronologies and validate them using carbon 14 techniques (Brienen et al., 2009; Groenendijk et al., 2014; Islam et al., 2018; Lisi et al., 2008). Peru has few

studies on the potential of growth rings (Beltrán and Valencia, 2013; Marcelo-Peña et al., 2020), even more, knowing its high biodiversity and types of climate urges the need to know both tree species tropical that form annual growth rings and with the same importance, those that do not form annual rings. Where different methodologies can be applied, from classic and basic studies on the anatomy of wood oriented to growth rings (Beltrán and Valencia, 2013; Marcelo-Peña et al., 2020), cambial marking (Lisi et al., 2008), X-ray densitometry (Tomazello et al., 2008), autofluorescence (Godoy et al., 2019), blu intensity (Buckley et al., 2018), among other methodologies that have the purpose of analyzing and verifying the annuality of the growth rings in tropical forests.

In this sense, Peru, a tropical South American country, stands out for having the second largest area of tropical native forests (and the fourth for forest plantations) in the American continent, and for hosting incredible biodiversity (Pitman et al., 2002; Vásquez et al., 2018; Wittmann et al., 2006). 84 of the 117 world life zones are present in the country (Asner et al., 2017; Brack, 2004; Cossío et al., 2014; P. Oliveira et al., 2007). Where studies on dendrochronology were carried out in Peru (Crispín et al., 2022; Pereyra, 2011; Rodríguez et al., 2005) but little is known about all the studies carried out, their advances, limitations and challenges, the few references we have about the history of dendrochronology in Peru are general (Rodríguez et al., 2005; Tomazello et al., 2009) and it is a priority to make the state of the art of dendrochronology in Peru and generate a base of general data of these studies including all the information (degree thesis, master's degree, doctorate, article in journals indexed in international databases and articles in other journals indexed in other databases) that may show their real status and be the scientific basis to project the results later studies.

On the other hand, El Niño-Southern Oscillation originates in the Tropical Pacific Ocean, which is an ocean-atmospheric phenomenon with unusual warm (El Niño) and cold (La Niña) fluctuations, which occurs in centuries from 2 to 7 years directly related to the Pacific trade winds and their strength, where through atmospheric teleconnections it influences climate variability and brings impacts throughout the world (McPhaden et al., 2006; Sulca et al., 2018). Where El Niño together with the Sea Surface Temperature (SST) of the Pacific and Atlantic oceans modify the path of the Intertropical Convergence Zone (ITCZ) in South America, being able to intensify the rains or interrupt them, for example, the displacement in the austral summer causes the ITCZ to be located further to the southeast of the continent where low pressure brings a rainy summer and the displacement of the ITCZ further north (Central America) results in a drier winter in South America due to high pressure (Jimenez et al., 2019; Marengo and Espinoza, 2016; Sulca et al., 2018). In this sense, several studies have shown the influence of the El Niño-Southern Oscillation and the Sea Surface Temperature (SST) on the growth of tropical trees through the study of growth rings (Aragão et al., 2022; Felfili et al., 2018; Menezes et al., 2022) and in Peru this kind of studies have also been carried out but on the coast and highlands of the country (Layme et al., 2018; Requena et al., 2020; Rodríguez et al., 2005), but in the Peruvian jungle there is no research on this subject, being this area of the country where the forestry is carried out, which is why it is necessary to investigate the influence of El Niño-Southern Oscillation and Sea Surface Temperature (SST) on the growth of commercial tropical species.

In addition, it is necessary to apply dendrochronological techniques to species that are highly threatened in the tropical forests of South America and it is possible to visualize growth rings so that the results can be applied to SFM. Among the endangered species of flora included in 2020 in Appendix II of the Convention on International Trade in Endangered Species of Fauna and Flora (CITES), are *Cedrela* spp., *Swietenia humilis*, *Swietenia macrophylla* and *Swietenia mahagoni* (CITES, 2020), species that belong to the botanical family Meliaceae, which are characterized by presenting a high value in tropical forests, due to their excellent technological properties and beauties, where *S. macrophylla* has been listed since 2002 in Appendix II CITES, where the intention is that their

trade does not harm their populations in natural ecosystems (Grogan et al., 2008), since they have been intensively exploited since the 70s and 80s, which generated a very significant impact on their natural populations in tropical forests (de Oliveira et al., 2020; Degen et al., 2013; Estrada et al., 2016; Sebbenn et al., 2012).

### 1.1. Outline of the thesis

In this doctoral thesis, we study the dendrochronology and dendroclimatology of tropical tree species from southeastern Peruvian Amazon, of the department of Madre de Dios is located in the triple border of the country, limited to Acre (Brazil) and Pando (Bolivia), this department is considered the biodiversity capital of Peru, due to its high rates of biological diversity (Foster et al., 1994) and considered a biodiversity hotspot (Myers et al., 2000; Olson and Dinerstein, 2002). All samples were collected from commercial trees from forestry concessions (slices/wedges) granted by the Peruvian state, conservation concessions (cores), and wooden cubes provided by the Xiloteca of the Universidad Nacional Amazónica de Madre de Dios. The main objective of this thesis is to analyze the tropical species of the Amazonian forest of Southeast Peru for dendrochronological and dendroclimatic studies.

This doctoral thesis aims to answer the main questions:

- 1) What is the state of the art in dendrochronology in Peru?
- 2) What are the anatomical and density characteristics of tree growth ring boundaries for the 34 species studied?
- 3) What are the growth rates and trajectories for the subset of trees for the 6 species studied?
- 4) Is it possible to construct the chronologies of the trees for the 6 species studied with acceptable statistics?
- 5) Is the growth of the trees of these 6 species correlated with the local climate?
- 6) Is the growth of the trees of these 6 species correlated with the sea surface temperature of the Pacific and Atlantic Oceans in species with the El Niño phenomenon?

We address these questions using 222 trees of 34 species from 18 botanical families with different phenological behaviors, anatomical structures, ages, densities, and growth strategies. For this, three chapters were developed to achieve the main objective:

In chapter 1 he made the history of art on dendrochronology in Peru from its beginnings to the present. To this end, a database of studies on dendrochronology in Peru was systematized and generated by compiling information from different sources: scientific articles electronically indexed in Scopus, Web of Science and Scielo; other academic articles not present in these indexes; and 51 online repositories from Peruvian universities containing bachelor's, masters and doctoral theses. It is one of the first investigations that shows the history of the art of dendrochronology in Peru, which will serve as the basis for further investigations on growth rings of tropical species.

In chapter 2 he evaluated the dendrochronological potential of 34 forest species growing in a tropical moist forest. For this, I relied on the macroscopic anatomy of the growth rings, and their presence and distinction; In addition, we use X-ray densitometry techniques to identify the limits of the growth rings. In a subset of six species, I analyze the growth rates and trajectories throughout the life of these species. The growth rings of 09 forest species are described for the first time.

In Chapter 3, you used the species from the subset from Chapter 2 to construct chronologies, relating growth to local climate and global climate variations. For this, we worked with 188 trees of 06 forest species. This thesis reports for the first time the construction of chronologies and the relationships with the local/global climate

of 03 species, in addition, it is highlighted that the 06 species were influenced by the climatic phenomenon El Niño. Finally, I make the final considerations of the thesis.

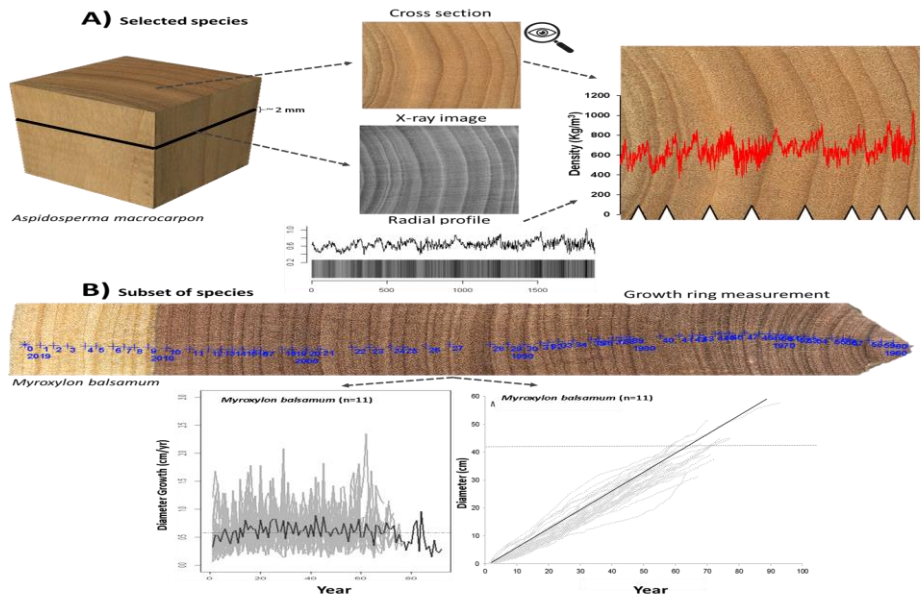
1.2. Graphical abstract

Dendrochronology and dendroclimatology of tropical tree species from southeastern Peruvian Amazon

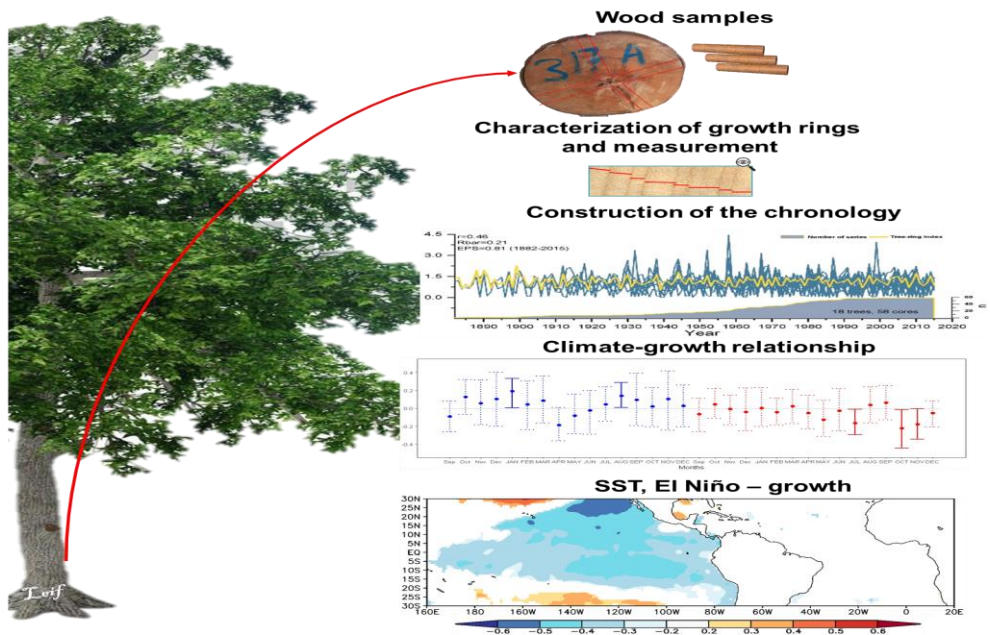
Chapter 1



Chapter 2



Chapter 3



## References

- Aguirre, J., Guerrero, E., Campana, Y. (2021). How effective are protected natural areas when roads are present? An analysis of the Peruvian case. *Environmental Economics and Policy Studies*. <https://doi.org/10.1007/s10018-021-00304-y>
- Aragão, J. R. V., Zuidema, P. A., Groenendijk, P. (2022). Climate-growth relations of congeneric tree species vary across a tropical vegetation gradient in Brazil. *Dendrochronologia*, *71*, 125913. <https://doi.org/10.1016/j.dendro.2021.125913>
- Brienen, R., Schöngart, J., Zuidema, P. A. (2016). Tree Rings in the Tropics: Insights into the Ecology and Climate Sensitivity of Tropical Trees. En G. Goldstein L. S. Santiago (Eds.), *Tropical Tree Physiology* (Vol. 6, pp. 439-461). Springer International Publishing. [https://doi.org/10.1007/978-3-319-27422-5\\_20](https://doi.org/10.1007/978-3-319-27422-5_20)
- Cardoso, D., Särkinen, T., Alexander, S., Amorim, A., Bittrich, V., Celis, M., Daly, D., Fiaschi, P., Funk, V., Giacomín, L., Goldenberg, R., Heiden, G., Iganci, J., Kelloff, C., Knapp, S., Cavalcante de Lima, H., Machado, A., dos Santos, R., Mello-Silva, R., ... Forzza, R. (2017). Amazon plant diversity revealed by a taxonomically verified species list. *Proceedings of the National Academy of Sciences*, *114*(40), 10695-10700. <https://doi.org/10.1073/pnas.1706756114>
- Chisholm, R. A., Müller-Landa, H. C., Abdul, K., Bebbler, D., Bohlman, S. (2013). Scale-dependent relationships between tree species richness and ecosystem function in forests. *Journal of Ecology*, *101*, 1214-1224. <https://doi.org/10.1111/1365-2745.12132>
- CITES, 2020. (2020). *Apéndices I, II y III. CONVENCIÓN SOBRE EL COMERCIO INTERNACIONAL DE ESPECIES AMENAZADAS DE FAUNA Y FLORA SILVESTRES*. <https://cites.org/sites/default/files/esp/app/2020/S-Appendices-2020-08-28.pdf>
- de Oliveira, S., Campos, T., Sebbenn, A., d'Oliveira, M. (2020). Using spatial genetic structure of a population of *Swietenia macrophylla* King to integrate genetic diversity into management strategies in Southwestern Amazon. *Forest Ecology and Management*, *464*, 118040. <https://doi.org/10.1016/j.foreco.2020.118040>
- Deb, J. C., Phinn, S., Butt, N., Mcalpine, C. A. (2018). Climate change impacts on tropical forests: Identifying risks for tropical Asia. *JOURNAL OF TROPICAL FOREST SCIENCE*, *30*(2), 182-194. <https://doi.org/10.26525/jtfs2018.30.2.182194>
- Degen, B., Ward, S. E., Lemes, M. R., Navarro, C., Cavers, S., Sebbenn, A. M. (2013). Verifying the geographic origin of mahogany (*Swietenia macrophylla* King) with DNA-fingerprints. *Forensic Science International: Genetics*, *7*(1), 55-62. <https://doi.org/10.1016/j.fsigen.2012.06.003>
- Détienne, P. (1989). Appearance and Periodicity of Growth Rings in some Tropical Woods. *LAWA Journal*, *10*(2), 123-132. <https://doi.org/10.1163/22941932-90000480>
- Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., Wilcove, D. S. (2019). Conservation of Tropical Forests in the Anthropocene. *Current Biology*, *29*(19), R1008-R1020. <https://doi.org/10.1016/j.cub.2019.08.026>
- Ehrenberg, F., Peña, M. (2020). Twenty years of forest management certification in the tropics: Major trends through time and among continents. *Forest Policy and Economics*, *111*, 102050. <https://doi.org/10.1016/j.forpol.2019.102050>
- Estrada, I., Equihua, M., Laborde, J., Martínez, E., Sánchez, L. (2016). Current and Future Distribution of the Tropical Tree *Cedrela odorata* L. in Mexico under Climate Change Scenarios Using MaxLike. *PLOS ONE*, *11*(10), e0164178. <https://doi.org/10.1371/journal.pone.0164178>



- Fan, L., Wigneron, J.-P., Ciais, P., Chave, J., Brandt, M., Fensholt, R., Saatchi, S. S., Bastos, A., Al-Yaari, A., Hufkens, K., Qin, Y., Xiao, X., Chen, C., Myneni, R. B., Fernandez-Moran, R., Mialon, A., Rodriguez-Fernandez, N. J., Kerr, Y., Tian, F., Peñuelas, J. (2019). Satellite-observed pantropical carbon dynamics. *Nature Plants*, 5(9), 944-951. <https://doi.org/10.1038/s41477-019-0478-9>
- Foster, R., Parker, T., Gentry, A. (Eds.). (1994). *The Tambopata-Candamo reserved zone of southeastern Perú: A biological assessment*. Conservation International, Department of Conservation Biology.
- Grogan, J., Jennings, S., Landis, R., Schulze, M., Baima, A., Lopes, J., Norghauer, J., Oliveira, L., Pantoja, F., Pinto, D., Silva, J., Vidal, E., Zimmerman, B. (2008). What loggers leave behind: Impacts on big-leaf mahogany (*Swietenia macrophylla*) commercial populations and potential for post-logging recovery in the Brazilian Amazon. *Forest Ecology and Management*, 255(2), 269-281. <https://doi.org/10.1016/j.foreco.2007.09.048>
- Jiménez-Muñoz, J. C., Mattar, C., Barichivich, J., Santamaría-Artigas, A., Takahashi, K., Malhi, Y., Sobrino, J. A., Schrier, G. van der. (2016). Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Scientific Reports*, 6(1), 33130. <https://doi.org/10.1038/srep33130>
- Lakerveld, R. P., Lele, S., Crane, T. A., Fortuin, K. P. J., Springate-Baginski, O. (2015). The social distribution of provisioning forest ecosystem services: Evidence and insights from Odisha, India. *Ecosystem Services*, 14, 56-66. <https://doi.org/10.1016/j.ecoser.2015.04.001>
- Layme, E. T., Ferrero, M. E., Palacios, K. S., Requena, E. J. (2018). *Cedrela nebulosa*: A novel species for dendroclimatological studies in the montane tropics of South America. *Dendrochronologia*, 50, 105-112. <https://doi.org/10.1016/j.dendro.2018.06.004>
- Malhi, Y., Phillips, O. L., Lloyd, J., Baker, T., Wright, J., Almeida, S., Arroyo, L., Frederiksen, T., Grace, J., Higuchi, N., Killeen, T., Laurance, W. F., Leão, C., Lewis, S., Meir, P., Monteagudo, A., Neill, D., Vargas, P. N., Panfil, S. N., ... Vinceti, B. (2002). An international network to monitor the structure, composition and dynamics of Amazonian forests (RAINFOR). *Journal of Vegetation Science*, 13(3), 439-450. [https://doi.org/10.1658/1100-9233\(2002\)013\[0439:AINTMI\]2.0.CO;2](https://doi.org/10.1658/1100-9233(2002)013[0439:AINTMI]2.0.CO;2)
- Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., Nobre, C. A. (2008). Climate Change, Deforestation, and the Fate of the Amazon. *Science*, 319(5860), 169-172. <https://doi.org/10.1126/science.1146961>
- Marengo, J. A., Espinoza, J. C. (2016). Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. *International Journal of Climatology*, 36(3), 1033-1050. <https://doi.org/10.1002/joc.4420>
- Marengo, J., Souza, C., Thonicke, K., Burton, C., Halladay, K., Betts, R., Alves, L., Soares, W. (2018). Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science*, 6, 228. <https://doi.org/10.3389/feart.2018.00228>
- Mariaux, A. (1967). Les cernes dans les bois tropicaux africains, nature et periodicite. *Rev. Bois For. Trop.*, 113, 3-14.
- Nasi, R., Putz, F., Pacheco, P., Wunder, S., Anta, S. (2011). Sustainable Forest Management and Carbon in Tropical Latin America: The Case for REDD+. *Forests*, 2(1), 200-217. <https://doi.org/10.3390/f2010200>
- Nobre, C., Sampaio, G., Borma, L., Castilla-Rubio, J., Silva, J., Cardoso, M. (2016). Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm. *Proceedings of the National Academy of Sciences*, 113(39), 10759-10768. <https://doi.org/10.1073/pnas.1605516113>
- Qin, Y., Xiao, X., Dong, J., Zhou, Y., Wang, J., Doughty, R., Chen, Y., Zou, Z., Moore, B. (2017). Annual dynamics of forest areas in South America during 2007–2010 at 50-m spatial resolution. *Remote Sensing of Environment*, 201, 73-87. <https://doi.org/10.1016/j.rse.2017.09.005>
- Schöngart, J., Bräuning, A., Barbosa, A., Lisi, C., de Oliveira, J. (2017). Dendroecological Studies in the Neotropics: History, Status and Future Challenges. En M. Amoroso, L. Daniels, P. Baker, J. Camarero (Eds.), *Dendroecology* (Vol. 231, pp. 35-73). Springer International Publishing. [https://doi.org/10.1007/978-3-319-61669-8\\_3](https://doi.org/10.1007/978-3-319-61669-8_3)

- Sebbenn, A. M., Licona, J. C., Mostacedo, B., Degen, B. (2012). Gene flow in an overexploited population of *Swietenia macrophylla* King (Meliaceae) in the Bolivian Amazon. *Silvae Genetica*, 61(1-6), 212-220. <https://doi.org/10.1515/sg-2012-0027>
- Slik, J. W. F., Arroyo-Rodríguez, V., Aiba, S.-I., Alvarez-Loayza, P., Alves, L. F., Ashton, P., Balvanera, P., Bastian, M. L., Bellingham, P. J., van den Berg, E., Bernacci, L., da Conceição Bispo, P., Blanc, L., Böhning-Gaese, K., Boeckx, P., Bongers, F., Boyle, B., Bradford, M., Brearley, F. Q., ... Venticinque, E. M. (2015). An estimate of the number of tropical tree species. *Proceedings of the National Academy of Sciences*, 112(24), 7472-7477. <https://doi.org/10.1073/pnas.1423147112>
- Sulca, J., Takahashi, K., Espinoza, J., Vuille, M., Lavado, W. (2018). Impacts of different ENSO flavors and tropical Pacific convection variability (ITCZ, SPCZ) on austral summer rainfall in South America, with a focus on Peru. *International Journal of Climatology*, 38(1), 420-435. <https://doi.org/10.1002/joc.5185>
- UNECE, FAO. (2018). *Forest Products Annual Market Review 2014-2015*. <https://unece.org/fileadmin/DAM/timber/publications/2015-FPAMR-E.pdf>
- Worbes, M. (2002). One hundred years of tree-ring research in the tropics – a brief history and an outlook to future challenges. *Dendrochronologia*, 20(1-2), 217-231. <https://doi.org/10.1078/1125-7865-00018>
- Xu, L., Saatchi, S. S., Yang, Y., Yu, Y., Pongratz, J., Bloom, A. A., Bowman, K., Worden, J., Liu, J., Yin, Y., Domke, G., McRoberts, R. E., Woodall, C., Nabuurs, G.-J., de-Miguel, S., Keller, M., Harris, N., Maxwell, S., Schimel, D. (2021). Changes in global terrestrial live biomass over the 21st century. *Science Advances*, 7(27), eabe9829. <https://doi.org/10.1126/sciadv.abe9829>



## 2. THIRTY-FOUR YEARS OF DENDROCHRONOLOGICAL STUDIES IN PERU: A REVIEW OF ADVANCES AND CHALLENGES

### 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 review provides an historic overview and state-of-the-art overview of dendrochronological studies in Peru, 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 18 families, 32 genera and 49 tree species. The most studied families have been Fabaceae (15 studies), Meliaceae (11), Rosaceae (05), and Bignoniaceae (03), and the most studied genera were *Cedrela* (12), *Pohlylepis* (07) and *Prosopis* (06). The development of chronologies was mainly applied in climatic reconstructions, forest conservation and management. We identify underrepresentations or sampling gaps regarding climatic and geographic complexity. The high diversity of Peru 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 Peru.

Keywords: climatology, forest management, tropical trees, tree-ring

### 2.1. 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 is observed in most species in temperate climates. From the 1950s onwards, there was an increase in tropical tree ring research (Worbes, 2002) showing that many of them form annual growth rings triggered by seasonal variations in the climate (Koriba, 1958; Mariaux, 1967; D tienne and Mariaux, 1975; Brien et al., 2006; Groenendijk et al., 2014). The fact that many tropical species form annual rings makes it possible to build chronologies that allow reconstructing environmental history for different biomes (Brien et al., 2016; Zuidema et al., 2022). 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, Groenendijk, Vlam, et al., 2015), allowing the reconstruction of the climate in the main atmospheric regulators of the planet (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 (Brien et al., 2016; Sch ngart et al., 2017; ter Steege et al., 2015). Therefore, it is important to review the existing studies, identifying the quality of the species for dendrochronological studies and identifying the 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 Peru. This South-American country stands out for having the second largest area of tropical native forests (and fourth in forest plantation) on the American continent, and for harboring incredible biodiversity (Pitman et al., 2002; Vásquez et al., 2018; Wittmann et al., 2006). A 84 out of the 117 world life zones are present in the country (Asner et al., 2017; Brack, 2004; Cossío et al., 2014; Oliveira et al., 2007). This high biodiversity combined with the country's relatively small size reinforces the great potential of Peru as an ideal country to advance dendrochronological studies in the tropics.

Our main objectives are to *i.* establish an historical overview of Dendrochronology in Peru; *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 Peru. This study thus presents a qualitative and quantitative inventory of the chronologies available for Peru 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.

## 2.2. Material and Methods

The database of dendrochronological studies in Peru was built by collecting information from different sources: scientific articles electronically indexed in Scopus ([www.scopus.com](http://www.scopus.com)), Web of Science ([www.webofscience.com](http://www.webofscience.com)), and Scielo ([www.scielo.br](http://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 that 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 Peru.

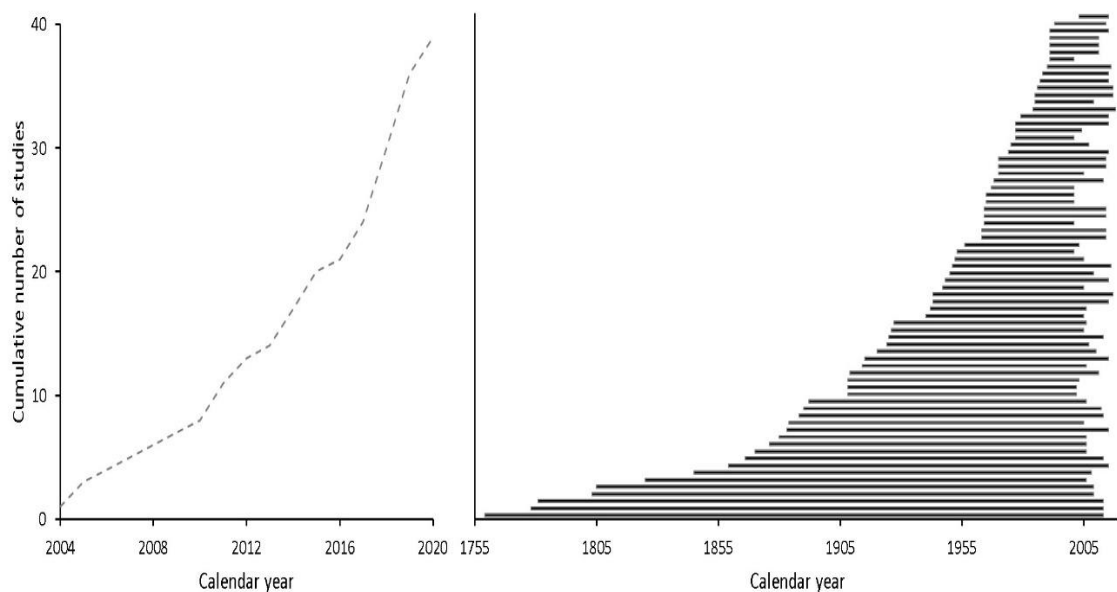
We used the following keywords: "Dendrochronology", "Dendroecology", "Dendroclimatology", "Growth rings", "Peru" and considered all publications available up to june 2022. All publications were read, analyzed, systematized and we only considered those studies that presented a constructed chronology, 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, and the department in Peru 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, and the characteristics of the chronologies and to know the species already investigated, where the investigations have been carried out and the coverage of the environmental envelope (precipitation and temperature). Finally, we examined studies that applied tree-rings to answer applied questions related to forest management in the country.

## 2.3. Results and Discussion

We were able to find a total of 45 publications (Table 1), consisting mostly of grey literature: theses (53%), articles published in non-indexed journals (9%) and publications from journals indexed in SCOPUS, Web of Science, and Scielo formed 38% of the publications reviewed here. Surprisingly, only 20% of these results were published in indexed journals. In this context, scientific information on dendrochronological research in Peru remains mainly in the repositories of Peruvian universities.

### 2.3.1. Track record and historic overview

The first report published in Peru 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 the late 1980s, the first attempts to apply dendroclimatology in Peru were carried out by the University of Piura in collaboration with the Geophysical Institute of Peru 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 1980s, the first dendrochronology laboratory in Peru was installed in 2001 at the University of Piura (Rodríguez et al., 2005). The first chronology validated with dendrochronological parameters in Peru 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.



**Figure 1.** Cumulative number of dendrochronological studies in Peru (left panel) and the temporal coverage of these chronologies (right panel).

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 Universidade de São Paulo 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 Universidad de Piura, where mainly undergraduate theses on dendrochronology were produced (Ancajima, 2017; Córdova, 2003; Flores, 1994; Martinez, 2002; Ortiz, 2019), the Universidad Nacional del Central Perú, where undergraduate theses were also generated (Beltran 2011; Inga 2011; Pereyra 2011; Ramirez 2018; Valencia 2011), and more recently also the Universidad Continental, the Universidad Nacional Amazónica de Madre de Dios and the Universidad Nacional de Jaén have also organized courses, often in collaboration with researchers from Brazil, Argentina, and Colombia.

### 2.3.2. Taxonomic coverage

In total, the reviewed studies included 18 botanical families, 32 genera and 49 species. Among all families studied, four comprise the largest number of investigations, being: Fabaceae (15 studies), Meliaceae (11), Rosaceae (05), and Bignoniaceae (03). It is worth noting that Fabaceae is the most studied family, with 15 investigations covering 11 species. In general, Fabaceae species are known to have distinct growth rings by the presence of a marginal parenchyma band (InsideWood 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). These particular conditions expands sampling possibilities in large areas of the Neotropics. In relation to the most considered genera in this survey, it is mentioned *Cedrela* (12), *Polylepis* (07) and *Prosopis* (06), with 45 researches. The genus *Cedrela* is one of the most studied in South America. Its species form well distinct rings marked by a 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 ( $^{13}\text{C}$ ) (Anholetto 2013), Oxygen isotopes ( $^{18}\text{O}$ ) (Brienen et al. 2012) and  $^{14}\text{C}$  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) and Peru is considered the center of the diversity of this genus, with 10 of the existing 17 species present in the country (Pennington and Styles 2010). In addition, the genus *Cedrela* has four species of restricted distribution, considered endemic in the country (*C. kuelapensis*, *C. molinensis*, *C. longipetiolumlata*, and *C. weberbaueri*) (SERFOR, 2020). The dendrochronological potential and wide distribution of *Cedrela* give this genus an important role to extend tree ring studies in the country. The derived information would also serve as an important input for the management and protection of this species, intensely exploited for the high quality of its wood.

### 2.3.3. 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), *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, with maximum ages of 207 years (Brienen et al., 2016), 186 years (Locosselli et al., 2020) and 214 (Groenendijk et al. 2014) being reported.

The highest intercorrelations of the 49 species studied in dendrochronology is in the northern coast portion of Peru (Fig. 2), where the correlations range between 0.34 to 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 Peru 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 Peru (Piura) was of significant increase to the precipitation that occurred in ENSO years (Holmgren et al. 2006). Fig. 2 show that the correlation with precipitation is higher in the drier sites, while correlation with temperature is lower in the more humid sites. These results give an idea of areas with important potential for dendroclimatic reconstructions in the country.

The level of intercorrelation between species varies, indicating 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* ( $r = 0.58$ ) and *Cedrela* ( $r = 0.45$ ) species stand out. These last two genera are noteworthy due to the potential longevity of their species (*Polylepis* = 414 years; *Cedrela* = 213 years) (Table 1). In general, the lowest correlations are linked to the climate of the tropical forest (Af), where we highlight the species of the botanical families Lauraceae and Fabaceae with low synchronisms, 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 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 available for this species (Portal, 2017).



**Table 1.** Basic information of the dendrochronological studies carried out in Peru. 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 = Intercorrelation; CLIM = Climate type (Koppen); Dep = Department. Gray rows are the indexed scientific articles (Scopus, Web of Science).

Species	Botanical family	WOSA	SAIN	SraIN	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 hyposericea</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>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 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>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 et al. (2019)
<i>Apuleia leiocarpa</i>	Fabaceae	Stump	7	2	7(100%)	1759-2013	255	0.04	...	Af	Madre de Dios	Portal (2017)
<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)

Table 1 (continued)

Species	Botanical family	WOSA	SAIN	SraIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/ EPS	CLIM	Dep	Reference
<i>Cedrelinga cateniformis</i>	Fabaceae	Stump	30	2	20(66%)	1943-2017	75	0.34	...	Af	Madre de Dios	Zavala and Rodríguez (2018)
<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)
<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)
<i>Beilschmiedia towarensis</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)

Table 1 (continued)

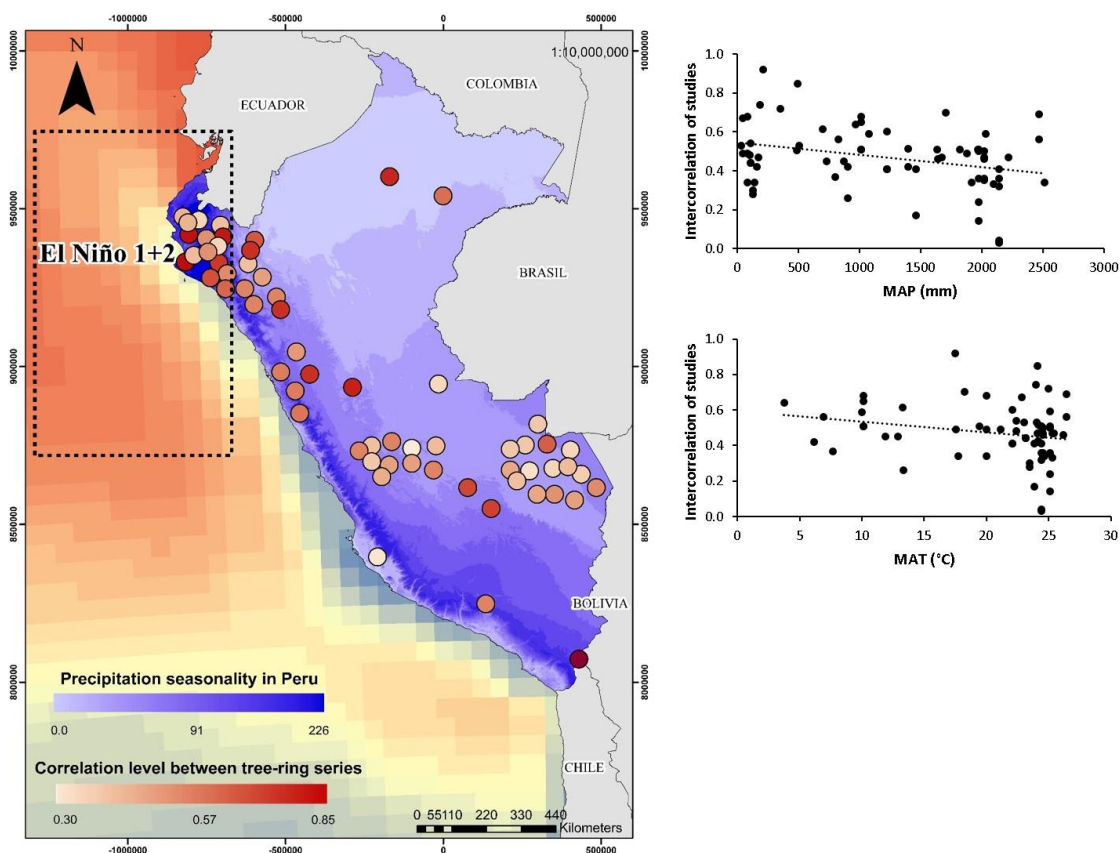
Species	Botanical family	WOSA	SAIN	SraIN	CRIN	CRPE	CRLE (yr)	Int	Rbar/ EPS	CLIM	Dep	Reference
<i>Ocotea bofo</i>	Lauraceae	Core	2	4	2(100%)	1915-2015	101	0.14	...	Af	Madre de Dios	Macedo (2018)
<i>Ocotea onalifolia</i>	Lauraceae	Core	2	4	2(100%)	1943-2015	73	-0.11	...	Af	Madre de Dios	Macedo (2018)
<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 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	Layme et al. (2018)
<i>Cedrela nebulosa</i>	Meliaceae	Core	13	...	11(81%)	1960-2016	57	0.49	...	Cwb	Junín	(Acevedo, 2018)
<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</i> sp.	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>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>Podocarpus glomeratus</i>	Podoarpaceae	...	80	1/2	...	1925-2013	88	...	...	Cwb	Apurímac	Villacorta et al. (2016)
<i>Pohlylepis flavipila</i>	Rosaceae	Stump	35	...	...	1951-2016	65	...	...	ET	Lima	Camel et al. (2019)
<i>Pohlylepis pepeí</i>	Rosaceae	Stump	17	3/4	...	1870-2006	137	0.65	/0.89	BSk	Cusco	Jomelli et al. (2012)
<i>Pohlylepis 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>Pohlylepis rodolfo-vasquezii</i> *	Rosaceae	S/c	50	2	40(80%)	1881-2016	135	0.58	0.31/0.82	Cwb	Junín	(Vidal, 2020)
<i>Pohlylepis 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 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.

### 2.3.4. 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: Tumbes, San Martín, Huancavelica, Ayacucho and Puno. Therefore, studies should be increased in these departments to expand the frontiers of dendrochronological knowledge in Peru.



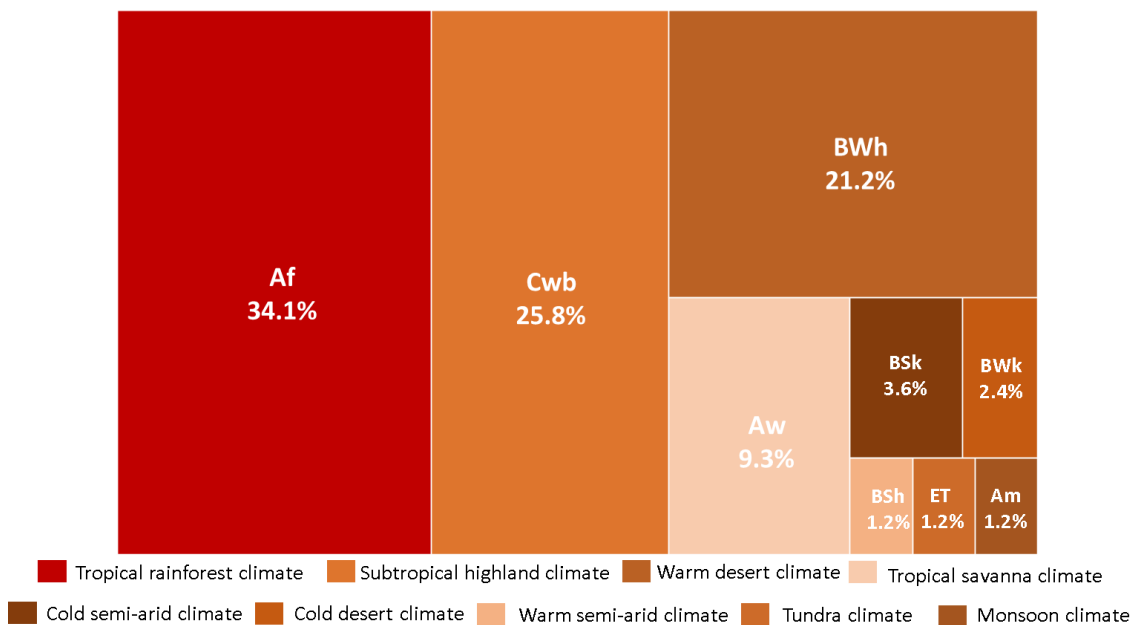
**Figure 2.** Map of Peru showing the intercorrelation value between tree-ring time series (circles) and rainfall seasonality (background gradation color calculated WorldClim data; Fick and Hijmans, 2017). The dotted line rectangle shows the area of influence of the El Niño 1 + 2 phenomenon on the north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

### 2.3.5. Spatial distribution of the chronologies

The climatic type that includes the highest percentage (34.1%) of dendrochronological studies correspond to the tropical rainforest (type Af; Fig. 3). The total area covered by these forests in Peru 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

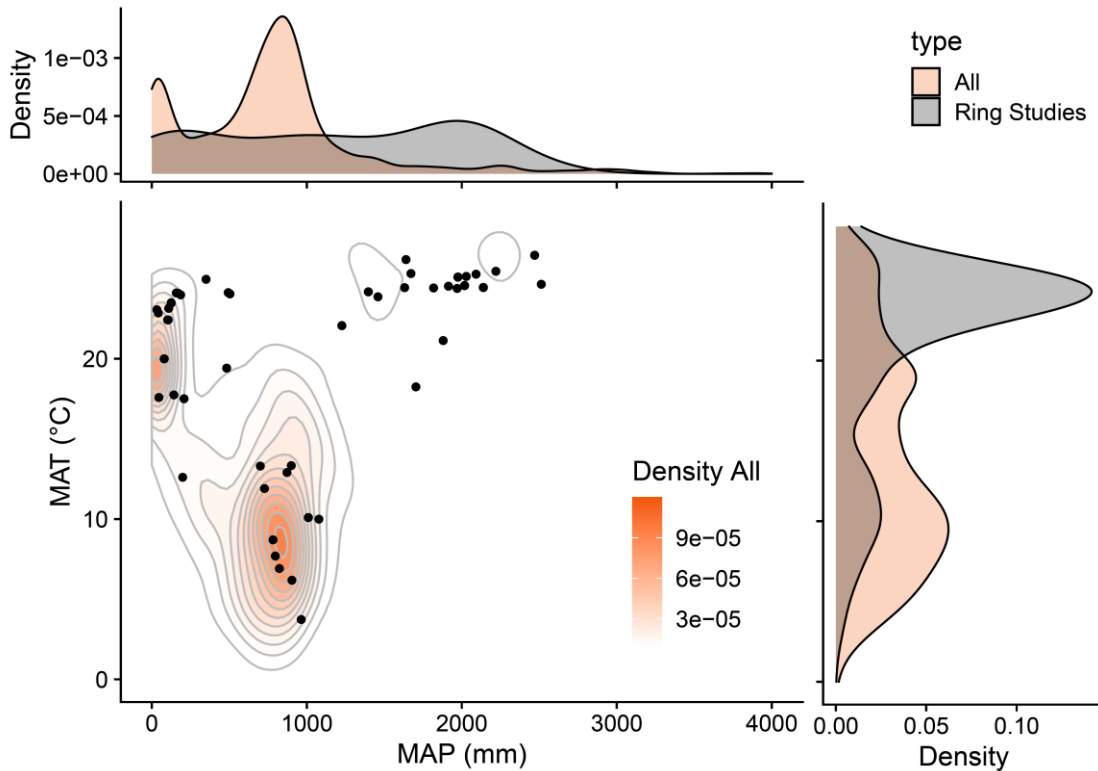
perspective, these forests area underrepresented in dendrochronological studies. Part of these tropical forests are subjected to commercial exploitation of native timber species, so there is a great availability of wood disc samples that facilitate obtaining chronologies with better data quality.

The subtropical highland climate (type Cwb) is the second type of climate with the largest number of studies (25.8%), followed by warm desert climate (type BWh) with 21.2% and tropical savanna climate (type Aw) with 9.3% (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 Peru, there is a need to increase efforts in the expansion of chronologies towards climatic areas that are dendrochronologically underrepresented.



**Figure 3.** Distribution of dendrochronological studies carried out in Peru in relation to the Köppen climate-type classification (REF).

The distribution of dendrochronological studies in Peru covers almost all climatic types, although with differences in representation. In terms of mean annual precipitation (MAP, mm yr<sup>-1</sup>) there is an acceptable number of studies above 1000 mm yr<sup>-1</sup>, 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 Peru, orange line; Fig. 4), however, below this level of precipitation, 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.



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

### 2.3.6. 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 also 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., Barçante Ladvocat Cintra et al., 2019). 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 Peru (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 (Beltran, 2011). The second is a study carried out in four departments of Peru (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 *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 Peru. 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 Peru. Two coastal departments, Tumbes and La Libertad did not register ENSO related research in scientific journals, highlighting unexplored potential areas of research. and Both regions present dry forests, that will have trees that probably are very responsive to climate. 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).

### 2.3.6.1. 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 Peru 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° 29763, 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.

### 2.3.6.2. <sup>14</sup>Carbon and stable isotopes

Constructed chronologies can be validated using the decay of the radioactive carbon <sup>14</sup>C. In the tropics, the peak in atmospheric <sup>14</sup>C 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 <sup>14</sup>C. Studies combining ring-width chronologies with stable isotope analyses (e.g. of the <sup>13</sup>C carbon isotope, or <sup>18</sup>O oxygen isotope) are scarce in Peru. These studies can be used to enhance climatic reconstructions (Brienen et al., 2012) or allow them in the absence of growth synchrony in 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 Peru, these analyses were performed focused on climatic signals, and only species for two species: *Prosopis* sp., ( $\delta^{18}\text{O}$ ) in the north of the country (Piura) (Evans and Schrag, 2004) and *Cedrela odorata* ( $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ ) in the northern (Loreto) and southern (Madre de Dios) parts of the Peruvian Amazon (Cintra et al., 2019). Due to the multiplicity of applications that isotope studies allow, these studies should be more widely applied along the Peruvian climate and vegetation types.



## 2.4. Conclusions

As a tree species mega-diverse country and along its environmental gradients, Peru 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 the of the El Niño Southern Oscillation temporal dynamics through tree-ring research.

The number of dendrochronological studies in Peru has been increasing rapidly in 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 49 tree species from 18 botanical families, which are related to a variety of phytophysiognomic and climatic types. In this sense, the teaching of the discipline in research institutes and universities has been the key to sowing new research groups to further consolidate dendrochronological studies in the country. However, there are still challenges to strengthen dendrochronological research in Peru, including the financing of research programs, the implementation of other methodologies (e.g. stable-isotopes), and the possibilities of 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 Peru constitutes a challenge for the implementation of these topics, where dendrochronology is positioned as a relevant contributor.

## Acknowledgments

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

## References

- Asner, G., Martin, R., Knapp, D., Tupayachi, R., Anderson, C. B., Sinca, F., Vaughn, N., and Llactayo, W. (2017). Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation. *Science*, 355(6323), 385-389. <https://doi.org/10.1126/science.aaj1987>
- Acevedo, I. M. (2018). Identificación de la variable climática que controla el crecimiento de *Cedrela* sp., *Cedrela nebulosa* T.D. y *Cedrela angustifolia* C.DC.; en los bosques montanos del Perú [Tesis de grado, Universidad Alas Peruanas]. [https://condesan.org/wp-content/uploads/2020/12/TesisIngrith\\_Vega.pdf](https://condesan.org/wp-content/uploads/2020/12/TesisIngrith_Vega.pdf)
- Ancajima, E. (2017). Dendrocronología de *Prosopis* sp. En la región Piura [Tesis de grado, Universidad Nacional de Piura]. <http://repositorio.unp.edu.pe/bitstream/handle/UNP/1046/CIE-ANC-MOR-17.pdf?sequence=1&disAllowed=y>
- Angoboy, B., De Mil, T., Hubau, W., Van, J., Van den Bulcke, J., Fayolle, A., Bourland, N., Kapalay, O., Chantrain, A., Ewango, C., and Beeckman, H. (2020). Towards improving the assessment of rainforest carbon: Complementary evidence from repeated diameter measurements and dated wood. *Dendrochronologia*, 62, 125723. <https://doi.org/10.1016/j.dendro.2020.125723>

- Asner, G., Martin, R., Knapp, D., Tupayachi, R., Anderson, C. B., Sinca, F., Vaughn, N., and Llactayo, W. (2017). Airborne laser-guided imaging spectroscopy to map forest trait diversity and guide conservation. *Science*, 355(623), 385-389. <https://doi.org/10.1126/science.aaj1987>
- Baker, J. A., Santos, G. M., Gloor, M., and Brienen, R. W. (2017). Does *Cedrela* always form annual rings? Testing ring periodicity across South America using radiocarbon dating. *Trees*, 31(6), 1999-2009. <https://doi.org/10.1007/s00468-017-1604-9>
- Ballantyne, A. P., Baker, P. A., Chambers, J. Q., Villalba, R., and Argollo, J. (2011). Regional Differences in South American Monsoon Precipitation Inferred from the Growth and Isotopic Composition of Tropical Trees\*. *Earth Interactions*, 15(5), 1-35. <https://doi.org/10.1175/2010EI277.1>
- Becerra, V. (2011). Determinación del turno de corta de *Cedrela odorata* L., *Retrophyllum rospigliosii* Pilger y *Prumnopitys harmsiana* Pilger a través del estudio dendrocronológico en la región Cajamarca—Perú [Tesis de maestría]. Universidad Nacional Agraria La Molina.
- Beltran, L. (2011). Caracterización anatómica de anillos de crecimiento de especies forestales tropicales maderables con valor comercial para dendrocronología—Selva Central [Tesis de grado, Universidad Nacional del Centro del Perú]. <http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/2595/Beltran%20Gutierrez.pdf?sequence=1&disAllowed=y>
- Bergeron, Y., Denneler, B., Charron, D., and Girardin, M. (2002). Using dendrochronology to reconstruct disturbance and forest dynamics around Lake Duparquet, northwestern Quebec. *Dendrochronologia*, 20(1-2), 175-189. <https://doi.org/10.1078/1125-7865-00015>
- Brack, A. (2004). Biodiversidad y desarrollo sostenible.
- Brandes, A. F. das N., Lisi, C. S., da Silva, L. D. S. A. B., Rajput, K. S., and Barros, C. F. (2015). Seasonal cambial activity and wood formation in trees and lianas of Leguminosae growing in the Atlantic Forest: A comparative study. *Botany*, 93(4), 211-220. <https://doi.org/10.1139/cjb-2014-0198>
- Brienen, R., Helle, G., Pons, T., Boom, A., Gloor, M., Groenendijk, P., Clerici, S., Leng, M., and Jones, C. (2022). Paired analysis of tree ring width and carbon isotopes indicates when controls on tropical tree growth change from light to water limitations. *Tree Physiology*, 42(6), 1131-1148. <https://doi.org/10.1093/treephys/tpab142>
- Brienen, R., Helle, G., Pons, T. L., Guyot, J.-L., and Gloor, M. (2012). Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Niño-Southern Oscillation variability. *Proceedings of the National Academy of Sciences*, 109(42), 16957-16962. <https://doi.org/10.1073/pnas.1205977109>
- Brienen, R., P.A., and Daring, H. J. (2006). Autocorrelated growth of tropical forest trees: Unraveling patterns and quantifying consequences. *Forest Ecology and Management*, 237(1-3), 179-190. <https://doi.org/10.1016/j.foreco.2006.09.042>
- Brienen, R., Schöngart, J., and Zuidema, P. A. (2016). Tree Rings in the Tropics: Insights into the Ecology and Climate Sensitivity of Tropical Trees. En G. Goldstein and L. S. Santiago (Eds.), *Tropical Tree Physiology* (Vol. 6, pp. 439-461). Springer International Publishing. [https://doi.org/10.1007/978-3-319-27422-5\\_20](https://doi.org/10.1007/978-3-319-27422-5_20)
- Camel, V., Arizapana-Almonacid, M., Pyles, M., Galeano, E., Quispe-Melgar, H. R., Ninanya-Parra, Z., Ames-Martínez, F. N., Requena-Rojas, E., and Kessler, M. (2019). Using dendrochronology to trace the impact of the hemiparasite *Tristerix chodatianus* on Andean *Polylepis* trees. *Plant Ecology*, 220(9), 873-886. <https://doi.org/10.1007/s11258-019-00961-w>
- Campos, L. E. (2009). Dendrocronología en árboles de Tornillo, *Cedrelinga cateniformis* Ducke (Fabaceae), del Centro de Investigaciones Jenaro Herrera en el noreste de la Amazonia, Región Loreto – Perú. Universidad Nacional Agraria La Molina.

- Castañeda, M., Inga, J., and Arizapana, M. (2013). Aplicación de cuatro modelos de crecimiento a series dendrocronológicas de *Cedrela montana* (Meliaceae) - Comunidad Nativa de Shaani, región Ucayali, Perú. 26, 9.
- Cintra, B., Gloor, M., Boom, A., Schöngart, J., Locosselli, G. M., and Brienen, R. (2019). Contrasting controls on tree ring isotope variation for Amazon floodplain and terra firme trees. *Tree Physiology*, 39(5), 845-860. <https://doi.org/10.1093/treephys/tpz009>
- Colina, C. (2019). Dendrocronología de la especie *Zanthoxylum rhoifolium*, en un bosque de terraza alta en la región Madre de Dios [Tesis de grado]. Universidad Nacional Amazónica de Madre de Dios.
- Córdova, E. (2003). Reconstrucción climática a partir del anillado de los árboles de la costa norte del Perú [Tesis de grado, Universidad de Piura]. [http://www.biblioteca.udep.edu.pe/BibVirUDEP/tesis/pdf/1\\_546\\_147\\_364\\_3673.pdf](http://www.biblioteca.udep.edu.pe/BibVirUDEP/tesis/pdf/1_546_147_364_3673.pdf)
- Cossío, R., Menton, M., Cronkleton, P., and Larson, A. (2014). Community forest management in the Peruvian Amazon. CIFOR, 31.
- Crispín, D. B., Morales, Mariano. S., Andreu-Hayles, Laia., Christie, Duncan. A., Guerra, A., and Requena-Rojas, Edilson. J. (2022). High ENSO sensitivity in tree rings from a northern population of *Polylepis tarapacana* in the Peruvian Andes. *Dendrochronologia*, 71, 125902. <https://doi.org/10.1016/j.dendro.2021.125902>
- Dávila, T. (2020). Dendrocronología de la especie *Guazuma crinita* Mart. En bosque natural y plantación forestal de la provincia Tambopata-Madre de Dios [Tesis de grado, Universidad Nacional Amazónica de Madre de Dios]. <http://repositorio.unamad.edu.pe/handle/UNAMAD/676>
- Détienne, P., and Mariaux, A. (1975). Nature et periodicité des cernes dans le bois de Niangon. *Bois For. Trop.*, 159, 29-37.
- Domínguez, J. (2014). Evaluación de la influencia de la precipitación y temperatura en el crecimiento de *Pinus patula* y *Pinus muricata* en plantaciones de la Granja Porcon (Perú) a través de técnicas dendrocronológicas [Tesis de grado, Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/882/K10-D65-T.pdf?sequence=3&disAllowed=y>
- Egües, A. A. (2021). Caracterización anatómica de la madera y dendrocronología de *Juglans neotropica* Diels de áreas ribereñas de la provincia de Chachapoyas, Amazonas [Tesis de grado, Universidad Nacional Agraria La Molina]. <https://repositorio.lamolina.edu.pe/bitstream/handle/20.500.12996/4771/egues-nicoletti-andrea-adriana.pdf?sequence=1&disAllowed=y>
- Evans, M., and Schrag, D. (2004). A stable isotope-based approach to tropical dendroclimatology. *Geochimica et Cosmochimica Acta*, 68(16), 3295-3305. <https://doi.org/10.1016/j.gca.2004.01.006>
- Fick, S. E., and Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, 37(12), 4302-4315. <https://doi.org/10.1002/joc.5086>
- Flores, V. (1994). Relación dendrocronológica entre el crecimiento radial del sapote y eventos climáticos [Tesis de grado]. Universidad de Piura.
- Fu, T., Liang, E., Lu, X., Gao, S., Zhang, L., Zhu, H., Rossi, S., and Camarero, J. (2020). Tree growth responses and resilience after the 1950-Zayu-Medog earthquake, southeast Tibetan Plateau. *Dendrochronologia*, 62, 125724. <https://doi.org/10.1016/j.dendro.2020.125724>
- Ghezzi, I., and Rodríguez, R. (2015). Primera serie dendroarqueológica en los Andes Centrales: Resultados preliminares de Chankillo, Casma. *Bulletin de l'Institut français d'études andines*, 44 (1), 1-21. <https://doi.org/10.4000/bifea.7465>

- Groenendijk, P., Bongers, F., and Zuidema, P. A. (2017). Using tree-ring data to improve timber-yield projections for African wet tropical forest tree species. *Forest Ecology and Management*, 400, 396-407. <https://doi.org/10.1016/j.foreco.2017.05.054>
- Groenendijk, P., Sass-Klaassen, U., Bongers, F., and Zuidema, P. A. (2014). Potential of tree-ring analysis in a wet tropical forest: A case study on 22 commercial tree species in Central Africa. *Forest Ecology and Management*, 323, 65-78. <https://doi.org/10.1016/j.foreco.2014.03.037>
- Groenendijk, P., van der Sleen, P., Vlam, M., Bunyavechewin, S., Bongers, F., and Zuidema, P. A. (2015). No evidence for consistent long-term growth stimulation of 13 tropical tree species: Results from tree-ring analysis. *Global Change Biology*, 21(10), 3762-3776. <https://doi.org/10.1111/gcb.12955>
- Guzman, E., Ramos, C., and Dastgheib, A. (2020). Influence of the El Niño Phenomenon on Shoreline Evolution. Case Study: Callao Bay, Perú. 16.
- Hammerschlag, I., Macario, K. D., Barbosa, A. C., Pereira, G. de A., Farrapo, C. L., and Cruz, F. (2019). Annually Verified Growth of *Cedrela Fissilis* from Central Brazil. *Radiocarbon*, 61(4), 927-937. <https://doi.org/10.1017/RDC.2019.52>
- Holmgren, M., López, B., Gutiérrez, J., and Squeo, F. (2006). Herbivory and plant growth rate determine the success of El Niño Southern Oscillation-driven tree establishment in semiarid South America. *Global Change Biology*, 9.
- Holmgren, M., Stapp, P., Dickman, Ch., Gracia, C., Graham, S., Gutiérrez, J., Hice, Ch., Jaksic, F., Kelt, D., Letnic, M., Lima, M., López, B., Meserve, P., Milstead, W., Polis, G., Previtali, M., Richter, M., Sabaté, S., and Squeo, F. (2006). Extreme climatic events shape arid and semiarid ecosystems. *Frontiers in Ecology and the Environment*, 4(2), 87-95. [https://doi.org/10.1890/1540-9295\(2006\)004\[0087:ECESAA\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2006)004[0087:ECESAA]2.0.CO;2)
- Huamán, B. (2019). Evaluación del crecimiento de *Cedrela fissilis* Vell. Aplicando técnicas dendrocronológicas en áreas urbanas en el sector la joya de la ciudad de Puerto Maldonado, distrito Tambopata, provincia Tambopata, departamento de Madre de Dios-2019 [Tesis de grado, Universidad Nacional Amazónica de Madre de Dios]. <http://repositorio.unamad.edu.pe/handle/UNAMAD/693>
- Huaman, C. (2011). Dendrocronología de árboles de azúcar huayo (*Hymenaea courbaril* L.) en la región de Madre de Dios (provincia de Tahuamanu) - Perú [Tesis de maestría]. Universidad Nacional Agraria La Molina.
- Inga, J. (2011). Turno biológico de corta en *Juglans neotropica* Diels, a partir del análisis de anillos de crecimiento en Selva Central del Perú [Tesis de grado, Universidad Nacional del Centro del Perú]. <http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/2599/Inga%20Guillen.pdf?sequence=1&disAlloved=y>
- Inga, J., and del Valle, J. (2017). Log-relative growth: A new dendrochronological approach to study diameter growth in *Cedrela odorata* and *Juglans neotropica*, Central Forest, Peru. *Dendrochronologia*, 44, 117-129. <https://doi.org/10.1016/j.dendro.2017.03.009>
- Islam, M., Rahman, M., and Bräuning, A. (2018). Growth-Ring Boundary Anatomy and Dendrochronological Potential in a Moist Tropical Forest in Northeastern Bangladesh. *Tree-Ring Research*, 74(1), 76-93. <https://doi.org/10.3959/1536-1098-74.1.76>
- Jenkins, H. (2009). Amazon Climate Reconstruction Using Growth Rates and Stable Isotopes of Tree Ring Cellulose from the Madre de Dios Basin, Peru [Tesis de doctorado, Duke University]. [https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/1352/D\\_Jenkins\\_Hillary\\_a\\_200908.pdf?sequence=1&disAllowed=y](https://dukespace.lib.duke.edu/dspace/bitstream/handle/10161/1352/D_Jenkins_Hillary_a_200908.pdf?sequence=1&disAllowed=y)
- Jomelli, V., Pavlova, I., Guin, O., Soliz, C., Contreras, A., Toivonen, J. M., and Zetterberg, P. (2012). Analysis of the Dendroclimatic Potential of *Polylepis pepeii*, *P. subsericans* and *P. rugulosa* In the Tropical Andes (Peru-Bolivia). *Tree-Ring Research*, 68(2), 91-103. <https://doi.org/10.3959/2011-10.1>

- Koriba, K. (1958). On the periodicity of the tree-growth in the tropics, with reference to the mode of branching, the leaf-fall, and the formation of the resting bud. *Gardens Bull.*, S. 27, 11-85.
- Layme, E. T., Ferrero, M. E., Palacios-Lazaro, K. S., and Requena-Rojas, E. J. (2018). *Cedrela nebulosa*: A novel species for dendroclimatological studies in the montane tropics of South America. *Dendrochronologia*, 50, 105-112. <https://doi.org/10.1016/j.dendro.2018.06.004>
- Ligot, G., Fayolle, A., Gourlet-Fleury, S., Dainou, K., Gillet, J.-F., De Ridder, M., Drouet, T., Groenendijk, P., and Doucet, J.-L. (2019). Growth determinants of timber species *Triplochiton scleroxylon* and implications for forest management in central Africa. *Forest Ecology and Management*, 437, 211-221. <https://doi.org/10.1016/j.foreco.2019.01.042>
- Ljungqvist, F., Piermattei, A., Seim, A., Krusic, P., Büntgen, U., He, M., Kirilyanov, A., Luterbacher, J., Schneider, L., Seftigen, K., Stahle, D., Villalba, R., Yang, B., and Esper, J. (2020). Ranking of tree-ring based hydroclimate reconstructions of the past millennium. *Quaternary Science Reviews*, 230, 106074. <https://doi.org/10.1016/j.quascirev.2019.106074>
- López, J., Valdez, J., Terrazas, T., and Valdez, J. (2006). Anillos de crecimiento y su periodicidad en tres especies tropicales del estado de Colima, México. *Agrociencia*, 40(4), Article 4.
- Macedo, K. (2018). Evaluación del Potencial Dendrocronológico de tres Especies de la Familia Lauraceae en Madre de Dios—Perú [Tesis de grado]. Universidad Nacional Amazónica de Madre de Dios.
- Mamani, E. (2018). Dendrocronología en Árboles de *Cordia alliodora* (Ruiz and Pav.) Oken., en el Sector La Joya – Tambopata – Madre de Dios [Tesis de grado, Universidad Nacional Amazónica de Madre de Dios]. <http://repositorio.unamad.edu.pe/bitstream/handle/UNAMAD/387/004-2-3-083.pdf?sequence=1&disAllowed=y>
- Marcelo-Peña, J., Roig, F., Goodwin, Z., and Tomazello, M. (2020). Characterizing growth rings in the trees of Perú: A wood anatomical overview for potential applications in dendroecological-related fields. *Dendrochronologia*, 125728. <https://doi.org/10.1016/j.dendro.2020.125728>
- Marcelo-Peña, J., Santini, L., and Tomazello, M. (2019). Wood anatomy and growth rate of seasonally dry tropical forest trees in the Marañón River Valley, northern Peru. *Dendrochronologia*, 55, 135-145. <https://doi.org/10.1016/j.dendro.2019.04.008>
- Mariaux, A. (1967). Les cernes dans les bois tropicaux africains, nature et periodicite. *Rev. Bois For. Trop.*, 113, 3-14.
- Martinez, E. (2002). Reconstrucción climática a partir del anillado de árboles de la costa norte del Perú [Tesis de grado]. Universidad de Piura.
- Maxwell, J., Harley, G., and Rahman, A. (2018). Annual Growth Rings in Two Mangrove Species from the Sundarbans, Bangladesh Demonstrate Linkages to Sea-Level Rise and Broad-Scale Ocean-Atmosphere Variability. *Wetlands*, 38, 1159-1170. <https://doi.org/10.1007/s13157-018-1079-5>
- Melo, J. (2010). Dendrocronología de la especie *Pinus radiata* de plantaciones de la granja Porcón Cajamarca [Tesis de maestría, Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/1170/T003831.pdf?sequence=1&disAllowed=y>
- Menezes, M., Berger, U., and Worbes, M. (2013). Annual growth rings and long-term growth patterns of mangrove trees from the Bragança peninsula, North Brazil. *Wetlands Ecology and Management*, 11, 233-242.
- Metsaranta, J., and Liefvers, V. (2009). Using dendrochronology to obtain annual data for modelling stand development: A supplement to permanent sample plots. *Forestry*, 82(2), 163-173. <https://doi.org/10.1093/forestry/cpn051>

- Navarro, R., and Zevallos, P. (2015). Dendrocronología de la especie “moena marilla” *Nectandra reticulata* (Ruiz and Pav.) Mez (Lauraceae) en Macuya, Tournavista, Huánuco—Perú. 11.
- Oliveira, P., Asner, G., Knapp, D., Almeyda, A., Galvan, R., Keene, S., Raybin, R., and Smith, R. (2007). Land-Use Allocation Protects the Peruvian Amazon. *Science*, 317(5842), 1233-1236. <https://doi.org/10.1126/science.1146324>
- Ortega, D. (2014). Evaluación de la influencia del raleo en el crecimiento de *Pinus patula* Schl. Et Cham. Aplicando técnicas dendrocronológicas en plantaciones de Cajamarca—Perú [Tesis de grado, Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/867/K10-O7-T.pdf?sequence=3&disAllowed=y>
- Ortiz, E. (2019). Desarrollo de una secuencia dendroarqueológica del Complejo Astronómico Chankillo usando *Prosopis* sp. En Casma. Región Ancash. 2015 [Tesis de grado, Universidad Nacional de Piura]. <http://repositorio.unp.edu.pe/bitstream/handle/UNP/1694/CIE-ORT-VAR-2018.pdf?sequence=1&disAllowed=y>
- Pécastaing, N. (2020). The impact of El Niño phenomenon on dry forest-dependent communities’ welfare in the northern coast of Peru. *Ecological Economics*, 10.
- Pennington, T. D., and Styles, B. T. (2010). A monograph of *Cedrela* (Meliaceae). The Manse, Chapel Lane. Milborne Port.
- Pereyra, M. (2011). Potencialidad de *Cedrela odorata* L. para estudios dendroclimáticos y dendroecológicos en Selva Central del Perú [Tesis de grado, Universidad Nacional del Centro del Perú]. <http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/2601/Pereyra%20Espinoza.pdf?sequence=1&disAllowed=y>
- Pitman, N., Terborgh, J., Silman, M., Núñez, P., Neill, D. A., Cerón, C., Palacios, W., and Aulestia, M. (2002). A comparison of tree species diversity in two upper amazonian forests. *Ecology*, 83(11), 3210-3224. [https://doi.org/10.1890/0012-9658\(2002\)083\[3210:ACOTSD\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083[3210:ACOTSD]2.0.CO;2)
- Portal, L. (2017). Potencial Dendrocronológico de Árvores da Família Fabaceae na Floresta Tropical Amazônica do Peru [Tesis de maestria, Universidade Federal Rural do Rio de Janeiro]. <https://tede.ufrj.br/jspui/bitstream/jspui/2060/2/2017%20-%20Leif%20Armando%20Portal%20Cahuana.pdf>
- Portal, L. (2019). Potencial dendrocronológico de la especie *Tachigali vasquezii* Pipoly y la relación con el cambio climático, en un bosque de terraza baja en el sur oriente del Perú (p. 28) [Informe final de investigación]. Universidad Nacional Amazónica de Madre de Dios. <http://repositorio.unamad.edu.pe/bitstream/handle/UNAMAD/432/003-2019-UNAMAD-VRI.pdf?sequence=1&disAllowed=y>
- Portal, L. A., Huamán, B. A., Mamani, E. M., Palermo, P. de M., and Latorraca, J. V. (2021). Dendrochronology of two forest species in the urban area of the city of Puerto Maldonado, Peru. 51(3), 10. <https://doi.org/10.5380/rf.v51.i3.72410>
- Portal, L., Cardozo, J., Santos, L., Saavedra, G., and Huamán, B. (2020). Dendrocronología de *Jacaranda copaia* que contiene registro ENSO en Madre de Dios, Perú. *Nativa*, 8(4), 572-578. <https://doi.org/10.31413/nativa.v8i4.10082>
- Ramirez, K. (2018). Etapas de crecimiento, incremento corriente anual e incremento medio anual de *Prunus serotina* Mcvaugh mediante dendrocronología, en los Distritos de Pilcomayo y Huamancaca Chico [Tesis de grado, Universidad Nacional del Centro del Perú]. [http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/5282/T010\\_43727719\\_T.pdf?sequence=1&disAllowed=y](http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/5282/T010_43727719_T.pdf?sequence=1&disAllowed=y)
- Requena, E. (2015). Dendrocronología de *Abnus acuminata* en el bosque reservado de San pedro de Saño, Huancayo. *Apuntes de Ciencia and Sociedad*, 05(02). <https://doi.org/10.18259/acs.2015035>

- Requena, E. J., Amoroso, M. M., Ticse-Otarola, G., and Crispin-Delacruz, D. B. (2021). Assessing Dendrochronological Potential of *Escallonia myrtilloides* in the High Andes of Peru. *Tree-Ring Research*, 77(2). <https://doi.org/10.3959/TRR2019-8>
- Requena, E. J., Morales, M., and Villalba, R. (2020). Dendroclimatological assessment of *Polylepis rodolfo-vasquezii*: A novel *Polylepis* species in the Peru highlands. *Dendrochronologia*, 62, 125722. <https://doi.org/10.1016/j.dendro.2020.125722>
- Rodríguez, R., Mabres, A., Luckman, B., Evans, M., Masiokas, M., and Ektvedt, T. M. (2005). “El Niño” events recorded in dry-forest species of the lowlands of northwest Peru. *Dendrochronologia*, 22(3), 181-186. <https://doi.org/10.1016/j.dendro.2005.05.002>
- Rosero, J. (2009). Dendrocronología de árboles de mogno, *Swietenia macrophylla* King., Meliaceae, ocorrentes na floresta tropical Amazônica do Departamento de Madre de Dios, Peru [Universidade de São Paulo]. <http://www.teses.usp.br/teses/disponiveis/11/11150/tde-18052009-165913/pt-br.php>
- Rosero, J. (2011). Análisis Dendrocronológico de tres especies forestales del Bosque seco Ecuatorial Estacional [Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/1671/K10.R8-T.pdf?sequence=1&disAllowed=y>
- Salazar, P., Navarro, R., Ancajima, E., Duque, J., Rodríguez, R., Ghezzi, I., and Mabres, A. (2018). Effect of climate and ENSO events on *Prosopis pallida* forests along a climatic gradient. *Forestry: An International Journal of Forest Research*, 91(5), 552-562. <https://doi.org/10.1093/forestry/cpy014>
- Schipper, A. (2011). Dendrocronología del cedro *Cedrela odorata* L. (Meliaceae) de la Amazonia sur del Perú, la región Madre de Dios [Tesis de maestría]. Universidad Nacional Agraria La Molina.
- Schofield, M., Barker, R., Gelman, A., Cook, E., and Briffa, K. (2016). A Model-Based Approach to Climate Reconstruction Using Tree-Ring Data. *Journal of the American Statistical Association*, 111(513), 93-106. <https://doi.org/10.1080/01621459.2015.1110524>
- Schöngart, J., Bräuning, A., Barbosa, A., Lisi, C., and de Oliveira, J. (2017). Dendroecological Studies in the Neotropics: History, Status and Future Challenges. En M. Amoroso, L. Daniels, P. Baker, and J. Camarero (Eds.), *Dendroecology* (Vol. 231, pp. 35-73). Springer International Publishing. [https://doi.org/10.1007/978-3-319-61669-8\\_3](https://doi.org/10.1007/978-3-319-61669-8_3)
- Schwyzer, A. (1988). Anillos de crecimiento en cuatro árboles tropicales. *Boletín de Lima*, 58, 83-86.
- Ley Forestal y de Fauna Silvestre N° 29763 y sus reglamentos, Pub. L. No. 29763, 345 (2015).
- Sulca, J., Takahashi, K., Espinoza, J., Vuille, M., and Lavado, W. (2018). Impacts of different ENSO flavors and tropical Pacific convection variability (ITCZ, SPCZ) on austral summer rainfall in South America, with a focus on Peru. *International Journal of Climatology*, 38(1), 420-435. <https://doi.org/10.1002/joc.5185>
- Takahashi, K. (2004). The atmospheric circulation associated with extreme rainfall events in Piura, Peru, during the 1997—1998 and 2002 El Niño events. *Annales Geophysicae*, 22(11), 3917-3926. <https://doi.org/10.5194/angeo-22-3917-2004>
- ter Steege, H., Pitman, N. C. A., Killeen, T. J., Laurance, W. F., Peres, C. A., Guevara, J. E., Salomão, R. P., Castilho, C. V., Amaral, I. L., de Almeida Matos, F. D., de Souza Coelho, L., Magnusson, W. E., Phillips, O. L., de Andrade Lima Filho, D., de Jesus Veiga Carim, M., Irumé, M. V., Martins, M. P., Molino, J.-F., Sabatier, D., ... Gamarra, L. V. (2015). Estimating the global conservation status of more than 15,000 Amazonian tree species. *Science Advances*, 1(10), e1500936. <https://doi.org/10.1126/sciadv.1500936>
- Tomazello, M., Roig, F. A., and Zevallos, P. A. (2009). Dendrocronología y dendroecología tropical: Marco histórico y experiencias exitosas en los países de América Latina. *Ecología en Bolivia*, 44(2), 73-82.

- UC. (2016). Libro de Resúmenes. Curso-Taller Dendrocronología y sus aplicaciones hidroclimáticas y ecológicas.
- Valencia, G. (2011). Caracterización anatómica de anillos de crecimiento de 40 especies forestales tropicales potenciales para estudios dendrocronológicos—Selva Central [Tesis de grado, Universidad Nacional del Centro del Perú]. <http://repositorio.uncp.edu.pe/bitstream/handle/UNCP/2606/Valencia%20%20Ramos.pdf?sequence=1&disAllowed=y>
- van der Sleen, P., Groenendijk, P., Vlam, M., Anten, N. P. R., Boom, A., Bongers, F., Pons, T. L., Terburg, G., and Zuidema, P. A. (2015). No growth stimulation of tropical trees by 150 years of CO<sub>2</sub> fertilization but water-use efficiency increased. *Nature Geoscience*, 8(1), 24-28. <https://doi.org/10.1038/ngeo2313>
- van der Sleen, P., Groenendijk, P., and Zuidema, P. A. (2015). Tree-ring  $\delta^{18}\text{O}$  in African mahogany (*Entandropbragma utile*) records regional precipitation and can be used for climate reconstructions. *Global and Planetary Change*, 127, 58-66. <https://doi.org/10.1016/j.gloplacha.2015.01.014>
- Vásquez, R., Rojas, R., Monteagudo, A., Valenzuela, L., and Huamantupa, I. (2018). Catálogo de los árboles del Perú (Vol. 9). Q'EUÑA.
- Vidal, O. D. (2020). Estructura dendroecológica de *Polylepis rodolfo-vasquezii* en la comunidad campesina de Pomamanta y Santa Rosa de Toldopampa, región Junín [Tesis de grado, Universidad Nacional del Centro del Perú]. [https://repositorio.uncp.edu.pe/bitstream/handle/20.500.12894/6685/T010\\_77464524\\_T.pdf?sequence=1](https://repositorio.uncp.edu.pe/bitstream/handle/20.500.12894/6685/T010_77464524_T.pdf?sequence=1)
- Villacorta, S., Rodríguez, Cl., Peña, Fl., Jaimes, F., and Luza, C. (2016). Caracterización geodinámica y dendrocronología como base para la evaluación de procesos geohidrológicos en la cuenca del río Mariño, Abancay (Perú). *Serie Correlación Geológica*, 32, 25-42.
- Vlam, M., van der Sleen, P., Groenendijk, P., and Zuidema, P. A. (2017). Tree Age Distributions Reveal Large-Scale Disturbance-Recovery Cycles in Three Tropical Forests. *Frontiers in Plant Science*, 7. <https://doi.org/10.3389/fpls.2016.01984>
- Wittmann, F., Schongart, J., Montero, J., Motzer, T., Junk, W. J., Piedade, M., Queiroz, H., and Worbes, M. (2006). Tree species composition and diversity gradients in white-water forests across the Amazon Basin. *Journal of Biogeography*, 33(8), 1334-1347. <https://doi.org/10.1111/j.1365-2699.2006.01495.x>
- Worbes, M. (2002). One hundred years of tree-ring research in the tropics—A brief history and an outlook to future challenges. *Dendrochronologia*, 20(1-2), 217-231. <https://doi.org/10.1078/1125-7865-00018>
- Worbes, M., and Junk, W. J. (1989). Dating Tropical Trees by Means of  $^{14}\text{C}$  From Bomb Tests. *Ecology*, 70(2), 503-507. <https://doi.org/10.2307/1937554>
- Zavala, R., and Rodríguez, L. (2018). Evaluación de la dinámica de crecimiento de *Cedrelinga cateniformis* (Ducke) Ducke mediante la dendrocronología, en bosques naturales de Las Piedras, Madre de Dios [Tesis de grado, Universidad Nacional Amazónica de Madre de Dios]. <http://repositorio.unamad.edu.pe/bitstream/handle/UNAMAD/413/004-2-3-085.pdf?sequence=1&disAllowed=y>
- Zegarra, L. (2018). Caracterización anatómica y dendrocronológica de *Guatteria hyposericea*, *Jacaranda copaia* y *Pourouma minor* de Junín Perú [Tesis de grado, Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/3715/zegarra-aguero-linda-elvira.pdf?sequence=1&disAllowed=y>
- Zuidema, P. A., Babst, F., Groenendijk, P., Trouet, V., Abiyu, A., Acuña-Soto, R., Adenky-Filho, E., Alfaro-Sánchez, R., Aragão, J. R. V., Assis-Pereira, G., Bai, X., Barbosa, A. C., Battipaglia, G., Beeckman, H., Botosso, P. C., Bradley, T., Bräuning, A., Brienen, R., Buckley, B. M., ... Zhou, Z.-K. (2022). Tropical tree growth driven by dry-season climate variability. *Nature Geoscience*, 15(4), 269-276. <https://doi.org/10.1038/s41561-022-00911-8>



Zuñiga, C. (2012). Aplicación de la dendrocronología para evaluar la influencia de la precipitación y la temperatura en el crecimiento de *Tectona grandis* Lf procedente del Fundo Génova-Junín [Universidad Nacional Agraria La Molina]. <http://repositorio.lamolina.edu.pe/bitstream/handle/UNALM/556/K10.Z9-T.pdf?sequence=1&disAllowed=y>

### 3. POTENTIAL FOR TREE-RING ANALYSIS OF 34 TREE SPECIES FROM THE PERUVIAN AMAZON

#### Abstract

The Amazon is the largest tropical forest in the world with mega biodiversity that requires basic ecological information of the native species that compose it to apply to sustainable forest management. However, this kind of information is scarce and only a few decades old, for this dendrochronology in the tropics is an important tool that can help us quickly, cheaply, and cover the entire life of the species. Here we evaluate the dendrochronological potential of 34 species from the Peruvian Amazon. We evaluated growth ring markers through wood anatomy and X-ray densitometry. We also determined the growth rates and trajectories of a subset of 6 species. Species with highly differentiated and moderately differentiated growth rings are 28 species. Only 6 species had difficulties in delineating growth rings by X-ray densitometry. The species subset showed strong ontogenetic patterns in growth rates and growth trajectories throughout the lifetime of all six species. These results highlight the importance of conducting studies of the dendrochronological potential in native tropical species. This knowledge is key to carrying out more complex studies in dendrochronology and that can help the forest management of tropical forests.

Keywords: X-ray densitometry, Tree-ring analysis, Tropical wet forest, Madre de Dios, Diameter growth rates, Growth trajectory

#### 3.1. Introduction

The Amazon is the largest tropical forest in the world, being a bastion of global biodiversity (Edwards et al., 2019), with 14,003 South American tree species registered (Cardoso et al., 2017). In addition, tropical forests accumulate 40 to 60% of the carbon contained in the world's terrestrial vegetation (Qin et al., 2017). Amazon deforestation and land clearing is a huge problem that got exacerbated by the COVID pandemics spurring illegal logging and threatening forest ecosystems. (Brancalion et al., 2020; Golar et al., 2020). This pressure for tropical forests and the demand for wood makes it vital to take action to carry out sustainable forest management since the remaining tropical forests are increasingly valuable for global biodiversity and the ecosystem services associated with it (Edwards et al., 2019).

The study of growth rings in tree species of tropical forests helps us understand the past, current situation and future projections of tropical forests (Rozendaal and Zuidema, 2011; Worbes and Fichtler, 2010), in times of change climate change, this knowledge is essential to manage these global carbon sinks (Zuidema et al., 2022). In the last two decades, various investigations have been carried out on tropical dendrochronology, covering basic aspects to much more complex and global aspects where the growth rings in tropical forests are allowing us to build long-term chronologies and we are knowing the oscillations of the ages of tropical trees (Crispín et al., 2022; Locosselli et al., 2020). This knowledge of the longevity of tropical species helps us to perform climate reconstructions (Boninsegna et al., 2009; Ljungqvist et al., 2020; van der Sleen et al., 2015), in addition, tree ring analysis can be used as a tool to obtain precise and long-term growth without the need for chronologies to apply this analysis in forest management (Brienen et al., 2006), and several species have been shown to form annual tree rings in tropical forests (Groenendijk et al., 2014; Schöngart, 2010; Vlam et al., 2017). Several studies have applied tree-ring data to measure the growth rates and growth trajectory of native tropical tree species to aid in forest management practices (Barbosa

et al., 2018; Brienen et al., 2006; Groenendijk et al., 2014). With these data, the ideal length of the extraction cycle can be calculated by species (e.g., Schöngart, 2008), or future wood yields can be projected to simulate wood productivity under different management scenarios (e.g., Brienen et al., 2016; Groenendijk et al., 2014; Rozendaal and Zuidema, 2011). In addition, carbon and oxygen isotopes have been used more frequently as proxies that allow the reconstruction of paleoclimatic variables and are helping our knowledge about the responses of tropical trees to climate change (Baker et al., 2015; Cintra et al., 2019; van der Sleen et al., 2015). There are also validations of the chronologies using carbon 14 (e.g., Groenendijk et al., 2014; Inga and del Valle, 2017; Santos et al., 2021), finally, there is the analysis of the growth rings oriented to the chemical analysis that it has a high annual resolution that allows the analysis of nutrients, contaminants present, etc. being a proxy more derived from the growth rings (Aguilera-Betti et al., 2020; Hietz et al., 2015; Poussart et al., 2006).

Based on everything that can be addressed with the study of the growth rings of tropical trees, it is necessary to carry out more studies of the tropical tree species that mark growth rings and/or those that do not, since this information will help researchers and save them time and money (Groenendijk et al., 2014). Where different methodologies can be applied, from classic and basic studies on the anatomy of wood oriented to growth rings (e.g., Beltrán and Valencia, 2013; Marcelo-Peña et al., 2020), cambial marking (e.g., Lisi et al., 2008; Mariaux, 1967), X-ray densitometry (e.g., Tomazello et al., 2008), autofluorescence (e.g., Godoy et al., 2019), blue intensity (e.g., Buckley et al., 2018), among other methodologies whose purpose is to help in the analysis and thereby verify the annuality of the growth rings in tropical forests.

Of the methods mentioned above, X-ray densitometry allows obtaining the variation profile of wood density in the radial direction (pith-bark) (Portal et al., 2019; Tomazello et al., 2008), having a high resolution (readings obtained in distances in microns) of the apparent density in the growth rings on an annual or inter-annual basis and until having the apparent density of the initial wood and late wood within a growth ring (De Mil et al., 2018; Gaitan et al., 2019; Pagotto et al., 2017). That is why X-ray densitometry can help in the identification of growth ring boundaries and false rings in tropical tree species and has been used in several climatology and dendrochronology studies (Jacquin et al., 2017; Tomazello et al., 2008).

To apply tree-ring analyses on new tropical locations, a first essential step is finding species with visible growth rings and then assessing their potential for tree-ring studies (e.g., Groenendijk et al., 2014). A macroscopic description of the ring-boundary types is essential (e.g., Fichtler and Worbes, 2012) and anatomical thin sections can be used to improve these descriptions (e.g., Aragão et al., 2019). Inter- and intra-annual variations in wood density along radial cross-sections, obtained by X-ray densitometry (Pagotto et al., 2017; Portal et al., 2019), can be combined with the macroscopic and anatomical descriptions to improve ring-boundary definition in tropical species (Gaitan et al., 2019; Pagotto et al., 2017; Quintilhan et al., 2021).

Here we present an evaluation of the tree-ring analysis potential of 34 species from the Madre de Dios region in the Peruvian Amazon. We describe the growth ring boundaries of the 34 species macroscopically and with the aid of X-ray densitometry. On a subset of 6 species we measured rings of 10-27 individuals to determine growth rates and growth trajectories. We address the following questions: (a) what are the anatomical characteristics of the growth-ring boundaries of the 34 studied species? (b) For how many species can X-ray densitometry aid in the ring identification? and (c) What are the growth rates and growth trajectories of the subset of species?

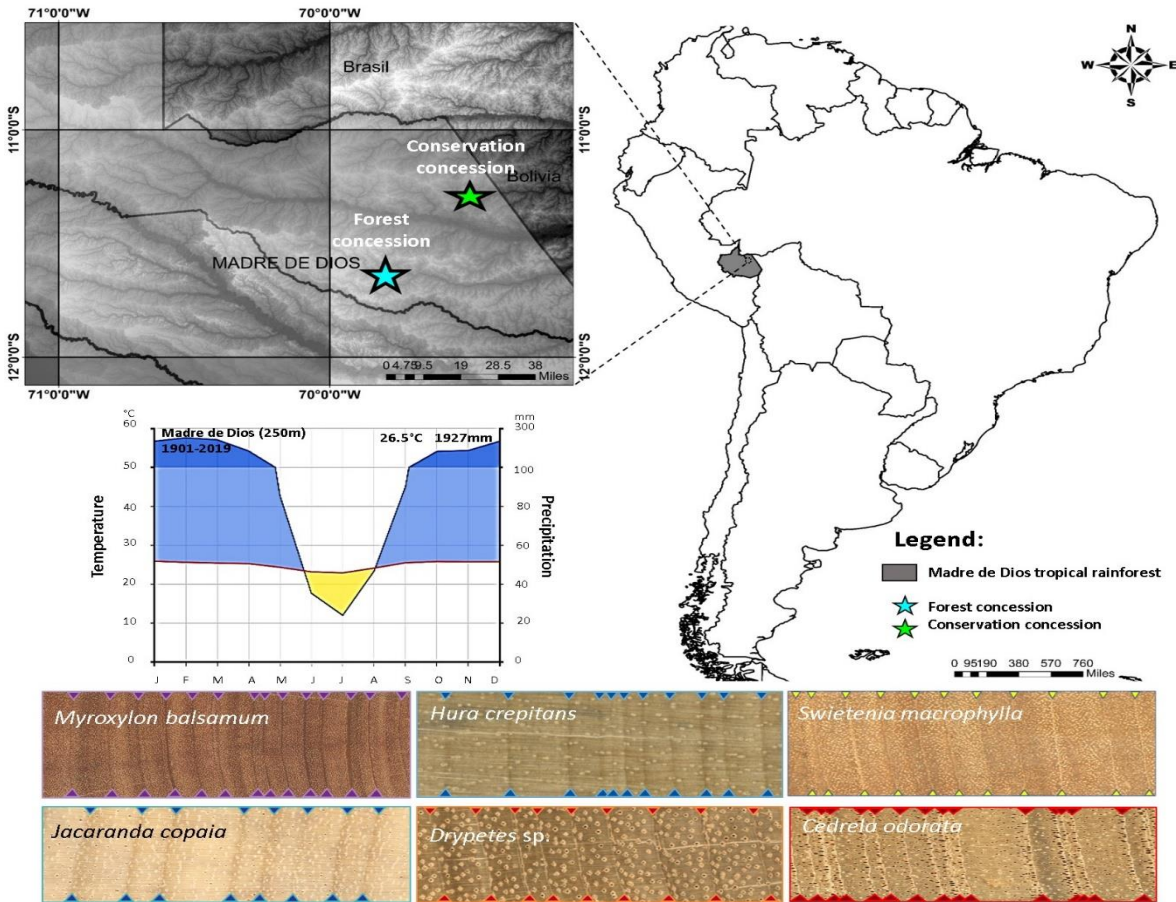
We address these questions using 34 tree species of the Peruvian Amazon from different botanical families. We describe the macroscopic anatomy of the growth-ring boundaries together with the density variations

associated with them. Finally, we describe the growth rates and growth trajectories for 6 commercially exploited tree species.

## **3.2. Materials and Methodology**

### **3.2.1. Study area**

The wood samples come from two Amazon forest sites in the Madre de Dios region in south-eastern Peru: the “CORPFOREST” and “Rodal Semillero Tahuamanu” concessions granted by the Peruvian state, located in the province of Tahuamanu in the Madre de Dios region (Figure 1). The region is characterized by humid tropical forests. These samples were obtained from the Xiloteca of the National Amazonian University of Madre de Dios - UNAMAD, said region (9 ° 57 'and 13 ° 20', south latitude, 68 ° 39 'and 72 ° 31') presents a great diversity of flora, fauna, ecosystems, etc., denominated as the capital of Peru's biodiversity by Law No. 26311 from 1994 to the present (Foster et al., 1994) and important for global conservation considered as a biodiversity hotspot (Myers et al., 2000). According to the Köppen classification, it has three types of climate: Tropical humid (Af), Tropical dry forest (Aw) and Tropical monsoon (Am)(Köppen, 1948); the weather is seasonal where the average annual precipitation is 2500 mm and with a dry season of 3 months between June - August with precipitation less than 100 mm and an average annual temperature of 25°C (Araujo et al., 2011), with 84.2% annual average relative humidity (Sánchez-Cuervo et al., 2020).



**Figure 1.** Location of the study areas in the Madre de Dios region (grey area on the map) in Peru Site 1 (light blue star) is the CORPFOREST S.R.L. forest concession and Site 2 (green star) is the “Rodal Semillero Tahuamanu” conservation concession. The climate diagram (cf. Walter and Lieth, 1960) is also shown: the red line shows the average temperature, the yellow area represents the dry months (temperature > precipitation line), the blue area represents the humid months, and the dark blue area represents super-humid months (>100mm precipitation). The lower two rows show macroscopic images of the tangential wood surface to indicate the ring boundaries of the 6 studied species (triangles indicate growth ring limits).

### 3.2.2. Selected species

We performed a screening of a larger set of 34 native forest species (one tree per species) from 19 botanical families (Table 1). We worked with wood blocks of 5x5x5 cm to describe the tree-ring structures and perform subsequent analyses. Each sample has a corresponding botanical identification deposited in the Alwyn Gentry herbarium of the same university. On a subset of six species, we collected a larger number of samples and measured tree rings for 10-27 individuals to obtain lifetime growth rates and trajectories for these species. This subset of species was collected in three different forest concessions granted by the Peruvian state, located in the Madre de Dios region. Four species were collected in 2020 in the forest management unit of the company Corporación Forestal Tres Fronteras S.R.L. "CORPFOREST S.R.L." (11 ° 16'S; 69 ° 39'W): *Jacaranda copaia* (Aubl.) D. Don. (Bignoniaceae), *Hura crepitans* L. (Euphorbiaceae), *Myroxylon balsamum* (L.) Harms (Fabaceae) and *Drypetes* sp. (Putranjivaceae). These four species were chosen because they present anatomically visible ring boundaries, have commercial value and were being felled in the study area in 2020 (annual felling plot No. 19).

For these species, we randomly selected 10-11 felled individuals and collected radial cross-sections (disks) from the end of the first log (at approximately 9 m height above the ground) to avoid growth deviations caused by buttress roots (cf. Granato-Souza et al. 2019). Each disk was sectioned in four 5cm-wide planks to facilitate transportation, handling and storage. The other two species, *Swietenia macrophylla* and *Cedrela odorata* (both Meliaceae), were collected in 2015 in the “Rodal Semillero Tahuamanu” conservation concession (11° 12’S; 69° 27’W). These species were selected because they are valuable species with a high commercial value and are included in Appendix II of the Convention on International Trade in Threatened Wild fauna and flora species "CITES". For these species, we randomly selected 18-27 individuals and collected four radial increment cores (5.15mm diameter, and max. 40cm length) at a height of approximately 1.30 m from the soil. For *C. odorata*, we increased the sampling with 7 discs collected in the Madre de Dios region that were already present in the Wood Anatomy and X-ray Densitometry Laboratory of the University of Sao Paulo at the "Luiz de Queiroz" College of Agriculture USP/ESALQ in Piracicaba – Brazil. All samples were transported and processed at the USP/ESALQ laboratory.

### 3.2.3. Sample processing and growth ring classification

Increment cores were glued to wooden holders and we sanded the tangential crosssections of all samples with increasingly finer sandpaper (grit from 80 to 1200 grains/cm<sup>2</sup>) to visualize and describe the anatomical ring-boundary markers (Granato et al., 2019; Marcelo-Peña et al., 2019). Sanded samples were digitized with an EPSON Expression 11000XL scanner at 1200 dpi resolution, and images were saved in “.tif” format.

With the sanded cross-sectional samples, the cross-sections (supplementary material) were characterized at the macroscopic level according to IAWA (1989) and we classified the distinction and the type of marking of the growth rings of the 34 forest species (Fig. 2) following the classification proposed by Marcelo-Peña et al. (2020) with four growth-ring distinctiveness: A) highly distinct, B) moderately distinct, C) poorly distinct, D) indistinct or absent, and with five growth-ring boundary types: A) change in thickness of the fiber wall, B) change in thickness of the fiber wall and marginal parenchyma, C) marginal parenchyma, D) semi-porous and marginal parenchyma and E) marginal parenchyma and phloem.

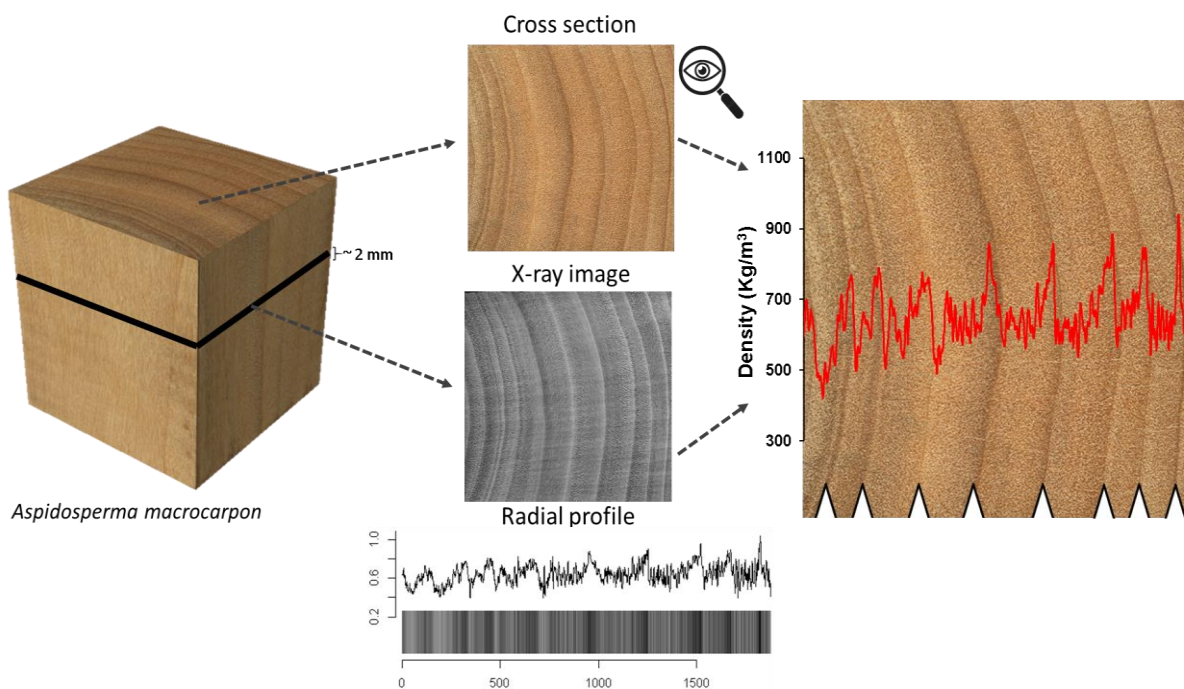
### 3.2.4. Determination of apparent density by X-ray

To obtain X-ray density profiles for each of the 34 species, we extracted a subsample of ca. 2 mm thickness from the 5x5x5 cm blocks with the help of a band saw. These samples (slices) were then stored in a climatic chamber for 24 hours at 20°C and 60% relative air humidity, until the wood reached 12% humidity. Faxitron X-Ray equipment, model LX-60, 5.9 kV, was used to obtain the X-ray profiles for each sample. Samples were placed in the irradiation chamber of the Faxitron together with a cellulose acetate calibration wedge. Images of the cross-sections of each species were digitally radiographed at high resolution (approximately 513 dpi), using the Faxitron version DX 1.0 software. Images were captured using an X-ray exposure time of 33 seconds and saved in .jpg format. Subsequently, the xRing package of the statistical software R was used to extract densitometric data from X-ray images (Campelo et al., 2019). We calibrated each image with the cellulose acetate wedge that had eight known different thicknesses and a known density of 1.274 g/cm<sup>3</sup> (Quintilhan et al., 2021). We computed the bulk wood density values of each cross-sectional sample using the calibrated images and the known thickness of each sample.

Data on the density profiles were extracted from the xRing to tables and we produced graphs of each profile using Microsoft Excel software. Radial density profiles were subsequently placed as an overlay on the scanned samples (Figure 2). With the superposed graphs we performed a qualitative classification of the potential to use X-ray densitometry to identify the growth-ring limits: A) good potential, B) regular potential, and C) no potential.

### 3.2.5. Growth patterns and ages to achieve minimum cutting diameters

On our subset of 6 species, we measured the width of the growth rings in scanned “.tif” images using the Cybis CooRecorder software version 7.8 (Larsson, 2014) along four radii per tree. The wood samples did not present holes or rots in the pith, however there were missing rings in some samples due to the mechanical processing of the samples. We computed average annual diameter increments by multiplying the average growth rates of all radii by two. We then calculated cumulative diameters (in cm) per age by adding each subsequent ring for each individual (plus an eventual missing distance to the pith). For each species we describe their lifetime diameter growth patterns, that is, average, minimum and maximum growth rates (cm/year), ontogenetic trends in growth, and differences between individuals in diameter growth rates and ages to reach minimum logging diameters (Figure 2).



**Figure 2.** The graphic sequence of the analysis performed on the samples of the 34 species studied.

### 3.3. Results

We briefly describe the growth rings of all species (Table 1) and provide further details in the supplemental material, providing further descriptions of the growth-ring delimitations at the macroscopic level and

the support of X-ray densitometry to identify growth rings (Appendix A). We compare our results with relevant information from the literature and provide our evaluation of the potential of each species for dendrochronology.

### **3.3.1. Tree-ring structures and distinctness of ring boundaries by X-ray densitometry**

Of the 34 forest species, 38% (i.e., n = 13) presented highly distinct growth rings, 44% (n = 15) presented moderately distinct growth rings, 15% presented poorly distinct rings (n = 5) and finally, 3% presented indistinct or absent growth rings (n = 1). Regarding the type of anatomical ring boundary, 56% of the species (n = 19) presented changes in the thickness of the fiber walls, 21% (n = 7) presented fiber-wall thickness changes combined with marginal parenchyma, 12% (n = 4) presented marginal parenchyma, 6% (n = 2) presented semi ring porosity combined with marginal parenchyma, and 3% (n = 1) presented marginal phloem (Table 1).

The six subset species showed highly distinct growth rings, visible by the naked eye and/or with the help of a 10x magnification magnifying glass. Three of these species had thick-walled latewood fibers delimiting growth rings together with differences in vessel diameters (*J. copaia*, *M. balsamum* and *H. crepitans*), two species had growth rings delimited by marginal parenchyma only (*Drypetes* sp., *S. macrophylla*) and one species presented semi-porous growth rings together with marginal parenchyma (*C. odorata*) (Figure 1). We were able to observe false rings in all the studied species, formed by variations in the tonality of the fibrous areas (in *J. copaia*, *M. balsamum* and *H. crepitans*), or as confluent axial parenchyma bands with numerous fine irregular cells, of more subdued color, and often discontinuous (*Drypetes* sp., *S. macrophylla* and *C. odorata*).



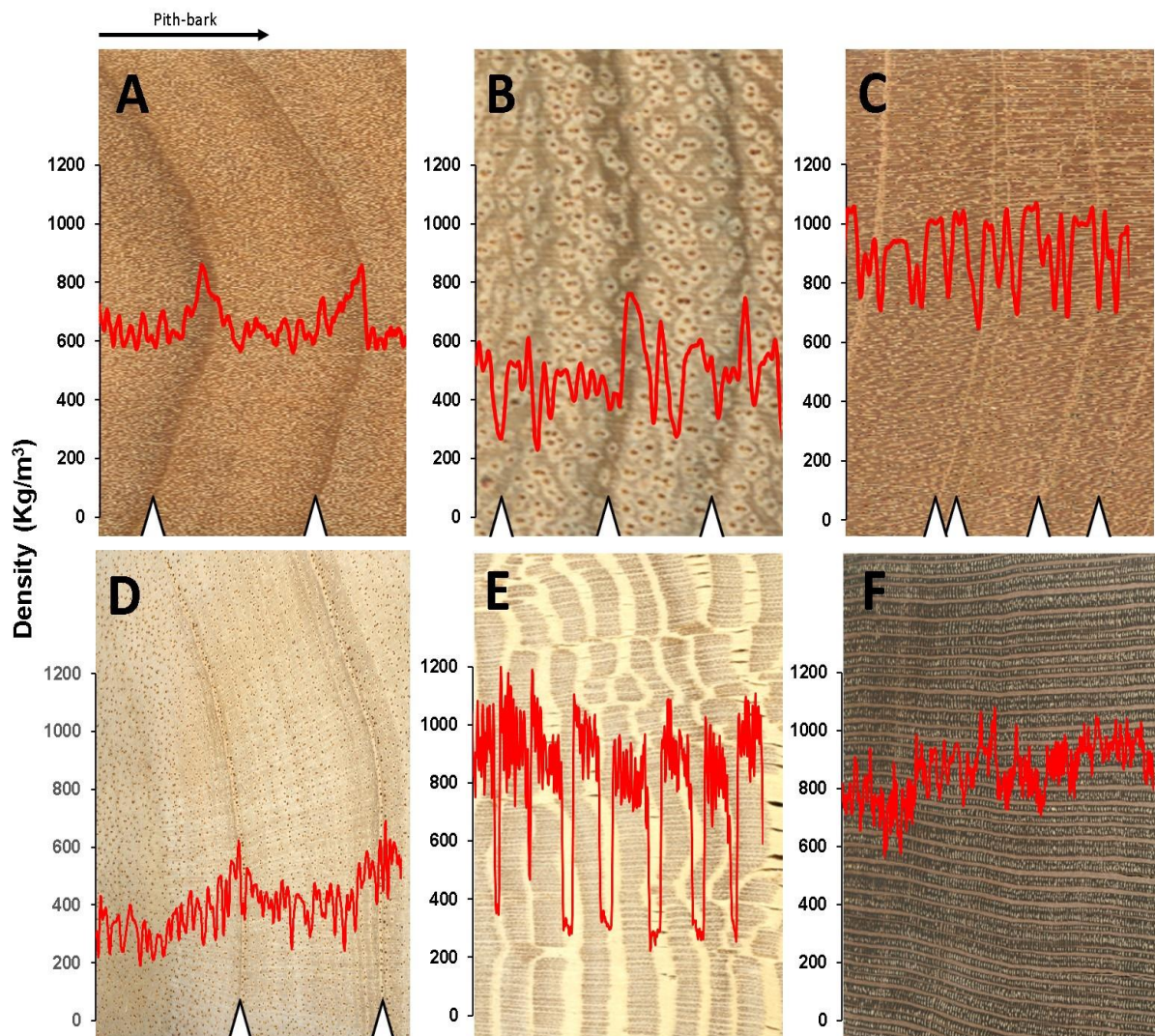
**Table 1.** List of the 34 studied Peruvian Amazon forest species, ordered by their respective families. Provided are: leaf habit; growth-ring distinctness (HD = highly distinct; MD = moderately distinct; PD = poorly distinct; IoA = indistinct or absent); ring-boundary type (FWT = changes in fiber-wall thickness, FWT-MP = change in fiber-wall thickness combined with marginal parenchyma, MP = marginal parenchyma, SRP-MP = semi-ring porosity combined with marginal parenchyma, MPH = marginal phloem), potential for X-ray densitometry to aid growth-ring boundary identification (GP = good potential, RP = regular potential, NP = no potential); and reference studies on growth rings of the species.

Family	Scientific name	Leaf habit	Uses of woods	Growth ring boundary distinctness	Anatomical boundary descriptor	Densitometry potential	Growth ring study reference
Annonaceae	<i>Rollinia pittieri</i> Saff.	Semideciduos	Has no known uses	HD	FWT	GP	
Apocynaceae	<i>Aspidosperma macrocarpon</i> Mart.	Deciduous	Flooring, exterior	HD	FWT	GP	Marcelo et al. (2020)
	<i>Aspidosperma subincanum</i> Mart. Ex A. DC.	Deciduous	Flooring, parquet	HD	FWT	RP	Marcelo et al. (2020)*, Mendivelso et al. (2013)*, Lidio; Villalba (2020)*
Bignoniaceae	<i>Jacaranda copaia</i> (Aubl.) D. Don	Deciduous	Plywood, veneer	HD	FWT	GP	Marcelo et al. (2020), Portal et al. (2020)
Bursaceae	<i>Dacryodes peruviana</i> (Loes.) H.J. Lam	Evergreen	Simple carpentry	PD	FWT	RP	
	<i>Tetragastris altissima</i> (Aubl.) Swart	Evergreen	Flooring, heavy packing	MD	FWT-MP	GP	
Combretaceae	<i>Terminalia catappa</i> L.	Deciduous	Plywood, veneer	MD	FWT	GP	Marcelo et al. (2020)*, Fichtler et al. (2010)*
Euphorbiaceae	<i>Hevea brasiliensis</i> (Willd. Ex A. Juss.) Mull. Arg.	Semideciduos	Plywood, veneer	MD	FWT	GP	Ohashi, et al. (2001)
	<i>Hura crepitans</i> L.	Semideciduos	Carpentry, plywood	MD	FWT	GP	Groenendijk et al. (2015), Marcelo et al. (2020)
	<i>Amburana cearensis</i> (Allemao) A.C. Sm.	Deciduous	Decorative veneer	HD	FWT-MP	GP	Paredes et al. (2015), Godoy et al. (2021)
	<i>Andira surinamensis</i> (Bondt) Splitg. Ex Pulle	Evergreen	Flooring, exterior	MD	FWT	NP	
Fabaceae	<i>Apuleia leiocarpa</i> (Vogel) J. F. Macbr.	Deciduous	Flooring, parquet	MD	FWT-MP	GP	Brandes et al. (2015), Marcelo et al. (2020)
	<i>Dipteryx micrantha</i> Harms	Semideciduos	Flooring, parquet	MD	FWT-MP	RP	Schöngart et al. (2017), Marcelo et al. (2020)
	<i>Myroxylon balsamum</i> (L.) Harms	Semideciduos	Flooring, parquet	MD	FWT-MP	RP	Lisi et al. (2008), Marcelo et al. (2020)
	<i>Ormosia paraensis</i> Ducke	Evergreen	Flooring, veneer	HD	FWT	NP	
	<i>Schizobolium paralyba</i> (Vell.) S.F. Blake	Deciduous	Paneling, light packing	HD	FWT-MP	GP	Latorraca et al. (2015), Brienen et al. (2015)
Lauraceae	<i>Tachigali</i> sp.	Semideciduos	Paneling, veneer	HD	FWT	GP	Brienen, Zuidema (2005)*
	<i>Ocotea bojo</i> Kunth	Evergreen	General carpentry	HD	FWT	RP	Marcelo et al. (2020), Reis, Oliveira (2017)
	<i>Guaesuma ulmifolia</i> Lam.	Deciduous	Paneling, laminates	MD	FWT	GP	Barbosa et al. (2018)
Malvaceae	<i>Ochroma pyramidale</i> (Cav. ex Lam.) Urb.	Evergreen	Acoustic insulation	MD	FWT	GP	
	<i>Apeiba tiburbona</i> Aubl.	Evergreen	Boards, light packing	PD	MP	RP	
	<i>Ceiba lupuna</i> P.E. Gibbs & Semir	Deciduous	Paneling, light packing	MD	MP	RP	Barbosa et al. (2018)*, Vasconcellos et al. (2019)*
	<i>Matisia cordata</i> Bonpl.	Evergreen	Paneling, light packing	MD	FWT	GP	Marcelo et al. (2020)
Meliaceae	<i>Swietenia macrophylla</i> King	Evergreen	Luxury furniture, decorative veneer	HD	MP	GP	Dünisch et al. (2003)
	<i>Cedrela odorata</i> L.	Deciduous	Luxury furniture, decorative veneer	HD	SRP-PM	GP	Inga, Del Valle (2017)
Moraceae	<i>Cedrela fissilis</i> Vell.	Deciduous	Luxury furniture, decorative veneer	HD	SRP-PM	GP	Pereira et al. (2018)
	<i>Clarisia racemosa</i> Ruiz & Pav.	Semideciduos	Decorative veneer	MD	FWT-MP	RP	Schöngart et al. (2017), Marcelo et al. (2020)
Myristicaceae	<i>Virola</i> sp.	Evergreen	Paneling, veneer	MD	FWT	GP	Schöngart et al. (2017), Marcelo et al. (2020)
Putranjivaceae	<i>Drypetes</i> sp.	Evergreen	Flooring, beams	HD	MP	RP	Marcelo et al. (2020)*
Petiveriaceae	<i>Gallesia integrifolia</i> (Spreng.) Harms	Semideciduos	Boards, shutter boards	MD	Mph	GP	Marcelo et al. (2020)
Proteaceae	<i>Roupala montana</i> Aubl.	Deciduous	Decorative veneer	IoA	--	NP	
Rubiaceae	<i>Calyophyllum spruceanum</i> (Benth.) Hook. f. ex K. Schum.	Semideciduos	Flooring, steps	PD	FWT	GP	Marcelo et al. (2020)
Sapotaceae	<i>Manilkara bidentata</i> (A. DC.) A. Chev.	Evergreen	Flooring, parquet	PD	FWT	RP	Schöngart et al. (2017), Marcelo et al. (2020)
Vochysiaceae	<i>Erisma uncinatum</i> Warm.	Evergreen	Beams, decorative veneer	PD	FWT	NP	Marcelo et al. (2020)*

The gray rows are the species that do not have studies on growth rings.

In Figure 3 we illustrate the types of anatomical ring-boundaries found in this study (and in the Supplementary Material details for all the species) with their corresponding X-ray apparent wood density profiles superposed. Apparent wood density by X-ray densitometry aided the ring-boundary delimitation for most species (Table 1), with wood density in general increasing at the end of each growth year (Fig. 3). When the growth rings are

wide, the density profiles of the wood allow the delimitation of the growth rings, while when the growth rings are narrow the apparent density profiles sometimes do not allow a clear differentiation, despite that such rings are present. Six species presented no apparent density variations associated with the ring boundaries. Two of these species, *Andira surinamensis* and *Ormosia paraensis*, presented abundant aliform and confluent parenchyma unrelated to the delimitation of the rings, that confounded the density profiles. Three other species, *Apeiba tibourbou*, *Gallesia integrifolia*, and *Erismia uncinatum*, presented parenchyma in wide bands that resulted in density variations (between the parenchymal tissue and the fibers) also unrelated to the boundaries of the growth rings of these species. Finally, for *Roupala montana*, the growth-ring boundaries were unclear or absent both macroscopically as well as in the density profiles, possibly influenced by the abundant scalariform parenchyma.



**Figure 3.** Growth-ring boundaries types of the studied species with a superposed radial X-ray density profile. A: change in fiber wall thickness (e.g., *Aspidosperma macrocarpon*). B: change in fiber wall thickness with marginal parenchyma (e.g., *Amburana cearensis*). C: marginal parenchyma (e.g., *Swietenia macrophylla*). D: semi-porous wood with marginal parenchyma (e.g., *Cedrela fissilis*). E: marginal phloem (e.g., *Gallesia integrifolia*). F: indistinct or absent (e.g., *Roupala montana*).

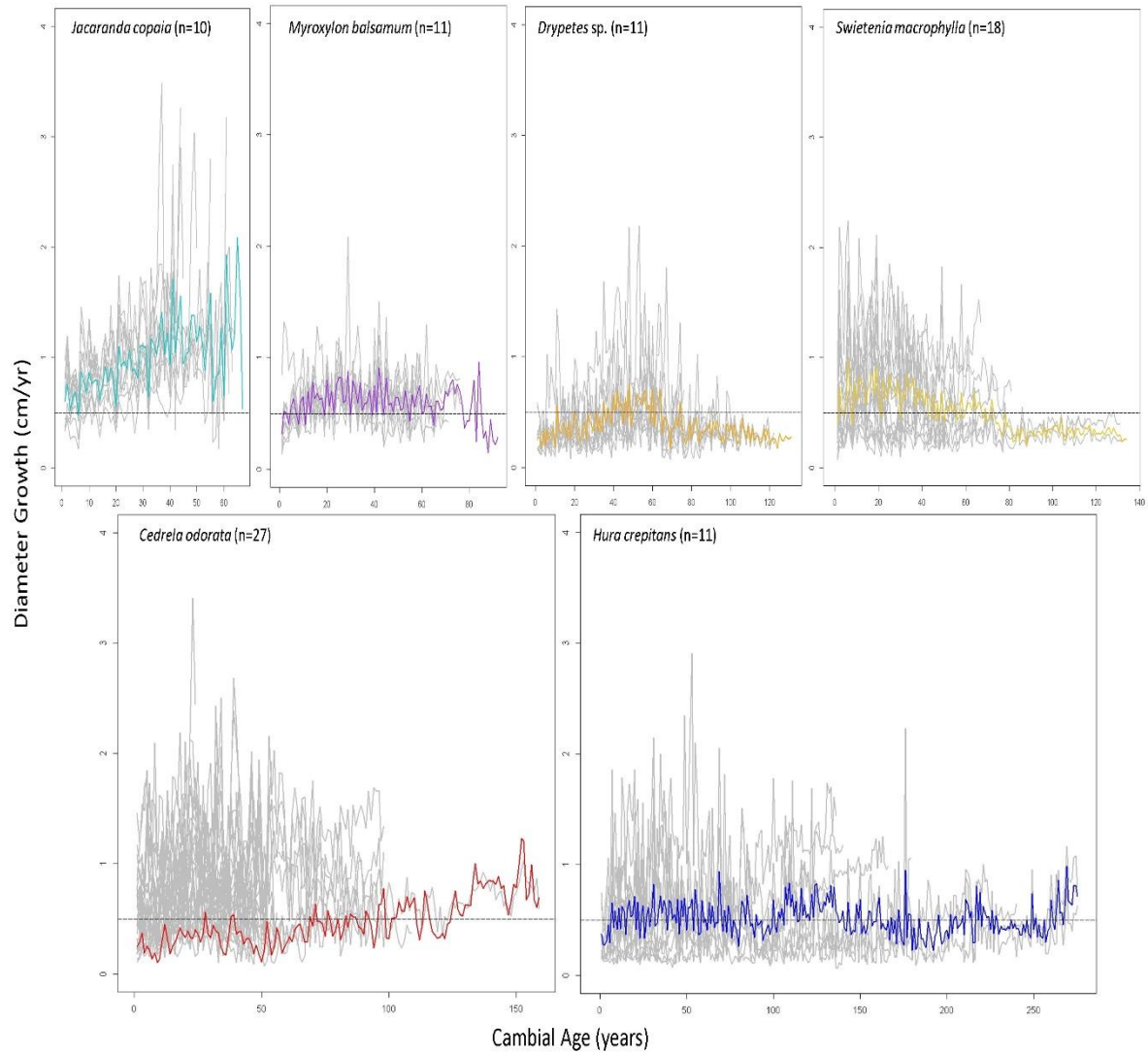
### 3.3.1. Growth rates and growth trajectories of the subset of species

Growth rates varied strongly between the subset species: between 0.35 mm per year for *Drypetes* sp. and 0.99 mm per year for *J. copaia*, (Table 2). Maximum ages differed between species: individuals of two species did not reach ages over 100 years (*J. copaia* and *M. balsamum*), four species reached ages over 100 years (*Drypetes* sp., *H. crepitans*, *C. odorata* and *S. macrophylla*), and one species (*H. crepitans*) reached ages over 250 years. The subset of species showed strong ontogenetic patterns in growth rates and growth trajectories throughout the life of the six species. Regarding the growth patterns, they also varied between species, with *H. crepitans*, it showed a fairly constant growth rate over time (Figure 4), only at the end it showed a greater trend; the species *Drypetes* sp. and *M. balsamum* showed low growth rates in their juvenile phase, which increase as a function of age and decrease again for older trees, the *C. odorata* species showed high growth rates throughout its life, concerning *S. macrophylla* in its juvenile phase showed high growth rates, which decreased depending on its age. The *J. copaia* trees exhibited a growth pattern of low growth rates, this being a species that demands light, however, it is observed that it was restricted to it for approximately 30 years, after having a greater growth, also understanding that they were collected in primary forests.

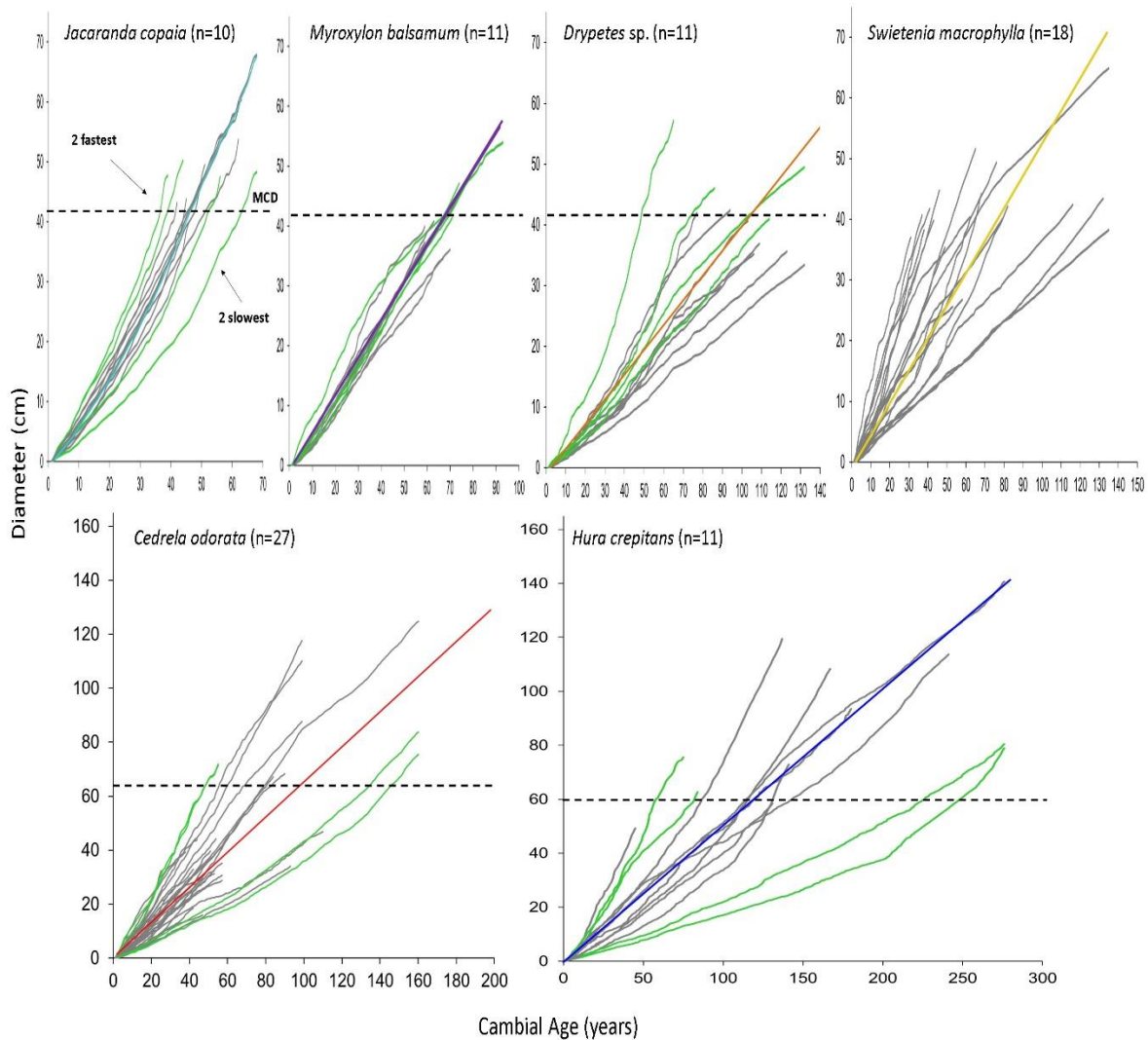
**Table 2.** Growth characteristics and chronology of four commercial species from a tropical humid forest in Peru. The following are provided: number of trees (and series in parentheses); Minimum cutting diameter (MCD); growth of the average diameter of the population; age range; Span: start and end of the measured rings.

Species	# Tres (series)	MCD (cm)	Age at MCD (year)	Diameter growth (cm/year, $\pm$ SD)	Age range (min-max)	Span
<i>Jacaranda copaia</i>	10 (24)	41	44	$0.99 \pm 0.29$	24-67	1952-2018
<i>Myroxylon balsamum</i>	11 (36)	41	66	$0.59 \pm 0.16$	57-92	1927-2018
<i>Drypetes</i> sp.	11 (24)	41	100	$0.35 \pm 0.12$	64-131	1888-2018
<i>Hura crepitans</i>	11 (28)	60	116	$0.45 \pm 0.16$	44-275	1744-2018
<i>Cedrela odorata</i>	27 (47)	65	83	$0.64 \pm 0.12$	37-184	1832-2015
<i>Swietenia macrophylla</i>	18 (58)	75	...	$0.47 \pm 0.18$	32-134	1882-2015

Growth rates also varied within the six species, which induced variation in the ages of individuals to reach the minimum cutting diameter (MCD). Individuals of the six species reached MCD on average after 44 -116 years (note that MCD varies between species; Table 2). The lowest average age to reach MCD of 55 years was found in *J. copaia*, while it takes, the *H. crepitans* 175 years to reach its MCD (Fig. 5, Table 2). Age to reach MCD also varied between individuals within species: in *J. copaia*, the fastest individual reached the MCD in only 35 years and the slowest-growing individual in 61 years. For *Hura crepitans*, these ages to reach MCD varied between 80 and 248 years. We were unable to compute ages to reach MCD for sampled trees (using increment corers) that had not yet reached the 75cm MCD of the species. By extrapolating the growth curve for the species, we estimate that *S. macrophylla* trees should take over 110 years to reach their MCD in the region.



**Figure 4.** Diameter growth rates vs. cambial age of the subset species. Light-colored lines represent the individual tree diameter growth values, darker colored lines show average growth rates. The dashed lines show the growth rates of each species in the Peruvian Amazon established by law.



**Figure 5.** Growth trajectory throughout the life of the subset species. Each lighter-colored line shows the growth trajectory over the life of an individual sample. The dashed horizontal lines indicate the minimum cut diameters (MCD) and the diagonal lines show the growth rates of each species.

### 3.4. Discussion

We determined the potential of the growth rings for tree-ring analyses of 34 forest species of a tropical humid forest in Peru, describing the clarity and type of growth-ring boundaries and the associated wood density profiles. Growth rings were visible in 28 out of the 34 studied tree species. For a subset of six species, we measured the growth rings of 10-27 trees. Tree ages and growth rates varied significantly between and within species, implying that different species reach the MCD at different ages, with consequences for species-specific management decisions.

#### 3.4.1. Tree-ring boundaries and application of X-ray densitometry

For most of the 34 tree species, there are anatomical descriptions of the wood (Acevedo and Kikata, 1994), the growth rings and the annuality of the formation of the growth rings have been studied for several of them

or for species from the same genera (Aragão et al., 2022; Barbosa et al., 2018; Marcelo-Peña et al., 2020; Schöngart et al., 2017). This is the first time that the potential for analysis of the growth rings of 8 species is described (Table 1).

Of the 34 forest species, 56% presented fiber-wall thickness changes in the latewood. The same type of growth ring boundary was found for 25% and 39% of the species in other studies in humid and dry tropical forests in Peru (Beltrán and Valencia, 2013; Marcelo-Peña et al., 2020). These types of ring growth limits can be induced by the phenological behavior of perennial or semi-deciduous species, when growth rings are present they are often defined by changes in fiber wall thickness (Bauer et al., 2020).

X-ray densitometry aided in the delimitation of the limits of the growth rings in 28 of the 34 species (i.e., in 82%). The types of anatomical markers that show density variations are fiber-wall thickness changes, presence of marginal parenchyma, the combination of the two and the semi-ring-porous wood. Similar patterns were reported and described in other investigations (De Mil et al., 2018; Gaitan et al., 2019; Jacquin et al., 2017; Pagotto et al., 2017; Tomazello et al., 2008). X-ray density can thus be a valuable tool to aid tropical tree-ring studies, but this tool does not aid ring-boundary identification in species that present a lot of parenchymal tissue (e.g., *A. surinamensis*, *O. paraensis*, *A. tiburou*, *G. integrifolia* and *E. uncinatum*).

### 3.4.2. Growth-ring data and application in forest management

Forest management in Peru is carried out using a polycyclic forest concession system. Forests belong to the state, but the use of the resources is granted to companies for a contract period of 40 years (Ley Forestal y de Fauna Silvestre N° 29763 y sus reglamentos, 2015). Cutting cycles of 20 years are being applied in the country (Ley N° 29763), allowing companies to carry out two commercial uses in the same cut plot. In polycyclic logging systems, the MCD, the intensity at which a species is exploited (i.e., the percentage of trees above MCD that are exploited) and/or the duration of cutting cycles can be adapted to ensure a specific species is not overexploited (Groenendijk et al. 2017). The MCD applied is pre-established for a group of ~45 species and ranges from 38 to 75 cm, while for all other tree species a general MCD of 41cm is used. To ensure species are not overexploited, future logging harvests are projected to determine ideal MCDs and harvest intensities per species. For these projections, a reference diameter growth value of 0.5 cm/year is used for all species (Ley Forestal y de Fauna Silvestre N° 29763 y sus reglamentos, 2015). We showed that growth of the studied species varies considerably from this standard, both in average value as well as over the lifespan of trees. For three species growth rates were lower than the reference value: for *Drypetes* sp. 30% lower, for *H. crepitans* 10% and for *S. macrophylla* 6%. On the other hand, three species showed higher growth rates than the reference value: *M. balsamum* 18% higher, *C. odorata* 28% higher and *J. copaia* 98%. Using a standard growth rate for all species over the entire lifespan of trees to project the sustainability of future timber harvests ignores the large variations in growth between and within species. These differences between legally established growth rates and actual growth rates can lead to the species being under or overexploited, highlighting the importance of measuring species-specific precise growth rates for each harvested species (Groenendijk et al., 2014).

Comparing the growth of the species of the subset, for the species *J. copaia* the results are higher than those found by Portal et al. (2020) at 0.80 cm/year, the annual growth of the species *S. macrophylla* and *C. odorata* was higher than that found by Dünisch et al. (2003) found 0.35 cm/year and 0.30 cm/year for the specific case of *S. macrophylla* inferior compared with the studies of Shono (2006); Susatya and Yansen (2016) that found 0.69 and 0.67 cm/year respectively, for the species *M. balsamum* coincides with the data found by Lisi et al. (2008) of 0.60 cm/year,

for the other two species (*H. crepitans* and *Drypetes* sp.) no information was found. The differences that can be found with the other studies are based on the years evaluated, the type of forest and the ecological factors that influence the growth of the species typical of each place, in addition to other environmental factors.

Growth rates also varied strongly within species. These differences are commonly found in (tropical forest) tree species and indicate persistent differences in tree growth between individual trees, leading to the age-diameter relationships of each species being fan-shaped (Groenendijk et al., 2014). Incorporating these persistent growth differences is crucial to obtaining realistic projections of future timber yields (Groenendijk et al., 2017; Rozendaal et al., 2010). In general, incorporating these persistent growth differences leads to higher projections in future timber yields (Brienen and Zuidema, 2007; Rozendaal et al., 2010). Tree-ring derived data provide realistic growth rates that incorporate these persistent growth differences and should be more widely applied to project future timber yields to aid in the sustainable use of tropical forests (Brienen et al., 2006; Brienen and Zuidema, 2007; Groenendijk et al., 2017; Rozendaal et al., 2010). Accurate projections of future yields do not only depend on the growth data and other ecological and reproductive aspects of each tree species need to be monitored to achieve long-term forest management of forests (Groenendijk et al., 2014; López and Villalba, 2015; Sebbenn et al., 2008). Yet, tree-ring studies can relatively quickly provide accurate growth rates that are species specific, incorporate ontogenetic patterns in growth as well as persistent differences in growth between individuals and thus have a strong potential to be applied in projections to improve tropical forest management.

In conclusion, we confirm the potential of 34 forest species for tree-ring studies in a tropical moist forest in the eastern Amazon of Peru. Over 80% of the studied species formed distinct rings and X-ray densitometry helped defining growth-ring boundaries. Growth data from these species can be used to better understand the ecology and growth behavior of tropical tree species. Dendrochronological analyses can be performed to understand climatic influences on tree growth and considering the longevity of some of the studied species, can be used to reconstruct climate over centennial scales. These type of studies help us to better understand the functioning and ecological processes of tropical forests as well as to identify functional strategies of tropical tree species. Complemented with other ecological information, tree-ring derived growth data can be also be applied to improve forest management practices in these crucial forests. We show the potential of tree-ring studies to contribute to the understanding and conservation of tropical forests in the Amazon forest in the Madre de Dios region in south-eastern Peru considered a biodiversity hotspot

## Acknowledgments

We would like to thank the forestry concession company “Corporación Forestal Tres Fronteras S.R.L.” and the “Rodal Semillero Tahuamanu” forest conservation concession for their support in the sample collections, and more specifically the forest engineers Erick Grandez Piña and Germán Payeza Tuesta. We also thank the colleagues of the Wood Anatomy and Identification Laboratory-LAIM of the University of São Paulo at the Luiz de Queiroz Higher School of Agriculture and the technician Aparecido Candido Siqueira for their support in the preparation of the samples. This study was possible thanks to the support financed by the National Scholarship and Educational Credit Program (PRONABEC) of the Ministry of Education of Peru. PG acknowledges funding from the São Paulo Research Foundation (FAPESP process number 2018/01847-0). This work was also carried out with the support of CAPES - Financing Code 001.

## References

- Acevedo, M., & Kikata, Y. (1994). *Atlas de Maderas del Perú: Vol. I (I, I)* [Computer software]. UNALM – Universidad de Nagoya.
- Aragão, J., Groenendijk, P., & Lisi, C. S. (2019). Dendrochronological potential of four neotropical dry-forest tree species: Climate-growth correlations in northeast Brazil. *Dendrochronologia*, *53*, 5-16. <https://doi.org/10.1016/j.dendro.2018.10.011>
- Aragão, J. R. V., Zuidema, P. A., & Groenendijk, P. (2022). Climate-growth relations of congeneric tree species vary across a tropical vegetation gradient in Brazil. *Dendrochronologia*, *71*, 125913. <https://doi.org/10.1016/j.dendro.2021.125913>
- Araujo, A., Parada, A., Terán, J., Baker, T., Feldpausch, T., Phillips, O., & Brien, R. (2011). Necromasa de los bosques de Madre de Dios, Perú; una comparación entre bosques de tierra firme y de bajos. *Revista Peruana de Biología*, *18*(1), 113-118. <https://doi.org/10.15381/rpb.v18i1.155>
- Barbosa, A. C., Pereira, G., Granato, D., Santos, R. M., & Fontes, M. A. (2018). Tree rings and growth trajectories of tree species from seasonally dry tropical forest. *Australian Journal of Botany*, *66*(5), 414. <https://doi.org/10.1071/BT17212>
- Bauer, D., Schmitt, J. L., & Oliveira, J. M. (2020). Xylem growth rings and leaf phenological patterns in tree species of a subtropical seasonal forest. *Acta Botanica Brasílica*, *34*(4), 680-693. <https://doi.org/10.1590/0102-33062019abb0395>
- Beltrán, L. A., & Valencia, G. M. (2013). Anatomía de anillos de crecimiento de 80 especies arbóreas potenciales para estudios dendrocronológicos en la Selva Central, Perú. *Revista de Biología Tropical*, *61*(3). <https://doi.org/10.15517/rbt.v61i3.11778>
- Brançalion, P. H. S., Broadbent, E. N., de-Miguel, S., Cardil, A., Rosa, M. R., Almeida, C. T., Almeida, D. R. A., Chakravarty, S., Zhou, M., Gamarra, J. G. P., Liang, J., Crouzeilles, R., Hérault, B., Aragão, L. E. O. C., Silva, C. A., & Almeyda-Zambrano, A. M. (2020). Emerging threats linking tropical deforestation and the COVID-19 pandemic. *Perspectives in Ecology and Conservation*, *18*(4), 243-246. <https://doi.org/10.1016/j.pecon.2020.09.006>
- Brien, R. J. W., & Zuidema, P. A. (2007). Incorporating persistent tree growth differences increases estimates of tropical timber yield. *Frontiers in Ecology and the Environment*, *5*(6), 302-306. [https://doi.org/10.1890/1540-9295\(2007\)5\[302:RCPTGD\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2007)5[302:RCPTGD]2.0.CO;2)
- Brien, R., P.A., & Daring, H. J. (2006). Autocorrelated growth of tropical forest trees: Unraveling patterns and quantifying consequences. *Forest Ecology and Management*, *237*(1-3), 179-190. <https://doi.org/10.1016/j.foreco.2006.09.042>
- Brien, R., Schöngart, J., & Zuidema, P. A. (2016). Tree Rings in the Tropics: Insights into the Ecology and Climate Sensitivity of Tropical Trees. En G. Goldstein & L. S. Santiago (Eds.), *Tropical Tree Physiology* (Vol. 6, pp. 439-461). Springer International Publishing. [https://doi.org/10.1007/978-3-319-27422-5\\_20](https://doi.org/10.1007/978-3-319-27422-5_20)
- Campelo, F., Mayer, K., & Grabner, M. (2019). xRing—An R package to identify and measure tree-ring features using X-ray microdensity profiles. *Dendrochronologia*, *53*, 17-21. <https://doi.org/10.1016/j.dendro.2018.11.002>
- Cardoso, D., Särkinen, T., Alexander, S., Amorim, A., Bittrich, V., Celis, M., Daly, D., Fiaschi, P., Funk, V., Giacomini, L., Goldenberg, R., Heiden, G., Iganci, J., Kelloff, C., Knapp, S., Cavalcante de Lima, H., Machado, A., dos Santos, R., Mello-Silva, R., ... Forzza, R. (2017). Amazon plant diversity revealed by a taxonomically verified species list. *Proceedings of the National Academy of Sciences*, *114*(40), 10695-10700. <https://doi.org/10.1073/pnas.1706756114>



- Cordonnier, T., Kunstler, G., Courbaud, B., & Morin, X. (2018). Managing tree species diversity and ecosystem functions through coexistence mechanisms. *Annals of Forest Science*, 75(3), 65. <https://doi.org/10.1007/s13595-018-0750-6>
- De Mil, T., Tarelkin, Y., Hahn, S., Hubau, W., Deklerck, V., Debeir, O., Van Acker, J., de Cannière, C., Beeckman, H., & Van den Bulcke, J. (2018). Wood Density Profiles and Their Corresponding Tissue Fractions in Tropical Angiosperm Trees. *Forests*, 9(12), 763. <https://doi.org/10.3390/f9120763>
- De Ridder, M., Van den Bulcke, J., Van Acker, J., & Beeckman, H. (2013). Tree-ring analysis of an African long-lived pioneer species as a tool for sustainable forest management. *Forest Ecology and Management*, 304, 417-426. <https://doi.org/10.1016/j.foreco.2013.05.007>
- Dünisch, O., Montóia, V., & Bauch, J. (2003). Dendroecological investigations on *Swietenia macrophylla* King and *Cedrela odorata* L. (Meliaceae) in the central Amazon. *Trees*, 17(3), 244-250. <https://doi.org/10.1007/s00468-002-0230-2>
- Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of Tropical Forests in the Anthropocene. *Current Biology*, 29(19), R1008-R1020. <https://doi.org/10.1016/j.cub.2019.08.026>
- Fichtler, E., & Worbes, M. (2012). Wood anatomical variables in tropical trees and their relation to site conditions and individual tree morphology. *LAWA Journal*, 33(2), 119-140. <https://doi.org/10.1163/22941932-90000084>
- Foster, R., Parker, T., & Gentry, A. (Eds.). (1994). *The Tambopata-Candamo reserved zone of southeastern Peru: A biological assessment*. Conservation International, Department of Conservation Biology.
- Gaitan, J., Moya, R., & Berrocal, A. (2019). The use of X-ray densitometry to evaluate the wood density profile of *Tectona grandis* trees growing in fast-growth plantations. *Dendrochronologia*, 55, 71-79. <https://doi.org/10.1016/j.dendro.2019.04.004>
- Golar, G., Malik, A., Muis, H., Herman, A., Nurudin, N., & Lukman, L. (2020). The social-economic impact of COVID-19 pandemic: Implications for potential forest degradation. *Heliyon*, 6(10), e05354. <https://doi.org/10.1016/j.heliyon.2020.e05354>
- Graaf, N. R., Filius, A. M., & Santos, A. R. (2003). Financial analysis of sustained forest management for timber Perspectives for application of the CELOS management system in Brazilian Amazonia. *Forest Ecology and Management*, 177, 287-299.
- Granato, D., Stahle, D., Barbosa, A., Feng, S., Torbenson, M., de Assis Pereira, G., Schöngart, J., Barbosa, J., & Griffin, D. (2019). Tree rings and rainfall in the equatorial Amazon. *Climate Dynamics*, 52(3-4), 1857-1869. <https://doi.org/10.1007/s00382-018-4227-y>
- Groenendijk, P., Bongers, F., & Zuidema, P. A. (2017). Using tree-ring data to improve timber-yield projections for African wet tropical forest tree species. *Forest Ecology and Management*, 400, 396-407. <https://doi.org/10.1016/j.foreco.2017.05.054>
- Groenendijk, P., Sass-Klaassen, U., Bongers, F., & Zuidema, P. A. (2014). Potential of tree-ring analysis in a wet tropical forest: A case study on 22 commercial tree species in Central Africa. *Forest Ecology and Management*, 323, 65-78. <https://doi.org/10.1016/j.foreco.2014.03.037>
- IAWA. (1989). COMMITTEE. *List of microscopic features of hardwood identification* (Vol. 3). IAWA Buletinl.
- Jacquin, P., Longuetaud, F., Leban, J., & Mothe, F. (2017). X-ray microdensitometry of wood: A review of existing principles and devices. *Dendrochronologia*, 42, 42-50. <https://doi.org/10.1016/j.dendro.2017.01.004>
- Jandl, R., Spathelf, P., Bolte, A., & Prescott, C. E. (2019). Forest adaptation to climate change—Is non-management an option? *Annals of Forest Science*, 76(2), 48. <https://doi.org/10.1007/s13595-019-0827-x>

- Köppen, W. (1948). *Climatología: Con un estudio de los climas de la tierra*.
- Larsson, L.-A. (2014). *Cybis CooRecord. Saltsjobaden: Cybis Elektronik & Data AB*. <http://www.cybis.se/>
- Ligot, G., Fayolle, A., Gourlet-Fleury, S., Dainou, K., Gillet, J.-F., De Ridder, M., Drouet, T., Groenendijk, P., & Doucet, J.-L. (2019). Growth determinants of timber species *Triplochiton scleroxylon* and implications for forest management in central Africa. *Forest Ecology and Management*, 437, 211-221. <https://doi.org/10.1016/j.foreco.2019.01.042>
- Lisi, C. S., Fo, M. T., Botosso, P. C., Roig, F. A., Maria, V. R., Ferreira-Fedele, L., & Voigt, A. R. (2008). Tree-ring formation, radial increment periodicity, and phenology of tree species from a seasonal semi-deciduous forest in southeast Brazil. *Iawa Journal*, 29(2), 189-207.
- López, L., & Villalba, R. (2015). Forest management criteria for 12 species of Tropical Native Forests of Bolivia based on dendrochronological methods. *Ecosistemas*, 24(2), 24-29. <https://doi.org/10.7818/ECOS.2015.24-2.04>
- Marcelo-Peña, J., Roig, F., Goodwin, Z., & Tomazello, M. (2020). Characterizing growth rings in the trees of Perú: A wood anatomical overview for potential applications in dendroecological-related fields. *Dendrochronologia*, 125728. <https://doi.org/10.1016/j.dendro.2020.125728>
- Marcelo-Peña, J., Santini, L., & Tomazello, M. (2019). Wood anatomy and growth rate of seasonally dry tropical forest trees in the Marañón River Valley, northern Peru. *Dendrochronologia*, 55, 135-145. <https://doi.org/10.1016/j.dendro.2019.04.008>
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403(6772), 853-858. <https://doi.org/10.1038/35002501>
- Pagotto, M., L., Carvalho, A., Nabais, C., M., Ribeiro, A., & Lisi, C. (2017). Evaluation of X-ray densitometry to identify tree-ring boundaries of two deciduous species from semi-arid forests in Brazil. *Dendrochronologia*, 42, 94-103. <https://doi.org/10.1016/j.dendro.2017.01.007>
- Portal, L. A., Figueiredo, J. V., Camargo, J. H., Vieira, G., Oliveira, D., Alves, L. M., & Figueiredo, J. (2019). Variabilidad radial física y anatómica del leño de árboles de *Amburana cearensis*. *Colombia forestal*, 22(1), 17-26. <https://doi.org/10.14483/2256201X.13083>
- Portal, L., Cardozo, J., Santos, L., Saavedra, G., & Huamán, B. (2020). Dendrocronología de *Jacaranda copaia* que contiene registro ENSO en Madre de Dios, Perú. *Nativa*, 8(4), 572-578. <https://doi.org/10.31413/nativa.v8i4.10082>
- Qin, Y., Xiao, X., Dong, J., Zhou, Y., Wang, J., Doughty, R., Chen, Y., Zou, Z., & Moore, B. (2017). Annual dynamics of forest areas in South America during 2007–2010 at 50-m spatial resolution. *Remote Sensing of Environment*, 201, 73-87. <https://doi.org/10.1016/j.rse.2017.09.005>
- Quintilhan, M. T., Santini, L., Ortega Rodriguez, D. R., Guillemot, J., Cesilio, G. H. M., Chambi-Legoas, R., Nouvellon, Y., & Tomazello-Filho, M. (2021). Growth-ring boundaries of tropical tree species: Aiding delimitation by long histological sections and wood density profiles. *Dendrochronologia*, 69, 125878. <https://doi.org/10.1016/j.dendro.2021.125878>
- Rosa, S. A., Barbosa, A. C. M. C., Junk, W. J., da Cunha, C. N., Piedade, M. T. F., Scabin, A. B., Ceccantini, G. C. T., & Schöngart, J. (2017). Growth models based on tree-ring data for the Neotropical tree species *Calophyllum brasiliense* across different Brazilian wetlands: Implications for conservation and management. *Trees*, 31(2), 729-742. <https://doi.org/10.1007/s00468-016-1503-5>
- Rozendaal, D. M. A., Soliz-Gamboa, C. C., & Zuidema, P. A. (2010). Timber yield projections for tropical tree species: The influence of fast juvenile growth on timber volume recovery. *Forest Ecology and Management*, 259(12), 2292-2300. <https://doi.org/10.1016/j.foreco.2010.02.030>

- Rozendaal, D. M., & Zuidema, P. A. (2011). Dendroecology in the tropics: A review. *Trees*, 25(1), 3-16. <https://doi.org/10.1007/s00468-010-0480-3>
- Sánchez-Cuervo, A. M., de Lima, L. S., Dallmeier, F., Garate, P., Bravo, A., & Vanthomme, H. (2020). Twenty years of land cover change in the southeastern Peruvian Amazon: Implications for biodiversity conservation. *Regional Environmental Change*, 20(1), 8. <https://doi.org/10.1007/s10113-020-01603-y>
- Schöngart, J. (2008). Growth-Oriented Logging (GOL): A new concept towards sustainable forest management in Central Amazonian várzea floodplains. *Forest Ecology and Management*, 256(1-2), 46-58. <https://doi.org/10.1016/j.foreco.2008.03.037>
- Schöngart, J. (2010). Growth-Oriented Logging (GOL): The Use of Species-Specific Growth Information for Forest Management in Central Amazonian Floodplains. En W. J. Junk, M. T. F. Piedade, F. Wittmann, J. Schöngart, & P. Parolin (Eds.), *Amazonian Floodplain Forests* (Vol. 210, pp. 437-462). Springer Netherlands. [https://doi.org/10.1007/978-90-481-8725-6\\_21](https://doi.org/10.1007/978-90-481-8725-6_21)
- Schöngart, J., Bräuning, A., Barbosa, A., Lisi, C., & de Oliveira, J. (2017). Dendroecological Studies in the Neotropics: History, Status and Future Challenges. En M. Amoroso, L. Daniels, P. Baker, & J. Camarero (Eds.), *Dendroecology* (Vol. 231, pp. 35-73). Springer International Publishing. [https://doi.org/10.1007/978-3-319-61669-8\\_3](https://doi.org/10.1007/978-3-319-61669-8_3)
- Sebbenn, A. M., Degen, B., Azevedo, V. C. R., Silva, M. B., de Lacerda, A. E. B., Ciampi, A. Y., Kanashiro, M., Carneiro, F. da S., Thompson, I., & Loveless, M. D. (2008). Modelling the long-term impacts of selective logging on genetic diversity and demographic structure of four tropical tree species in the Amazon forest. *Forest Ecology and Management*, 254(2), 335-349. <https://doi.org/10.1016/j.foreco.2007.08.009>
- Ley Forestal y de Fauna Silvestre N° 29763 y sus reglamentos, Pub. L. No. 29763, 345 (2015).
- Seydack, A. (1995). An unconventional approach to timber yield regulation for multi-aged, multispecies forests. I. Fundamental considerations. *Forest Ecology and Management*, 77(1-3), 139-153. [https://doi.org/10.1016/0378-1127\(95\)03577-W](https://doi.org/10.1016/0378-1127(95)03577-W)
- Shono, K. (2006). Growth of big-leaf mahogany (*Swietenia macrophylla*) in natural forests in Belize. *Journal of Tropical Forest Science*, 8.
- Susatya, A., & Yansen. (2016). Dendrochronology of young *Swietenia macrophylla* and the variation of its growth response to the past wet climate in Bengkulu, Indonesia. *Biodiversitas, Journal of Biological Diversity*, 17(2), 466-472. <https://doi.org/10.13057/biodiv/d170210>
- Tomazello, M., Brazolin, S., Chagas, M. P., Oliveira, J. T. S., Ballarin, A. W., & Benjamin, C. A. (2008). Application of X-ray technique in nondestructive evaluation of eucalypt wood. *Maderas. Ciencia y Tecnología*, 10(2), Article 2. <https://doi.org/10.4067/S0718-221X2008000200006>
- Vlam, M., van der Sleen, P., Groenendijk, P., & Zuidema, P. A. (2017). Tree Age Distributions Reveal Large-Scale Disturbance-Recovery Cycles in Three Tropical Forests. *Frontiers in Plant Science*, 7. <https://doi.org/10.3389/fpls.2016.01984>

## Appendix. Supplementary material

### 1. Botanical Family

### 2. Name of the species (Botanical family)

### 3. Potential for tree ring analysis from Peru:



### 4. Growth ring boundary distinctness

- Highly distinct; moderate distinct; poorly distinct; indistinct or absent.

### 5. Anatomical boundary descriptor

- Change in fiber wall thickness; change in fiber wall thickness combined with marginal parenchyma; marginal parenchyma; semi-ring porosity combined with marginal parenchyma; marginal parenchyma phloem.

### 6. Description of growth rings and wood (IAWA hardwood codes):

**Growth Rings:** (1) Growth ring boundaries distinct; (2) Growth ring boundaries indistinct or absent. **Vessels – Porosity:** (3) Wood ring-porous; (4) Wood semi-ring-porous; (5) Wood diffuse-porous. **Vessel arrangement:** (6) Vessels in tangential bands; (7) Vessels in diagonal and/ or radial pattern; (8) Vessels in the dendritic pattern. **Vessel groupings:** (9) Vessels exclusively solitary (90% or more); (10) Vessels in radial multiples of 4 or more common; (11) Vessel clusters common. **Tyloses and deposits in vessels:** (56) Tyloses common; (58) Gums and other deposits in heartwood vessels. (75) Axial parenchyma is absent or extremely rare. **Apotracheal axial parenchyma:** (76) Axial parenchyma diffuse; (77) Axial parenchyma diffuse-in-aggregates. **Paratracheal axial parenchyma:** (78) Axial parenchyma scanty paratracheal; (79) Axial parenchyma vasicentric; (80) Axial parenchyma aliform; (81) Axial parenchyma lozenge-aliform; (82) Axial parenchyma winged-aliform; (83) Axial parenchyma confluent; Axial parenchyma. **Banded parenchyma:** (85) Axial parenchyma bands more than three cells wide; (86) Axial parenchyma in narrow bands or lines up to three cells wide; (87) Axial parenchyma reticulate; (88) Axial parenchyma scalariform; (89) Axial parenchyma in marginal or in seemingly marginal bands. **Storied structure:** (118) All rays storied; (119) Low rays storied, high rays non-storied. **Cambial variants:** (134) Included phloem, diffuse. **Silica:** (159) Silica bodies present. (192) Wood of commercial importance. **Specific gravity:** (193) Basic specific gravity low,  $\leq 0.40$ ; (194) Basic specific gravity medium,  $0.40-0.75$ ; (195) Basic specific gravity high,  $\geq 0.75$ . **Odor:** (203) Distinct odor.

### 7. Sampling with increment cores

- Low or medium density wood; High or very high-density wood.

### 8. X-ray densitometry, for the identification of the growth ring boundary

- Good potential; regulate potential; no potential.

<b>1</b>	<b>Annonaceae</b>	<b>3</b>	
<b>2</b>	<b><i>Rollinia pittieri</i> Saff.</b>		
<b>4</b>	<b><u>Growth ring boundary distinctness</u></b>		
	<ul style="list-style-type: none"> <li>• Highly distinct</li> </ul>		
<b>5</b>	<b><u>Anatomical boundary descriptor</u></b>		
	<ul style="list-style-type: none"> <li>• Change in fiber wall thickness</li> </ul>		
<b>6</b>	<b><u>Description of growth rings and wood (IAWA hardwood codes):</u></b>		
	<ul style="list-style-type: none"> <li>• 1, 5, 7, 9, 88, 119, 193.</li> </ul>		
<b>7</b>	<b><u>Sampling with increment cores</u></b>		
	<ul style="list-style-type: none"> <li>• Low or medium density wood</li> </ul>		
<b>8</b>	<b><u>X-ray densitometry, for the identification of the growth ring boundary</u></b>		
	<ul style="list-style-type: none"> <li>• Good potential</li> </ul>		

<b>Annonaceae</b>			
<b><i>Rollinia pittieri</i> Saff.</b>			
<b>4</b>	<b><u>Growth ring boundary distinctness</u></b>		
	<ul style="list-style-type: none"> <li>• Highly distinct</li> </ul>		
<b>5</b>	<b><u>Anatomical boundary descriptor</u></b>		
	<ul style="list-style-type: none"> <li>• Change in fiber wall thickness</li> </ul>		
<b>6</b>	<b><u>Description of growth rings and wood (IAWA hardwood codes):</u></b>		
	<ul style="list-style-type: none"> <li>• 1, 5, 7, 9, 88, 119, 193.</li> </ul>		
<b>7</b>	<b><u>Sampling with increment cores</u></b>		
	<ul style="list-style-type: none"> <li>• Low or medium density wood</li> </ul>		
<b>8</b>	<b><u>X-ray densitometry, for the identification of the growth ring boundary</u></b>		
	<ul style="list-style-type: none"> <li>• Good potential</li> </ul>		

## Apocynaceae

### *Aspidosperma macrocarpon* Mart.

#### Growth ring boundary distinctness

- Highly distinct

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

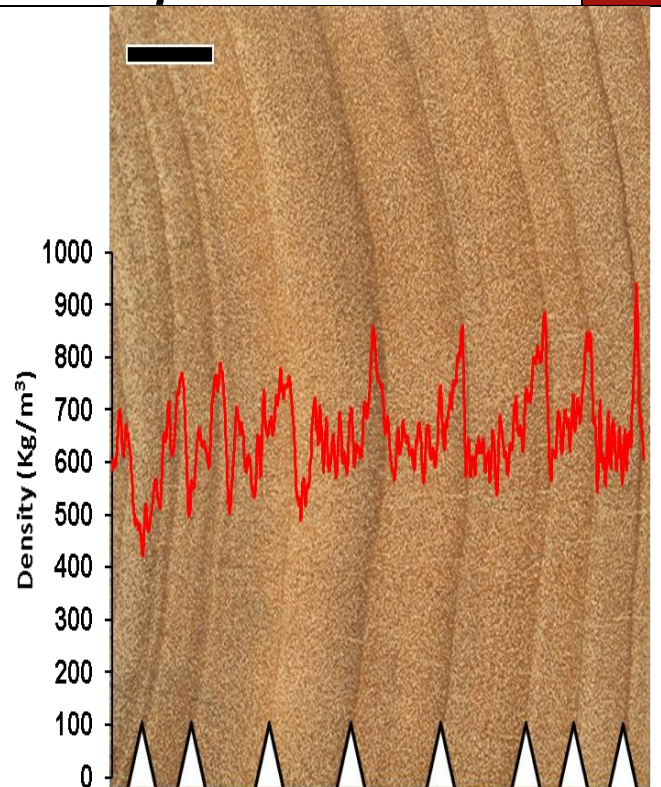
- 1, 5, 7, 9, 58, 76, 77, 119, 192, 194.

#### Sampling with increment cores

- High or very high-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Apocynaceae

### *Aspidosperma subincanum* Mart. Ex A. DC.

#### Growth ring boundary distinctness

- Highly distinct

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

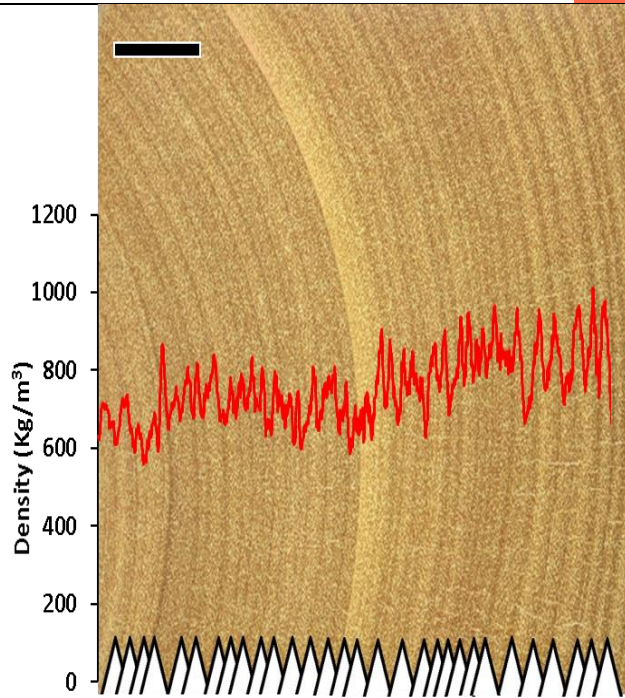
- 1, 5, 58, 76, 77, 119, 192, 194.

#### Sampling with increment cores

- High or very high-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential



## Bignoniaceae

### *Jacaranda copaia* (Aubl.) D. Don

#### Growth ring boundary distinctness

- Highly distinct

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

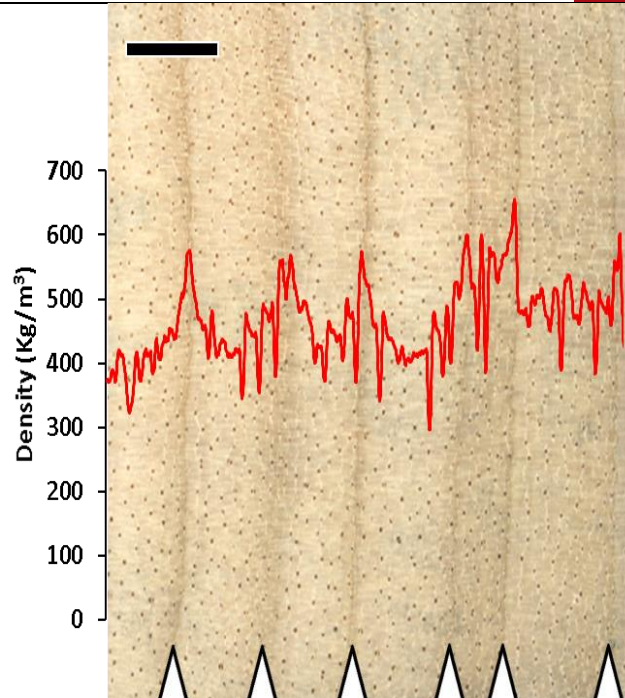
- 1, 5, 7, 9, 81, 83, 119, 192, 193.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Burseraceae

### *Dacryodes peruviana* (Loes.) H.J. Lam

#### Growth ring boundary distinctness

- Poorly distinct

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

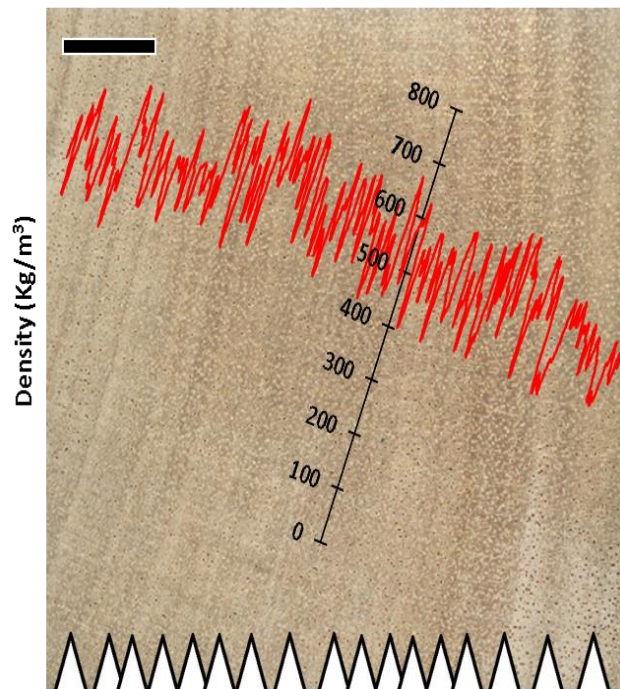
- 1, 5, 9, 58, 76, 119, 192, 194.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential.



## Burseraceae

### *Tetragastris altissima* (Aubl.) Swart

#### Growth ring boundary distinctness

- Moderate

#### Anatomical boundary descriptor

- Change in fiber wall thickness combined with marginal parenchyma

#### Description of growth rings and wood (IAWA hardwood codes):

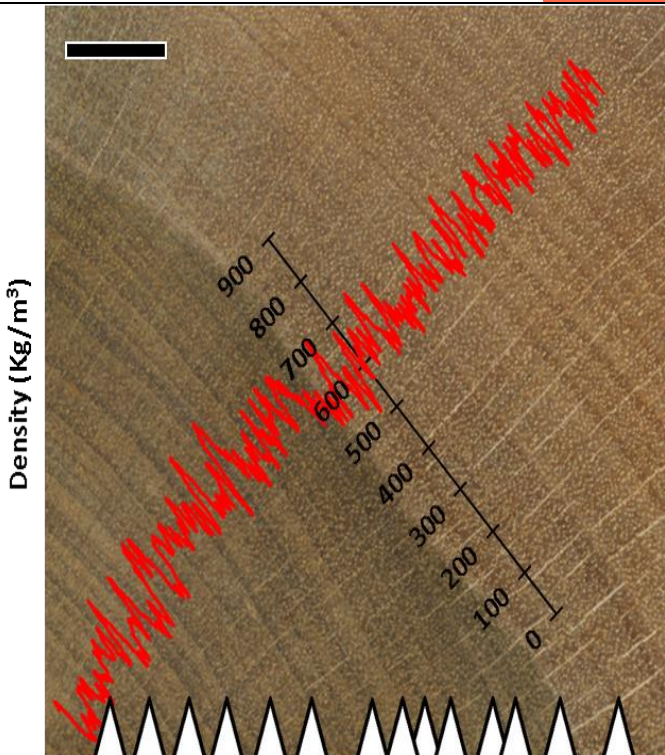
- 1, 5, 7, 11, 58, 79, 119, 192, 194.

#### Sampling with increment cores

- High or very high-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential





## Combretaceae

### *Terminalia catappa* L.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness.

#### Description of growth rings and wood (IAWA hardwood codes):

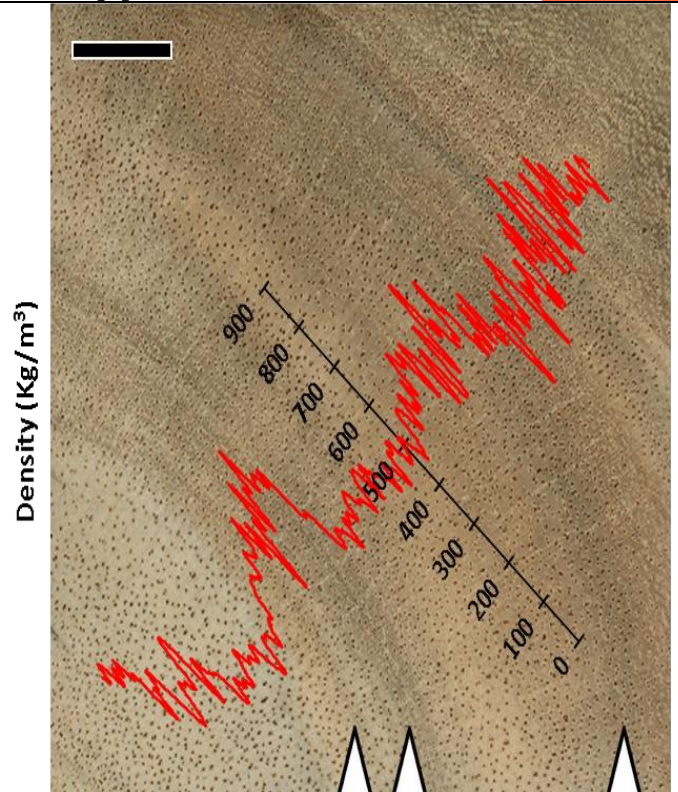
- 1, 5, 9, 58, 82, 83, 119, 194.

#### Sampling with increment cores

- Low or medium-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Euphorbiaceae

### *Hevea brasiliensis* (Willd. Ex A. Juss.) Mull. Arg.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness.

#### Description of growth rings and wood (IAWA hardwood codes):

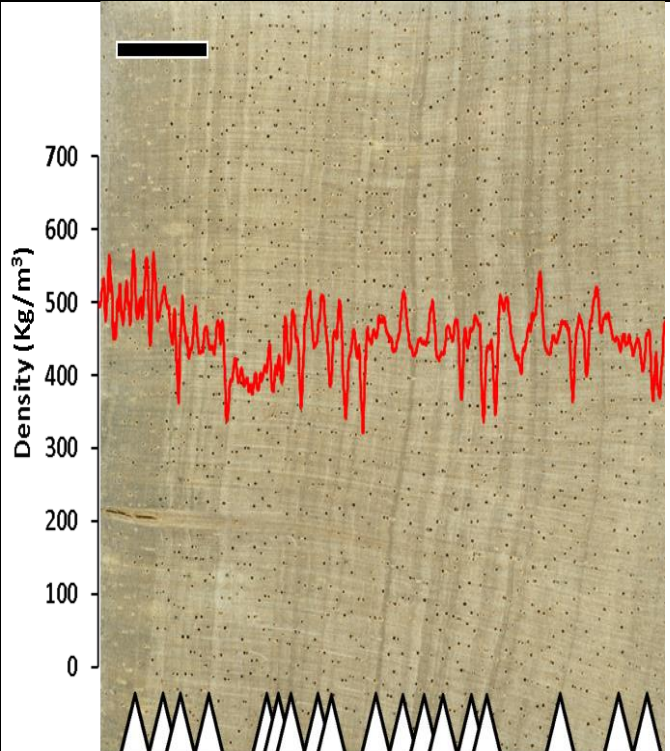
- 1, 5, 7, 11, 56, 87, 119, 192, 194.

#### Sampling with increment cores

- Low or medium-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Euphorbiaceae

### *Hura crepitans* L.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

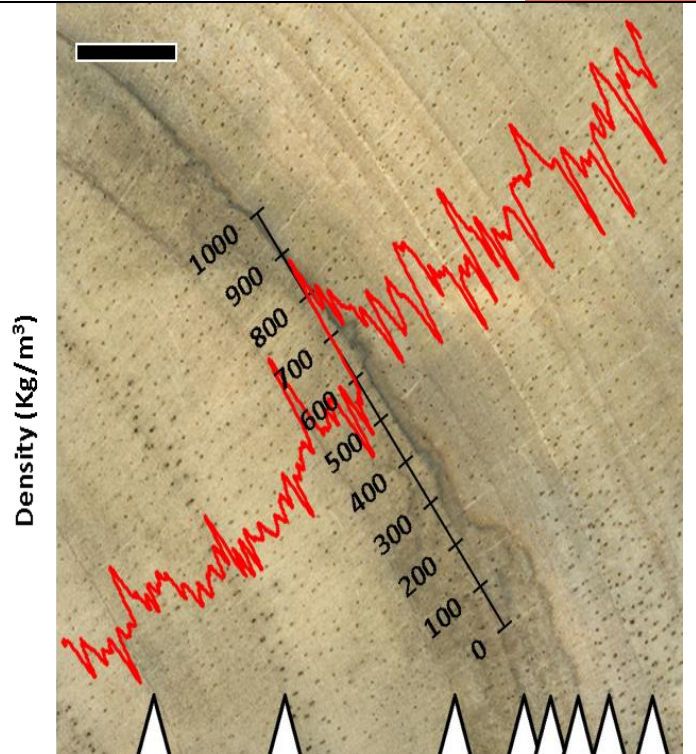
- 1, 5, 7, 11, 58, 76, 77, 119, 192, 194.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Fabaceae

### *Amburana cearensis* (Allemão) A.C. Sm.

#### Growth ring boundary distinctness

- Highly distinct.

#### Anatomical boundary descriptor

- Change in fiber wall thickness combined with marginal parenchyma

#### Description of growth rings and wood (IAWA hardwood codes):

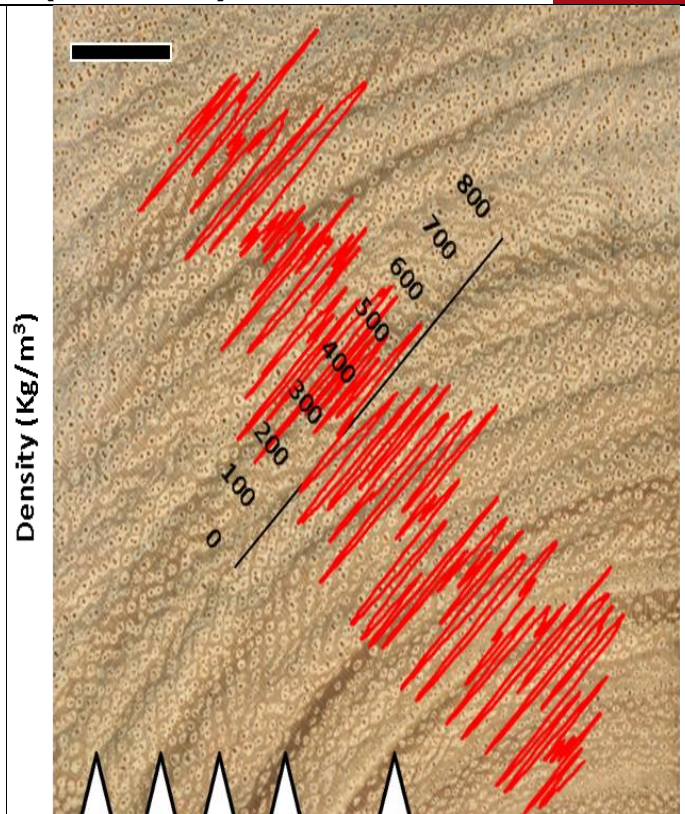
- 1, 5, 7, 11, 58, 79, 82, 83, 89, 119, 192, 194, 203.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



**Fabaceae*****Andira surinamensis* (Bondt) Splitg. Ex Pulle****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Change in fiber wall thickness

**Description of growth rings and wood (IAWA hardwood codes):**

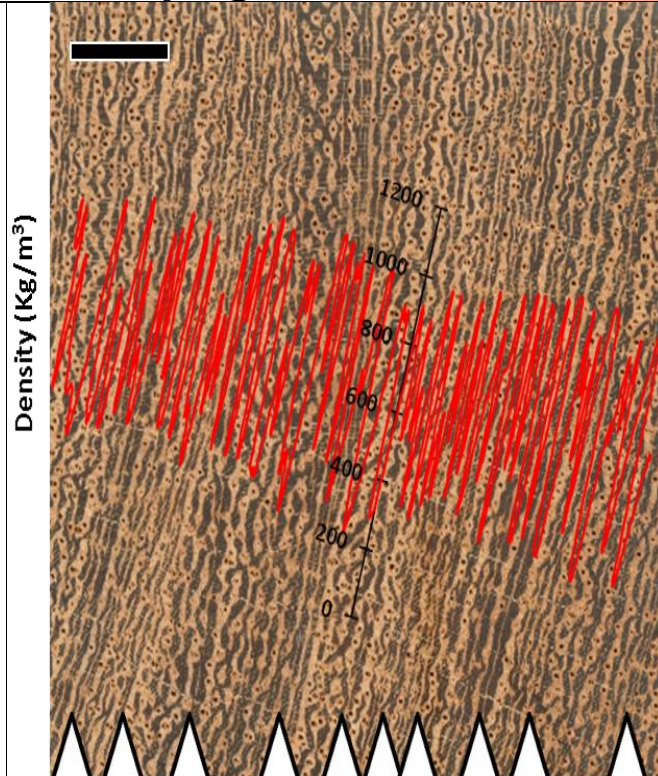
- 1, 5, 7, 11, 58, 82, 83, 119, 192, 194.

**Sampling with increment cores**

- High or very high-density wood.

**X-ray densitometry, for the identification of the growth ring boundary**

- No potential.

**Fabaceae*****Apuleia leiocarpa* (Vogel) J. F. Macbr.****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Change in fiber wall thickness combined with marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

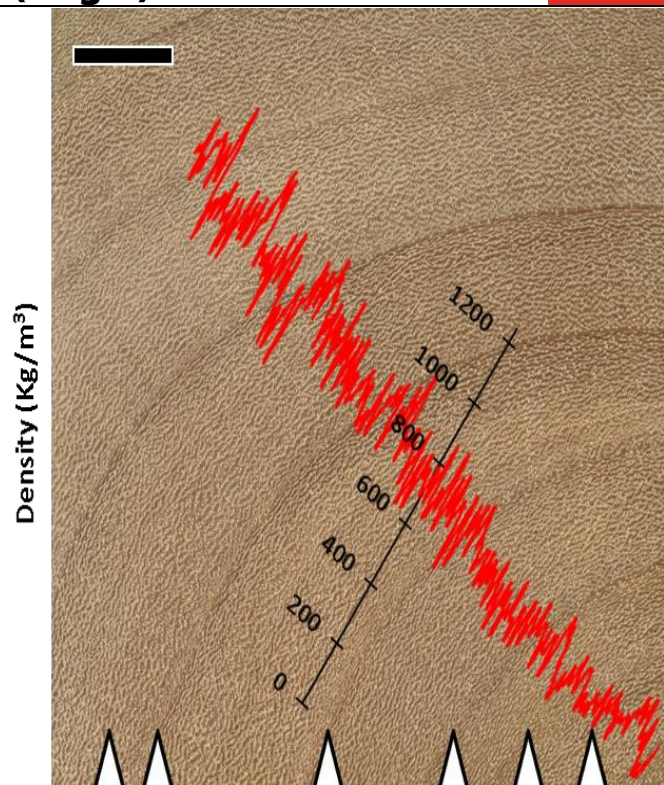
- 1, 5, 7, 11, 58, 81, 83, 118, 159, 192, 195.

**Sampling with increment cores**

- High or very high-density wood.

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential



## Fabaceae

### *Dipteryx micrantha* Harms.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness combined with marginal parenchyma.

#### Description of growth rings and wood (IAWA hardwood codes):

- 1, 5, 7, 9, 58, 82, 83, 118, 159, 192, 195.

#### Sampling with increment cores

- High or very high-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential.



## Fabaceae

### *Myroxylon balsamum* (L.) Harms.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness combined with marginal parenchyma.

#### Description of growth rings and wood (IAWA hardwood codes):

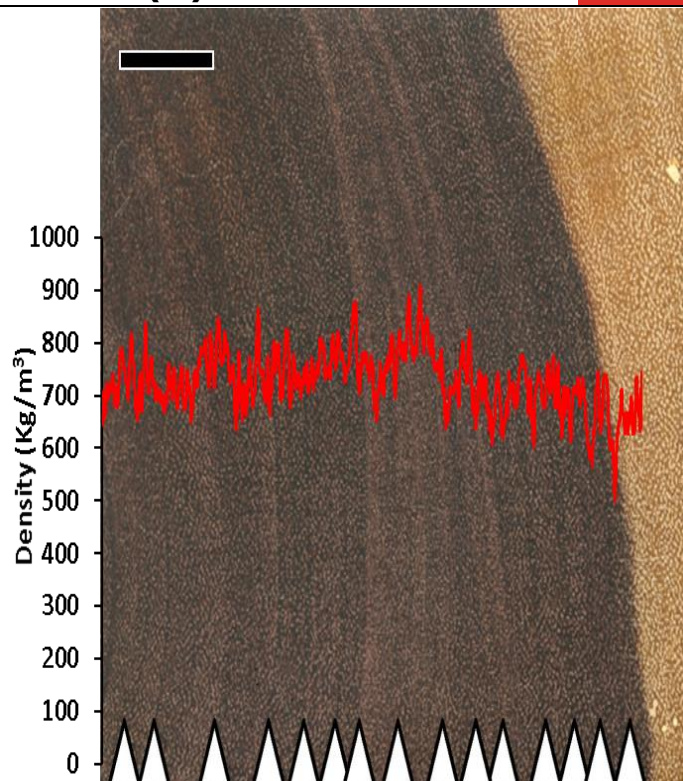
- 1, 5, 7, 9, 58, 79, 82, 83, 118, 159, 192, 195, 203.

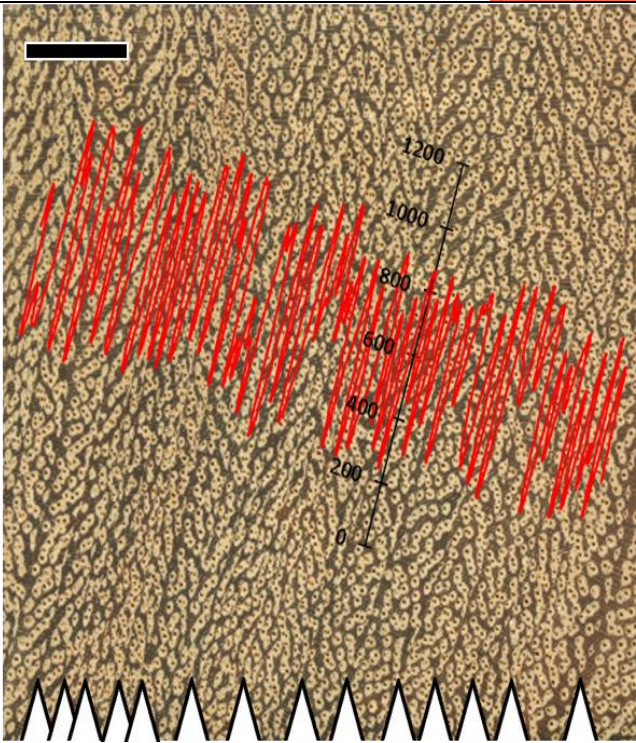
#### Sampling with increment cores

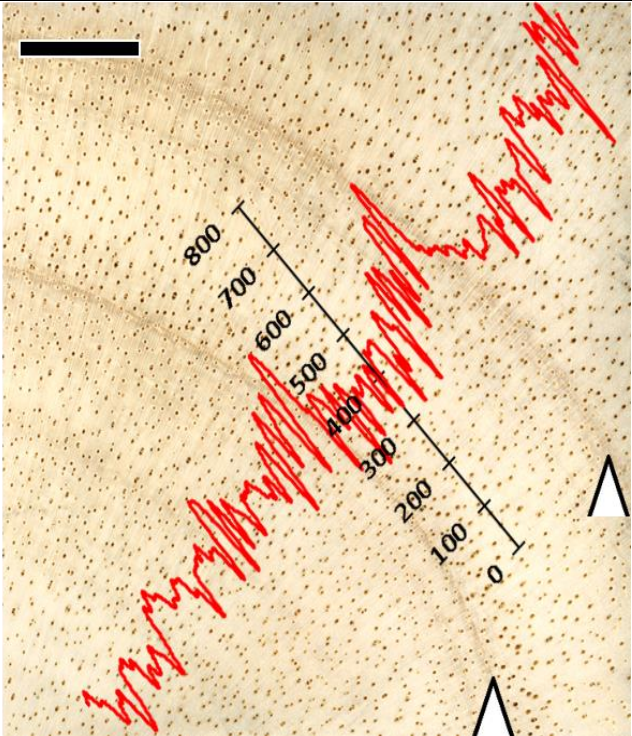
- High or very high-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential.



<b>Fabaceae</b>	
<b><i>Ormosia paraensis</i> Ducke.</b>	
<p><u>Growth ring boundary distinctness</u></p> <ul style="list-style-type: none"> <li>Highly distinct</li> </ul> <p><u>Anatomical boundary descriptor</u></p> <ul style="list-style-type: none"> <li>Change in fiber wall thickness</li> </ul> <p><u>Description of growth rings and wood (IAWA hardwood codes):</u></p> <ul style="list-style-type: none"> <li>1, 5, 7, 9, 58, 82, 83, 119, 192, 194.</li> </ul> <p><u>Sampling with increment cores</u></p> <ul style="list-style-type: none"> <li>High or very high-density wood.</li> </ul> <p><u>X-ray densitometry, for the identification of the growth ring boundary</u></p> <ul style="list-style-type: none"> <li>No potential.</li> </ul>	

<b>Fabaceae</b>	
<b><i>Schizolobium parahyba</i> (Vell.) S.F. Blake.</b>	
<p><u>Growth ring boundary distinctness</u></p> <ul style="list-style-type: none"> <li>Highly distinct</li> </ul> <p><u>Anatomical boundary descriptor</u></p> <ul style="list-style-type: none"> <li>Change in fiber wall thickness combined with marginal parenchyma.</li> </ul> <p><u>Description of growth rings and wood (IAWA hardwood codes):</u></p> <ul style="list-style-type: none"> <li>1, 5, 7, 9, 79, 82, 83, 119, 192, 194.</li> </ul> <p><u>Sampling with increment cores</u></p> <ul style="list-style-type: none"> <li>Low or medium-density wood</li> </ul> <p><u>X-ray densitometry, for the identification of the growth ring boundary</u></p> <ul style="list-style-type: none"> <li>Good potential.</li> </ul>	

**Fabaceae*****Tachigali sp.*****Growth ring boundary distinctness**

- Highly distinct

**Anatomical boundary descriptor**

- Change in fiber wall thickness

**Description of growth rings and wood (IAWA hardwood codes):**

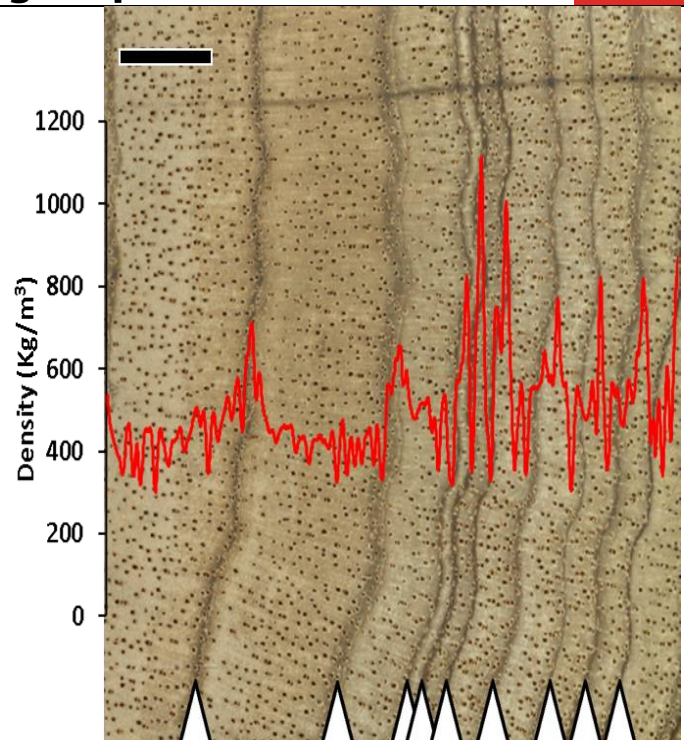
- 1, 5, 7, 11, 58, 82, 83, 119, 192, 194.

**Sampling with increment cores**

- Low or médium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential

**Lauraceae*****Ocotea bofo* Kunth.****Growth ring boundary distinctness**

- Highly distinct

**Anatomical boundary descriptor**

- Change in fiber wall thickness

**Description of growth rings and wood (IAWA hardwood codes):**

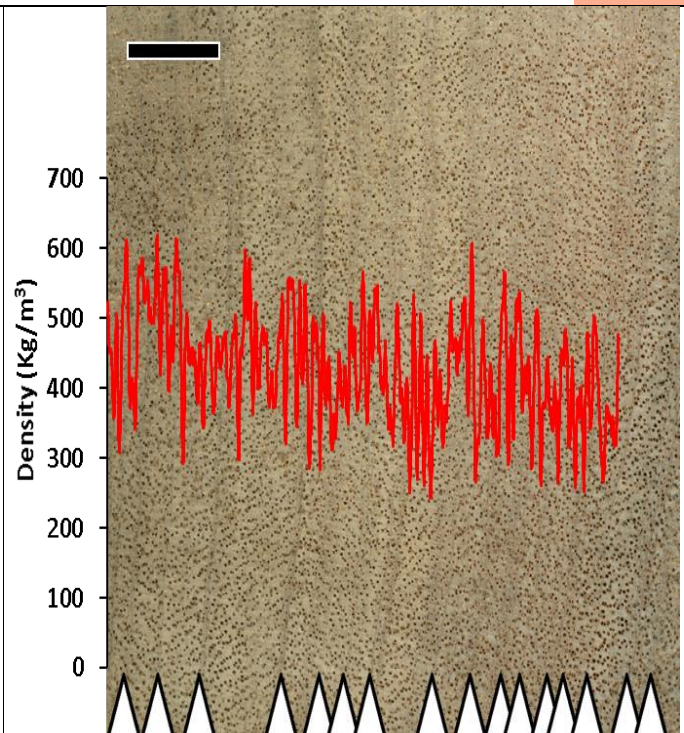
- 1, 5, 7, 11, 58, 79, 119, 192, 194.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Regulate potential.



## Malvaceae

### *Guazuma ulmifolia* Lam.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

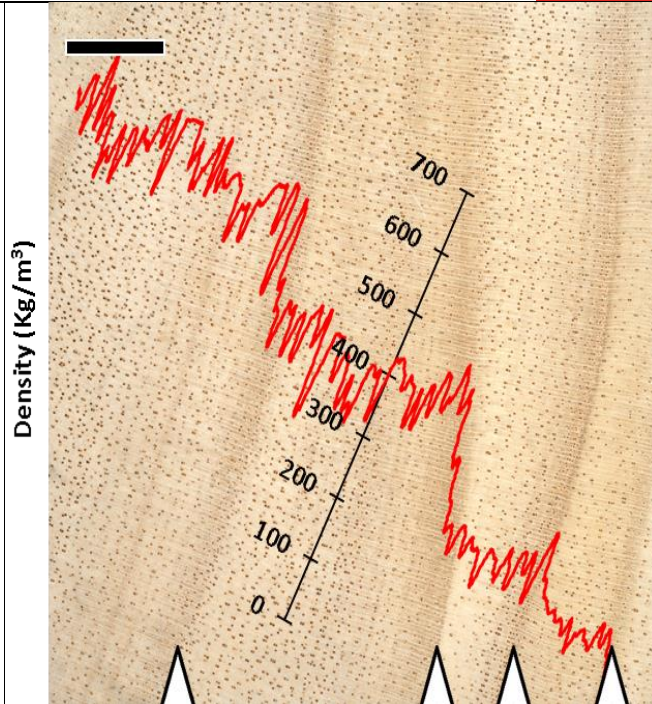
- 1, 5, 7, 11, 76, 77, 119, 192, 193.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



## Malvaceae

### *Ochroma pyramidale* (Cav. ex Lam.) Urb.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

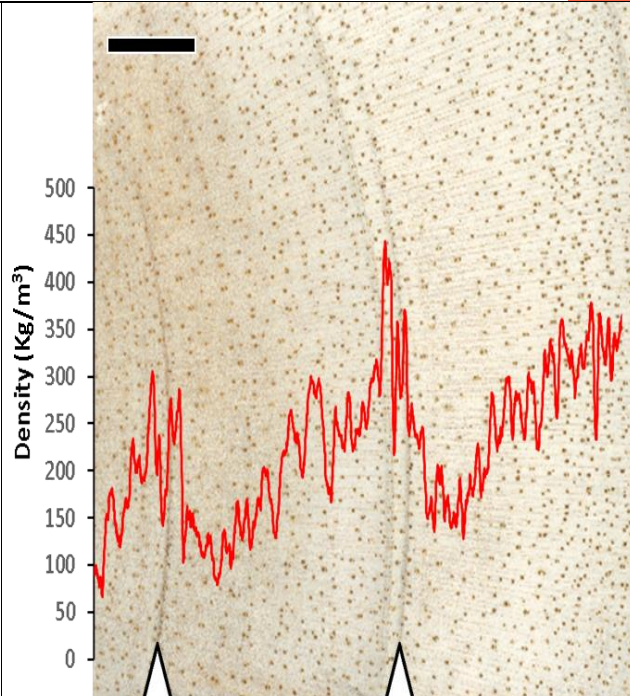
- 1, 5, 7, 9, 76, 77, 119, 192, 193.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



**Malvaceae*****Apeiba tibourbou* Aubl.****Growth ring boundary distinctness**

- Poorly distinct.

**Anatomical boundary descriptor**

- Marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

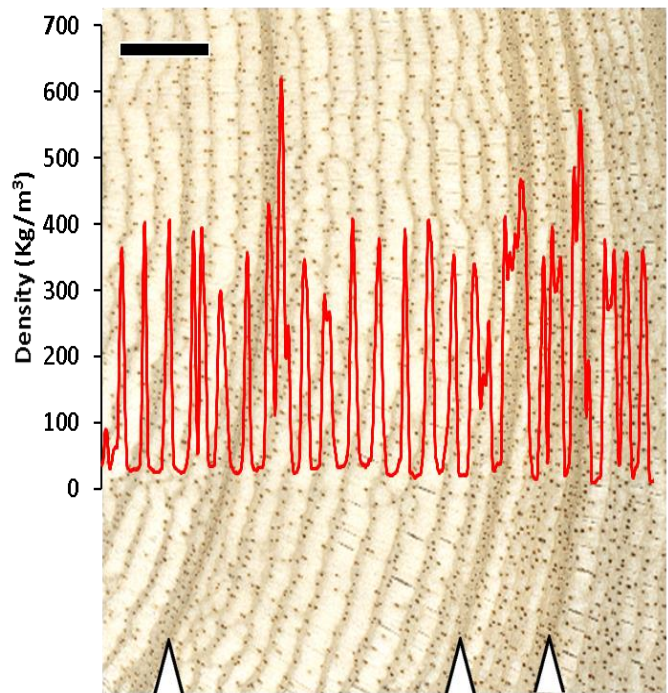
- 1, 5, 7, 9, 85, 118, 192, 193.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Regulate potential.

**Malvaceae*****Ceiba lupuna* P.E. Gibbs & Semir.****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

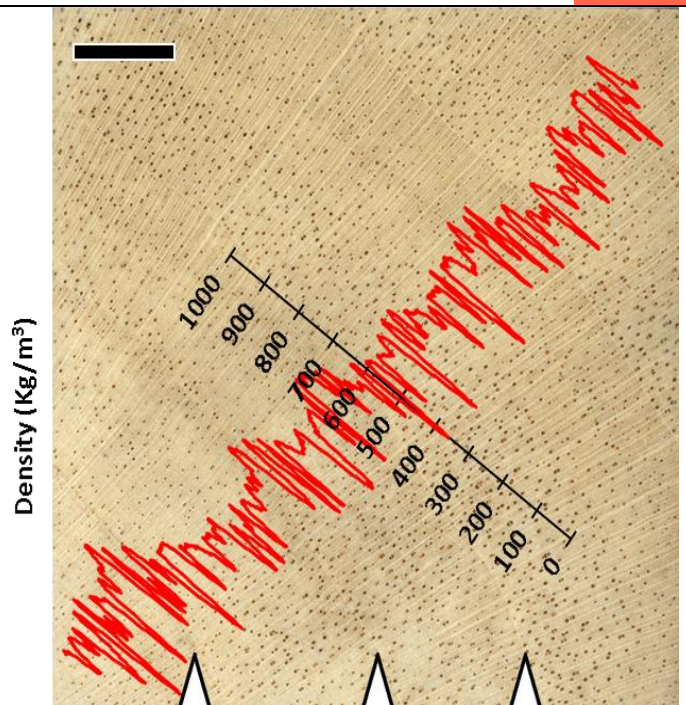
- 1, 5, 7, 9, 76, 77, 89, 119, 192, 193.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Regulate potential.





**Malvaceae*****Matisia cordata* Bonpl.****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Change in fiber wall thickness

**Description of growth rings and wood (IAWA hardwood codes):**

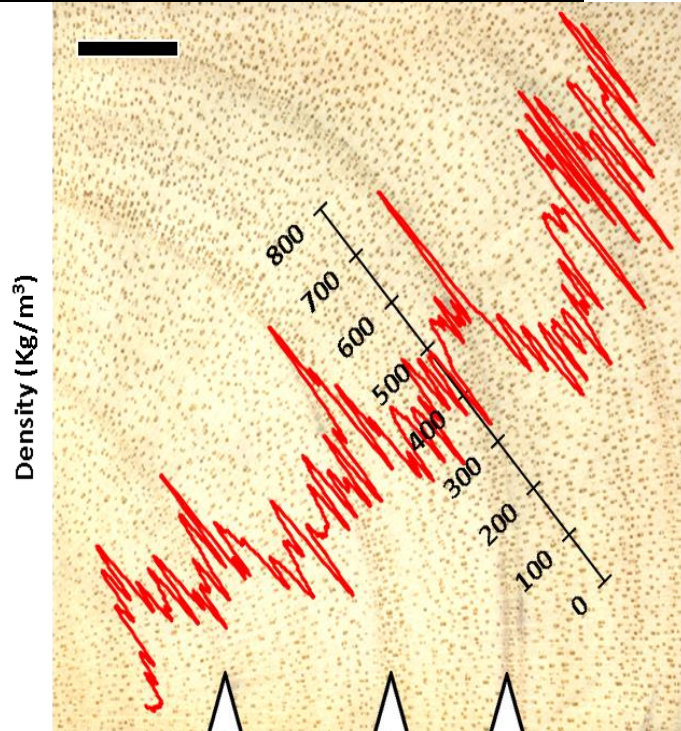
- 1, 5, 7, 11, 76, 77, 119, 192, 193.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential

**Meliaceae*****Swietenia macrophylla* King****Growth ring boundary distinctness**

- Highly distinct

**Anatomical boundary descriptor**

- Marginal parenchyma

**Description of growth rings and wood (IAWA hardwood codes):**

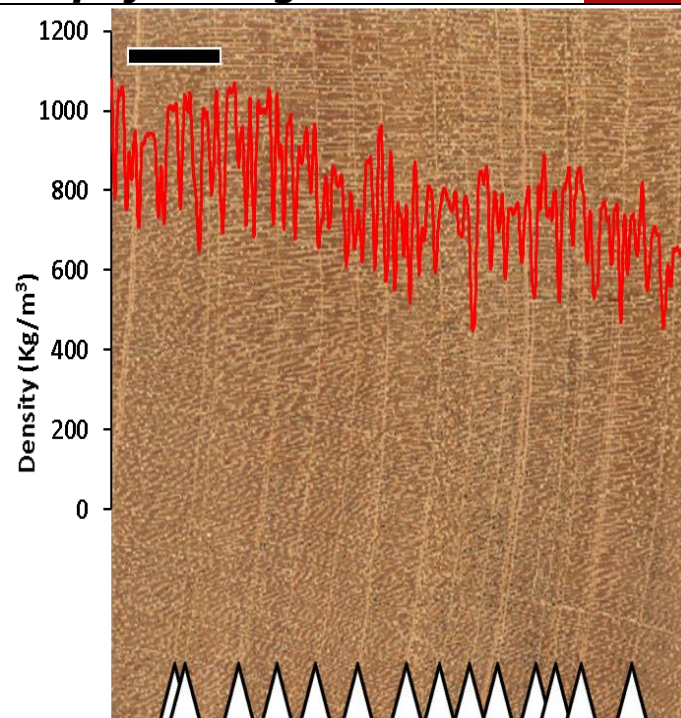
- 1, 5, 7, 10, 58, 79, 89, 118, 192, 194.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential



**Meliaceae*****Cedrela odorata* L.****Growth ring boundary distinctness**

- Highly distinct

**Anatomical boundary descriptor**

- Semi-ring porosity combined with marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

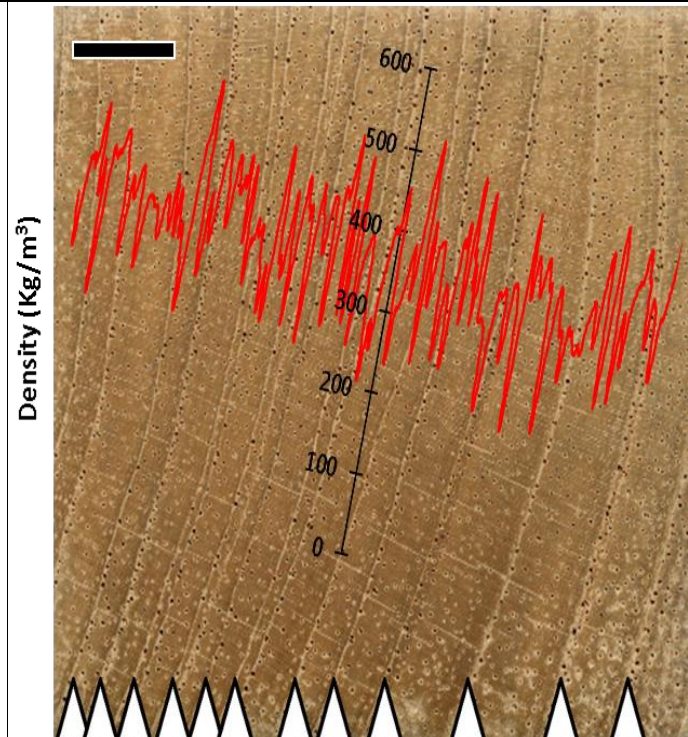
- 1, 4, 7, 11, 58, 79, 89, 119, 192, 193, 203.

**Sampling with increment cores**

- Low or medium density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential

**Meliaceae*****Cedrela fissilis* Vell.****Growth ring boundary distinctness**

- Highly distinct

**Anatomical boundary descriptor**

- Semi-ring porosity combined with marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

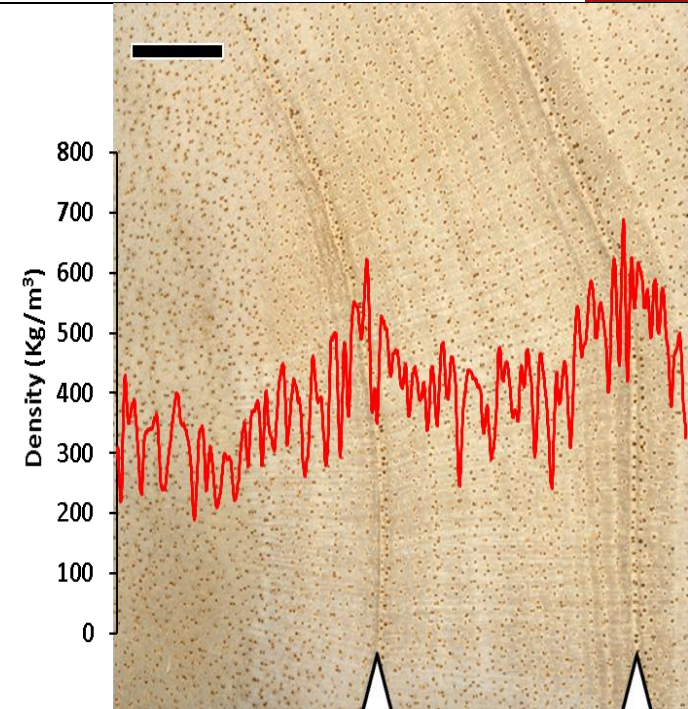
- 1, 4, 7, 11, 58, 79, 89, 119, 192, 193, 203.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential



**Moraceae*****Clarisia racemosa* Ruiz & Pav.****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Change in fiber wall thickness combined with marginal parenchyma.

**Description of growth rings and wood (IAWA hardwood codes):**

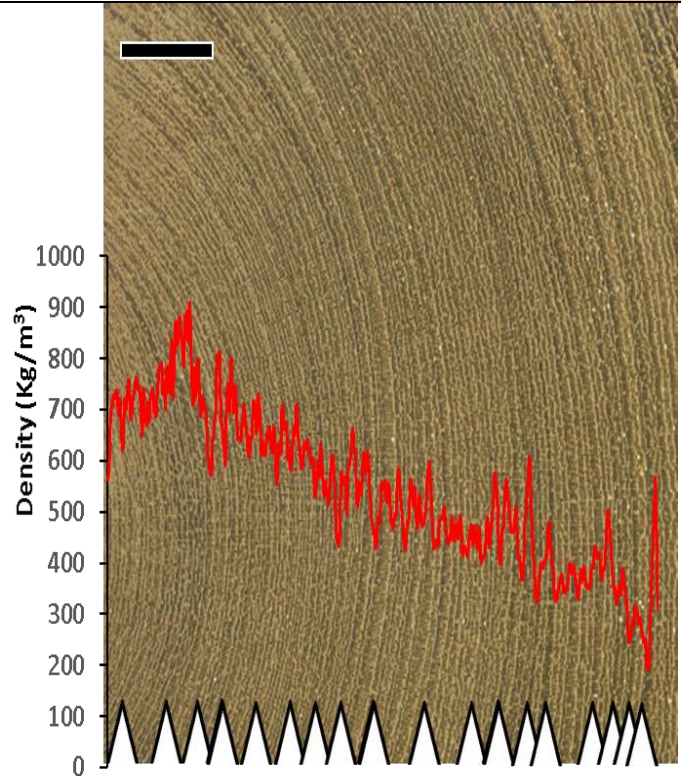
- 1, 5, 7, 11, 81, 83, 119, 159, 192, 195.

**Sampling with increment cores**

- High or very high-density wood.

**X-ray densitometry, for the identification of the growth ring boundary**

- Regulate potential.

**Myristicaceae*****Virola* sp.****Growth ring boundary distinctness**

- Moderate.

**Anatomical boundary descriptor**

- Change in fiber wall thickness

**Description of growth rings and wood (IAWA hardwood codes):**

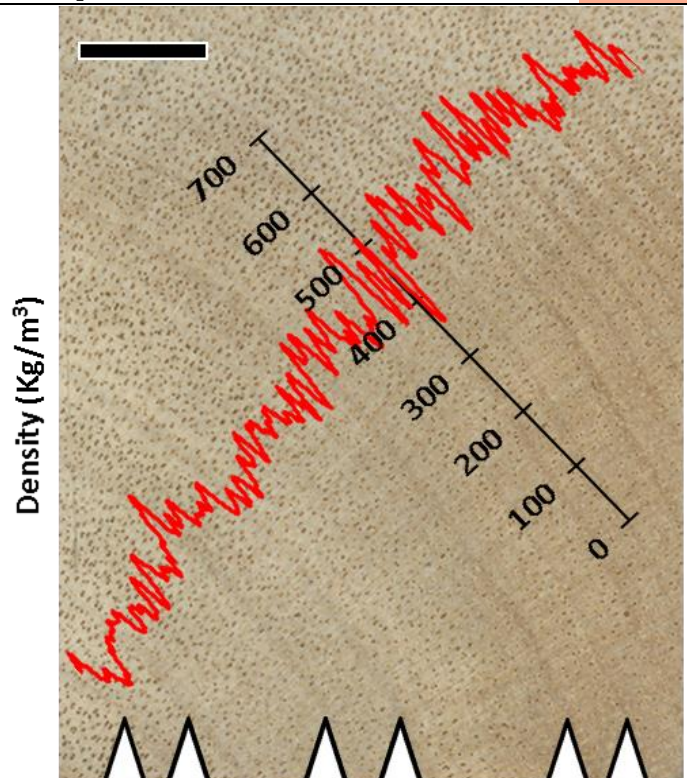
- 1, 5, 7, 11, 58, 79, 119, 192, 194.

**Sampling with increment cores**

- Low or medium-density wood

**X-ray densitometry, for the identification of the growth ring boundary**

- Good potential



## Putranjivaceae

### *Drypetes* sp.

#### Growth ring boundary distinctness

- Highly distinct

#### Anatomical boundary descriptor

- Marginal parenchyma

#### Description of growth rings and wood (IAWA hardwood codes):

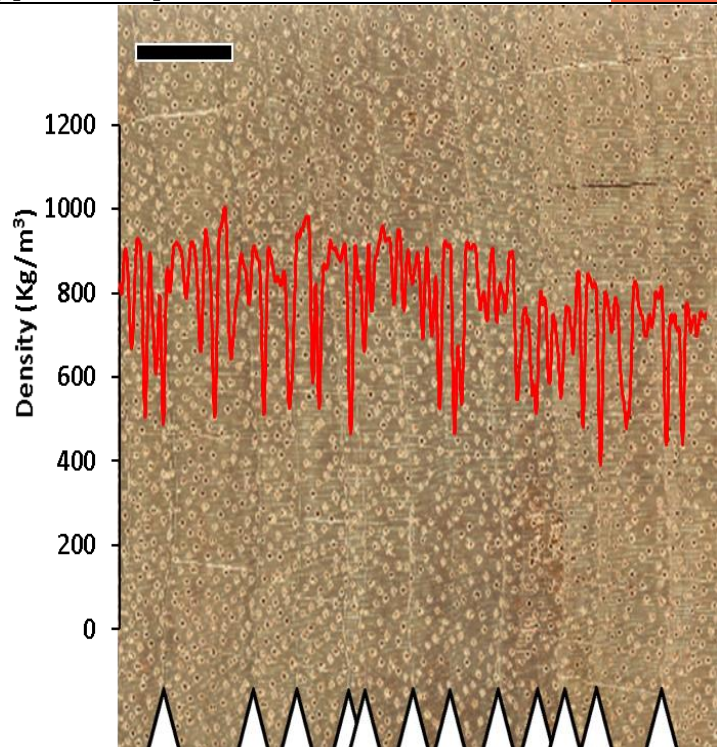
- 1, 5, 7, 9, 58, 82, 83, 89, 119, 192, 194.

#### Sampling with increment cores

- High or very high-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential.



## Petiveriaceae

### *Gallesia integrifolia* (Spreng.) Harms.

#### Growth ring boundary distinctness

- Moderate.

#### Anatomical boundary descriptor

- Marginal parenchyma phloem.

#### Description of growth rings and wood (IAWA hardwood codes):

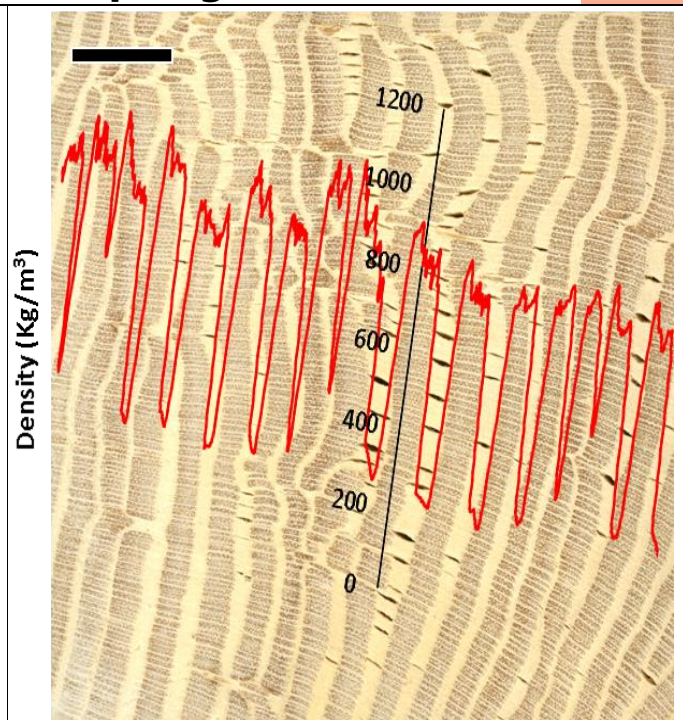
- 1, 5, 7, 9, 85, 119, 194, 203.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- Good potential



<b>Proteaceae</b>	
<b><i>Roupala montana</i> Aubl.</b>	
<b><u>Growth ring boundary distinctness</u></b>	
<ul style="list-style-type: none"> <li>• Indistinct or absent.</li> </ul>	
<b><u>Anatomical boundary descriptor</u></b>	
<ul style="list-style-type: none"> <li>• ---</li> </ul>	
<b><u>Description of growth rings and wood (IAWA hardwood codes):</u></b>	
<ul style="list-style-type: none"> <li>• 2, 5, 6, 11, 58, 88, 119, 192, 195.</li> </ul>	
<b><u>Sampling with increment cores</u></b>	
<ul style="list-style-type: none"> <li>• High or very high-density wood.</li> </ul>	
<b><u>X-ray densitometry, for the identification of the growth ring boundary</u></b>	
<ul style="list-style-type: none"> <li>• No potential.</li> </ul>	

<b>Rubiaceae</b>	
<b><i>Calycophyllum spruceanum</i> (Benth.) Hook. F. ex K. Schum.</b>	
<b><u>Growth ring boundary distinctness</u></b>	
<ul style="list-style-type: none"> <li>• Poorly distinct.</li> </ul>	
<b><u>Anatomical boundary descriptor</u></b>	
<ul style="list-style-type: none"> <li>• Change in fiber wall thickness</li> </ul>	
<b><u>Description of growth rings and wood (IAWA hardwood codes):</u></b>	
<ul style="list-style-type: none"> <li>• 1, 5, 7, 11, 75, 119, 192, 195.</li> </ul>	
<b><u>Sampling with increment cores</u></b>	
<ul style="list-style-type: none"> <li>• High or very high-density wood.</li> </ul>	
<b><u>X-ray densitometry, for the identification of the growth ring boundary</u></b>	
<ul style="list-style-type: none"> <li>• Good potential</li> </ul>	

## Sapotaceae

### *Manilkara bidentata* (A. DC.) A. Chev.

#### Growth ring boundary distinctness

- Poorly distinct.

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

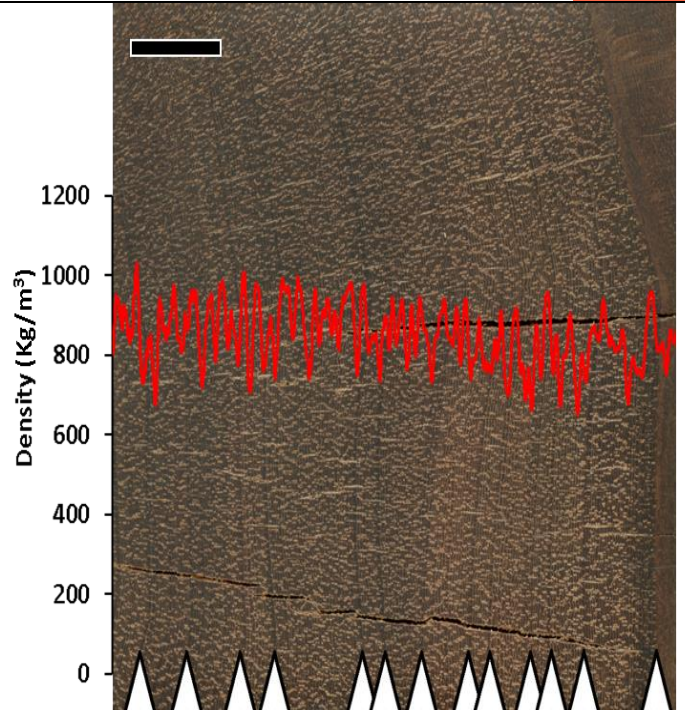
- 1, 5, 7, 9, 56, 86, 119, 192, 195.

#### Sampling with increment cores

- High or very high-density wood.

#### X-ray densitometry, for the identification of the growth ring boundary

- Regulate potential



## Vochysiaceae

### *Erismia uncinatum* Warm.

#### Growth ring boundary distinctness

- Poorly distinct.

#### Anatomical boundary descriptor

- Change in fiber wall thickness

#### Description of growth rings and wood (IAWA hardwood codes):

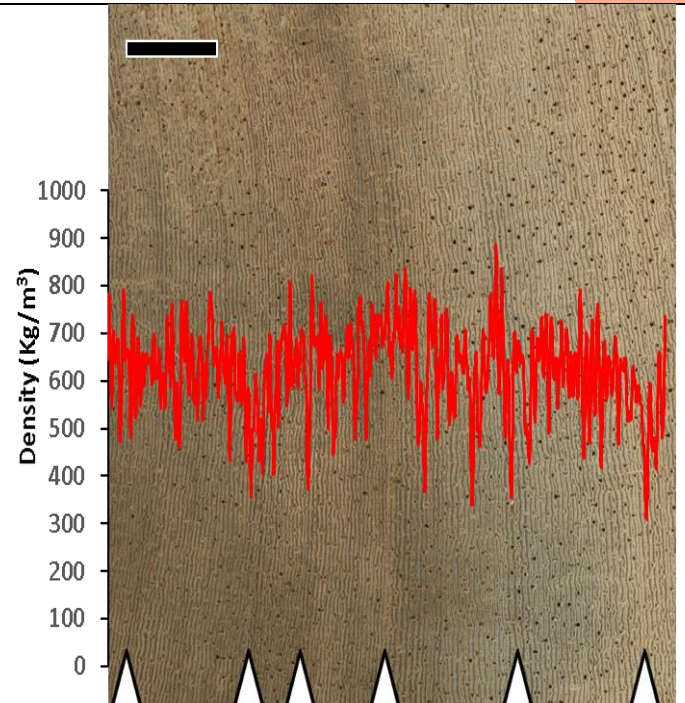
- 1, 5, 7, 9, 56, 85, 119, 192, 194.

#### Sampling with increment cores

- Low or medium-density wood

#### X-ray densitometry, for the identification of the growth ring boundary

- No potential.





## 4. LONG TERM RING WIDTH CHRONOLOGIES OF SIX SPECIES AND THEIR ASSOCIATIONS WITH CLIMATE AND ATMOSPHERIC VARIABLES IN SOUTHWESTERN AMAZON

### Abstract

Tropical humid forests are refuges for biodiversity and regulators of the local and global climate, however, they are fragile and vulnerable to climate change, anthropogenic actions of deforestation or pests., that's why it is necessary to know their dynamics, the longevity of their species and the relationships and influence of the climate on their growth, which is can be achieved with studies of growth rings. In this work, we evaluate the dendrochronological potential of six species in the tropical humid forest in the southern Amazon of Peru – *Jacaranda copaia*, *Myroxylon balsamum*, *Drypetes* sp., *Cedrela odorata*, *Swietenia macrophylla* and *Hura crepitans*, we verify the influence of the local climate and with the teleconnections of the Pacific and Atlantic oceans in the radial growth of the six species. The limits of the growth rings were characterized, where the anatomical descriptors showed that *J. copaia*, *M. balsamum* and *H. crepitans* were characterized by thick-walled posterior wood fiber and *Drypetes* sp., *C. odorata*, *S. macrophylla* were characterized by the marginal parenchyma, additionally *C. odorata* rings are semi-porous, six chronologies with good statistics were constructed, facilitated by the distinction and marking of the growth rings with chronologies of a little more than half a century to a little more than two and a half centuries the species *H. crepitans* with 274 years the most extensive chronology built in Peru to date. Regarding the influence of the local climate, our results show that there is no factor in the dominant radial growth of the species, except for *Drypetes* sp. and *C. odorata* that according to linear multiple regression precipitation had a strong influence, on teleconnections El Niño 3 (*J. copaia*), Southern Oscillation-SOI (*M. balsamum*), Eastern Asia-EA (*S. macrophylla*) and Tropical South Atlantic-TSA (*H. crepitans*). Our results reveal the department of Madre de Dios in the Peruvian Amazon as an area with great potential for studies of growth rings and long-lived species, and provide valuable information on the influence of local climate and teleconnections on the radial growth of species. This vegetation suffers the changes in the temperature of the oceans and therefore its future growth will be compromised according to the advance of the climatic change. In this way, protecting and guaranteeing the maintenance of this vegetation is of paramount importance to guarantee carbon storage and storage, essential for the reduction of climate change.

**Keywords:** Tropical humid forest, Dendrochronology, Dendroclimatology, Long-lived species, Tree-ring, El Niño events

### 4.1. Introduction

Tropical forests are the refuges of biodiversity, presenting countless direct and indirect ecosystem services, providing benefits to the world's human well-being (Aguirre et al., 2021; Edwards et al., 2019; Lakerveld et al., 2015) and evaporation and condensation on these forests are engines of global atmospheric circulation (Malhi et al., 2008). However, these tropical forests are under pressure, being susceptible to multiple disturbances, both environmental and anthropic, and may lead to a collapse in the future (Qin et al., 2017). For example, large-scale deforestation in recent decades has decreased the ability of these forests to remain a carbon sink in the long term (Exbrayat et al., 2017; Hubau et al., 2020; Pan et al., 2011; Quéré et al., 2018; Xu et al., 2021) and until the COVID-19 pandemic stimulated illegal logging of these forests (Brancalion et al., 2020; Golar et al., 2020).

Tropical forests are also affected by global environmental variables such as the influence of El Niño/La Niña and SST anomalies in the tropical Pacific and Atlantic, Atlantic Multidecadal Oscillation-AMO, Tropical Southern Atlantic-TSA, Western Hemisphere Warm Pool-WHWP (J. Marengo et al., 2018). Droughts or floods in the Amazon region are usually explained as a result of the combined effect of the anomalous circulation associated



with changes in the SST of the tropical Pacific and Atlantic oceans (Jimenez et al., 2019; Sulca et al., 2016), these variables global environmental factors influencing the growth of native tropical trees. These large-scale droughts and El Niño events are intensifying both in terms of intensity and frequency, generating direct implications for the vulnerability of tropical forests and long-term carbon stocks (Wigneron et al., 2020). For example, during El Niño-influenced years the growth of tropical trees that have strong positive responses to precipitation was stimulated (Zuidema et al., 2022). On the other hand, tropical forests that dominate the decadal variability of terrestrial carbon uptake are more effective in mitigating climate change (Zhang et al., 2018). However, the tropical forest carbon sink has peaked, is saturated and is in continuous decline (Hubau et al., 2020).

One way to evaluate the influence of local climate and global environmental variables in tropical forests is through the growth rings of trees, these studies on tropical forests have existed for more than 100 years and the annuality of the growth rings of tropical species (Worbes, 2002). Using it to know the growth past, know what the relationships of growth with the environment are and to reconstruct the climate (Mariaux, 1967; Détienne, 1989; Layme, Ferrero, Palacios, et al., 2018; Aragão et al., 2022). However, these studies of tree growth rings are still scarce in tropical forests, given that there are more than 40,000 species of tropical trees in the world and in South America, for example, 6,727 tree species are reported (Cardoso et al., 2017). But studies show us that only 220 to 230 species of tropical trees have been confirmed in all continents and climatic zones with annual formation (Brienen et al., 2016; Schöngart et al., 2017) with a gap in the Knowledge very broad and need for shortening.

Added to this is the fact that tropical forest trees grow on average twice as fast compared to trees in temperate and boreal forests, and live significantly less, with average growth between 186 years (Locosselli et al., 2020) and a maximum of 500-600 years (Brienen et al., 2016; Schöngart et al., 2017). Despite this, little is known about the growth dynamics of these forests and long-term studies capable of understanding the climatic past to predict their future are still scarce (Locosselli et al., 2020). Studying this biodiversity of long-lived species, the types of growth strategies in several different tropical species gives us an idea of the growth of the vegetation to interpret which are strategies to survive the environmental pressures that this type of vegetation suffers is vital to help the conservation of tropical forests (Rozendaal et al., 2020; Zuidema et al., 2020).

Tropical forest species, according to their functional strategies, face environmental variation in different ways, depending on their resilience capacity (Singh and Fetzer, 2022; Staal et al., 2018). The availability of water and high temperatures are environmental factors that can promote these different responses, limiting the increase in the number of groups of species (Malhi et al., 2008). For example, climate change potentially increases mortality, likely due to climate-induced physiological stress and its interactions (Zhou et al., 2013). Dendroclimatology studies allow the identification of the most affected species and the search for conservation solutions that reduce this impact (Mendivelso et al., 2014).

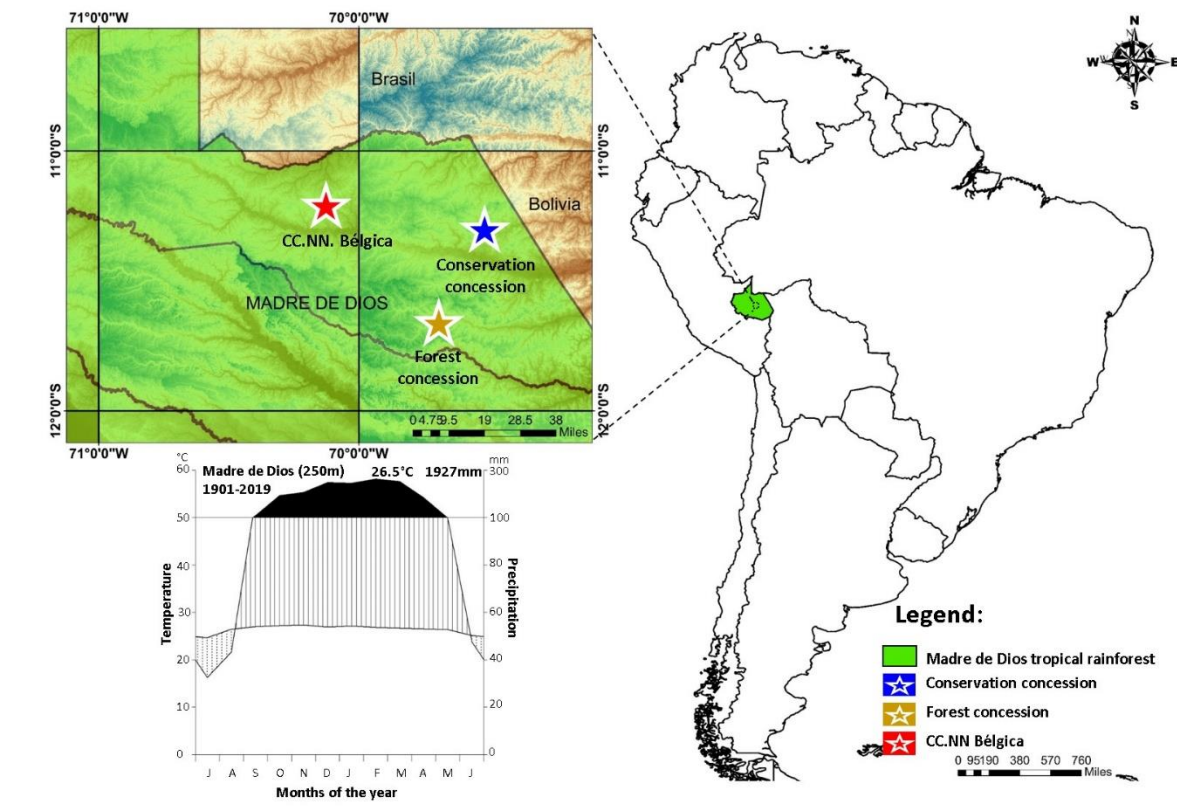
The department of Madre de Dios, located in southeastern Peru on the triple border with Brazil and Bolivia, has a Tropical Humid Forest that is an important ecoregion for global conservation, considered a biodiversity hotspot (Myers et al., 2000; Olson and Dinerstein, 2002). However, in the 1980s the Peruvian government promoted agricultural expansion in the Peruvian Amazon (Alvarez and Naughton-Treves, 2003; Puzzi et al., 2019). Madre de Dios has also experienced changes in land cover due to various anthropic actions such as road paving, deforestation, migratory agriculture, urban expansion and, mainly in the last two decades, gold mining, which has become an important factor in land degradation and heavy metal contamination, which is bringing serious consequences for the conservation of biodiversity in this part of Peru (Markham and Sangermano, 2018; Sánchez-Cuervo et al., 2020).

It is because of that that we evaluated the dendrochronological potential of six species in the Amazon of Madre de Dios. We characterize the limits of the growth rings, then we construct the chronology, of the species and determine the climatic response of the radial growth of the species with precipitation and temperature (local) and with the teleconnections of the Pacific and Atlantic oceans (large-scale). The annual growth rings of the six species studied and their longevity should be useful to reconstruct the past climate in southeastern Peru through dendroclimatology.

## 4.2. Methodology

### 4.2.1. Study area

We collected samples of trees located in the tropical humid forest in the eastern Amazon of Peru, in the region of Madre de Dios "MDD" that is located in the triple border of the country, bordering Acre (Brazil) and Pando (Bolivia). (Fig. 1). MDD is considered the biodiversity capital of Peru, due to its high levels of biological diversity (Foster et al., 1994), where the species of *Cedrela odorata* L., *Cedrela fissilis* Vell., *Cedrela longipetiolulata* Harms (SERFOR, 2020), *Swietenia macrophylla* King, *Bertholletia excelsa* Bonpl., among other species of economic and ecological interest. However, despite being a department of interest for world conservation (Myers et al., 2000), there are problems such as illegal logging, land use ownership and mainly the deforestation as a result of gold exploration (Puzzi et al., 2019; Román et al., 2015). According to the Köppen classification, it has three types of climate: Tropical humid (Af), Tropical monsoon (Am), and Tropical dry forest (Aw), where the study covered species in (Am and Aw) (Köppen, 1948); the average annual precipitation is around 2400 to 2600 mm and there is a dry season of 3 months between June and August with an average monthly rainfall of less than 100 mm and an average annual temperature of 24 to 25°C (Araujo et al., 2011), with an average annual relative humidity of 84.2% (Sánchez-Cuervo et al., 2020), the soils are of Pleistocene or Holocene origin and are classified as Ultisol (Quesada et al., 2010).



**Fig. 1.** Location of the study area, in the Madre de Dios region (green area). The study areas are marked with stars of different colors corresponding to the collection sites of the six species studied. In addition, climatic diagrams are provided for the period 1901 - 2019 (Walter and Lieth, 1960), where the gray lines show mean monthly temperatures, the black lines the mean precipitation and the dotted area show with indicating the dry season (precipitation < temperature) and the black area rainy season (>100 mm month<sup>-1</sup>).

#### 4.2.2. Sample collection and preparation

Discs of six tree species were cut at the top level of the first log (6 m) of felled trees, to minimize the influence of the roots (Granato, Stahle, et al., 2019). The samples were collected for trees of *J. copaia*, *M. balsamum*, *Drypetes* sp., *H. crepitans*, *S. macrophylla* and *C. odorata*, 25, 26, 24, 11, 29 and 19 discs respectively (For more details see Appendix Table A1). Additionally to this collection, 18 *S. macrophylla* trees and 29 *C. odorata* trees with four radii per tree were collected by 5.15 mm increment bores (Haglof type). *Jacaranda copaia* (Aubl.) D. Don. (Bignoniaceae), *Myroxylon balsamum* (L.) Harms (Fabaceae), *Drypetes* sp. (Putranjivaceae) and *Hura crepitans* L. (Euphorbiaceae) were collected in the Forest Management Unit "UMF" of the company Corporación Forestal Tres Fronteras S.R.L. *Swietenia macrophylla* King. and *Cedrela odorata* L. both from the Meliaceae family were collected in two places, the conservation concession "Rodal Semillero Tahuamanu", and the forest concession of the Native Community of Bélgica with FSC forest certification.

Four radii/samples (10 cm width and 5 cm thickness) from each disc were cut and transported to the Wood Anatomy and Tree-Ring Laboratory, ESALQ, University of Sao Paulo (LAIM/ESALQ/USP) to be air dried. The radial samples were polished gradually with sandpaper (from 80 to 600 grains inch<sup>-2</sup>) until tree rings were visible. Each cross-section was scanned at 1200 dpi resolution with an Epson Expression 10000XL scanner in ".tif" format.

### 4.2.3. Tree-ring chronologies

The growth rings were identified according to Brienen et al., (2016) and IAWA (1989), and a visual cross between the samples was carried out later, the series of annual ring width (RW) in the synchronized samples was measured from the cortex to the pith with a resolution of 0.01 mm using CDendro and Coorecorder® software (Cybis Electronic, 2013). The COFECHA software (Holmes, 1983), was used for quality control of tree ring width measurements (Brienen and Zuidema, 2005; Locosselli et al., 2019). Species chronology was constructed using ARSTAN software (Cook, 1985; Holmes, 1983). We performed a cubic spline with a 50% frequency response cutoff and 32 years of segment length, to eliminate the growth trends of the correctly dated series. We calculated a series of dendrochronological statistics to show us the quality of the chronologies, the intercorrelation between the growth ring width series for each tree and between trees of the same species using the COFECHA software, average correlations between standardized series ( $\bar{R}$ ) and the express population signal (EPS) using the ARSTAN software. For the calculations of climate-growth correlations, we assume that an EPS equal to or greater than 0.80 is adequate for tropical species (Mendivelso et al., 2014; Menezes et al., 2022).

### 4.2.4. Dendroclimatic analysis

To quantify the associations between the radial growth of the six species studied and the climate, correlation functions were used (Blasing et al., 1984). The climatic variables were compared with the interannual variations of the radial growth during a common period between the records: 1901-2019 for the precipitation and monthly local temperature; 1950-2019, 1970-2019 for the analysis of total annual precipitation and precipitation in the months with the highest correlation, 1952-2019 for El Niño (1.2, 3, 3.4, 4), Southern Oscillation-SOI, Atlantic Multidecadal Oscillation- AMO, Oceanic Niño-ONI, Tropical Northern Atlantic-TNA, Tropical Southern Atlantic-TSA, North Tropical Atlantic-NTA, Eastern Asia-EA, Western Hemisphere Warm Pool-WHWP.

As the growth in a given year could be influenced by the climatic conditions during the previous year, the comparisons extended from January in the previous growing season to December during the current growth, a temporary window of 16 months (Layme, Ferrero, Palacios-Lazaro, et al., 2018; López et al., 2022). To evaluate which climatic factors and which months were determining factors in the radial growth of the six species, multiple linear regression models were determined to generate a linear model in which the value of the dependent variable (tree growth) was determined based on a set of independent variables (climatic factors), adjusted R<sup>2</sup> was used to estimate the predictive strength of the regression model (Locosselli et al., 2013; Menezes et al., 2022; Nogueira et al., 2019). Also, we evaluated the influence of sea surface temperature (SST) with the master chronology through HadISST1 1.0° spatial correlations, to identify which ocean regions have an effect on local tree growth using the database KNMI-Climate Explorer <https://climexp.knmi.nl/start.cgi> (Trouet and Van Oldenborgh, 2013). Monthly analyzes were performed, but moving averages of up to 5 months were also performed, to consider the possible delays in the radial growth responses of the trees and autocorrelations of the data, we constructed spatial correlation maps for the six species studied (Aragão et al., 2019; Land et al., 2017; Menezes et al., 2022).

To carry out the analysis with the local, total annual precipitation and in the months of greatest correlation, a climatic reconstruction had to be carried out because the precipitation and temperature records of the study area provided by the National Service of Meteorology and Hydrology of Peru – SENAMHI was from 1998 to the present and contained a series of gaps in its data, it was decided to reconstruct the local precipitation with the

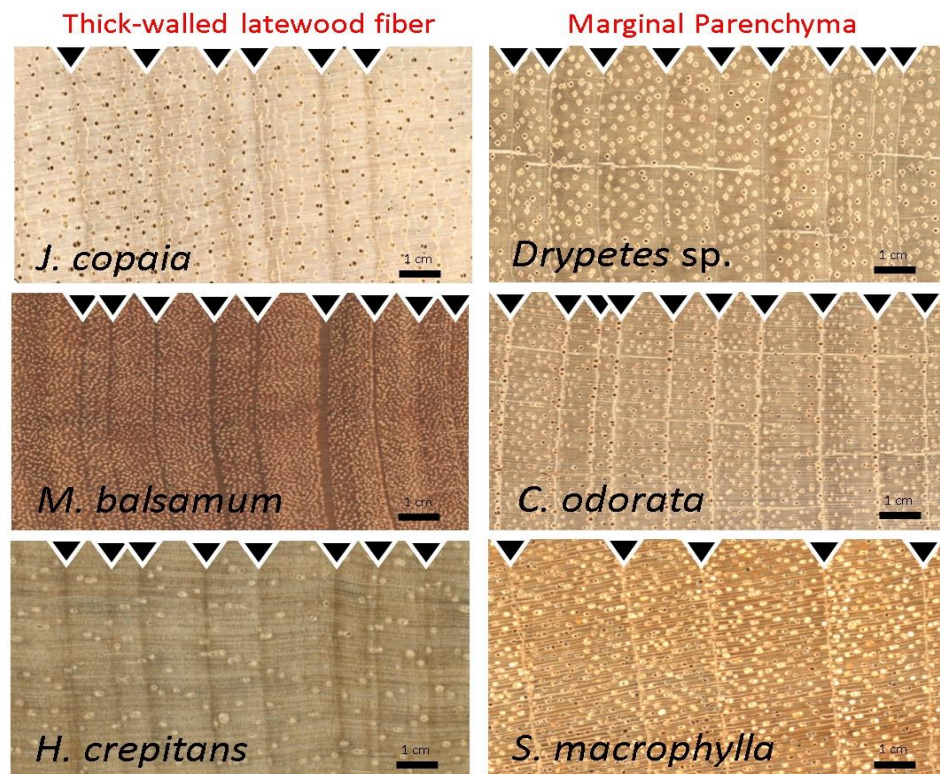
meteorological stations closest to the study area with data from the National Water Agency (ANA) of Brazil (<http://www.snirh.gov.br/hidroweb/apresentacao>) from the states of Acre and Rondonia border near the study area, in addition to data from the CRU TS v.4 (Harris et al., 2013) and of the city of Puerto Maldonado, said reconstruction included the stations of CRU, Rondonia, Brasileia, Rio Branco and Puerto Maldonado, said reconstruction was also validated through the KNMI-Climate Explorer <https://climexp.knmi.nl/start.cgi> (Trouet and Van Oldenborgh, 2013) (see appendix Fig. B2). For analysis with El Niño, SOI, AMO, ONI, TNA, TSA, NTA, EA and WHWP were obtained from the North American Monitoring Agency (NOAA; <https://psl.noaa.gov/data/climateindices/list/>). Proxy-climate analyzes (correlation) and multiple linear regression models were performed using RStudio software (RStudio Team, 2015) using the treeclim statistical package (Zang and Biondi, 2015).

### 4.3. Results

#### 4.3.1. Characterization of ring boundaries and chronologies

The growth rings of the six species studied were visible to the naked eye or with a 10x magnification loupe. Three species had thick-walled latewood fiber growth rings and differences in vessel diameters (*J. copaia*, *M. balsamum*, *H. crepitans*); three had growth rings delimited by the marginal parenchyma (*Drypetes* sp., *S. macrophylla*) and additionally presented a semicircular porosity (*C. odorata*) (Fig. 2). The six species presented false rings (intra-annual growth zones). For *J. copaia*, false rings were slightly marked by variations in their discontinuous density, in addition, the rings near the pith were poorly marked in all the trees *M. balsamum* some areas in the heartwood were poorly marked and made it difficult to identify as it is dark red wood and the rings due to variation in color density were also dark, in the case of *Drypetes* sp., *C. odorata* and *S. macrophylla* they presented marginal parenchyma divisions, in addition to *Drypetes* sp., showed confluent parenchyma with a tendency to form discontinuous lines (false continuous growth bands) mainly in the first two decades of tree life. When we analyze the growth rings, we distinguish traumatic resin channels in *C. odorata* and *S. macrophylla* repeatedly associated with their limits.

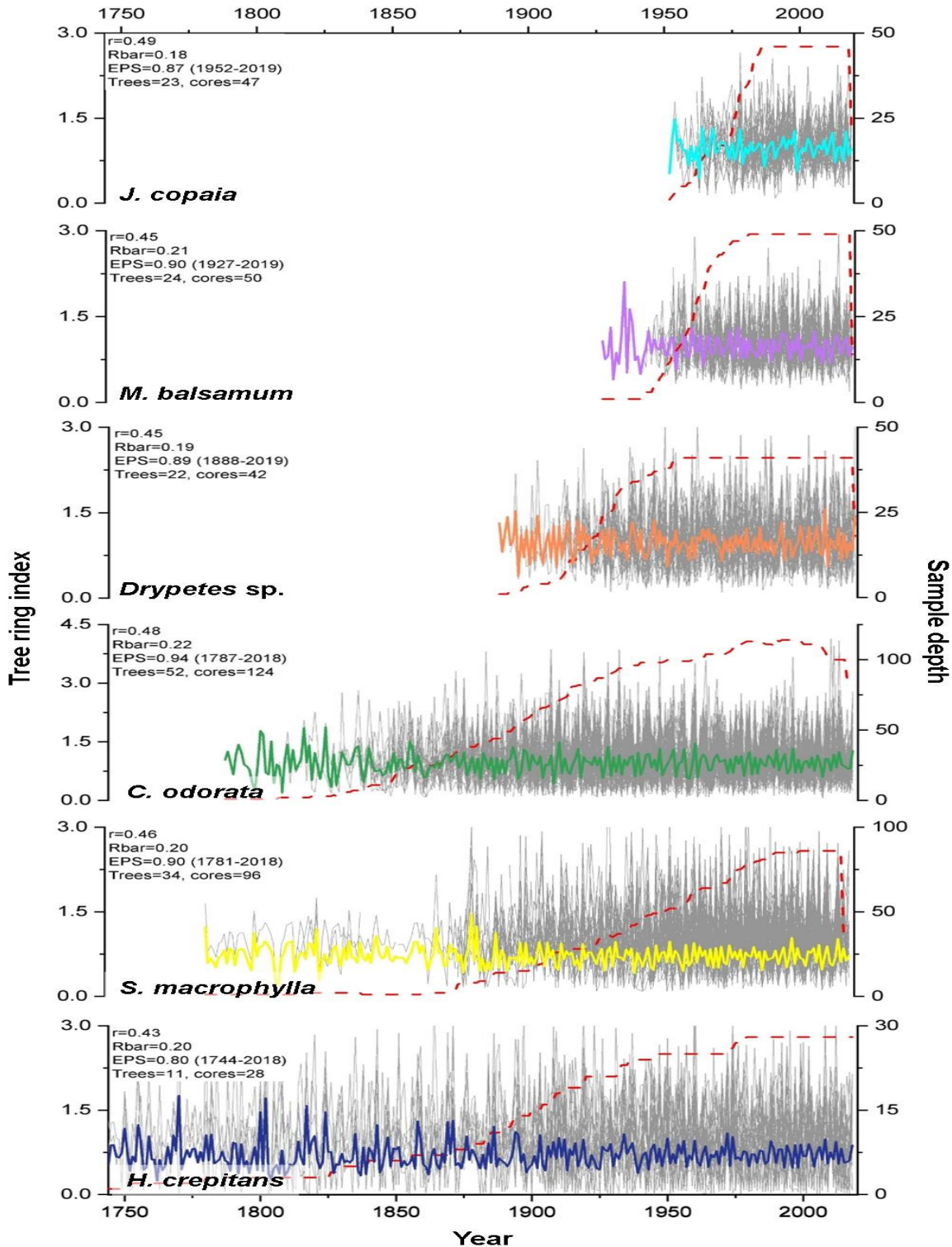
The chronology length is 67, 92, 131, 231, 237 and 274 years for *J. copaia*, *M. balsamum*, *Drypetes* sp., *C. odorata*, *S. macrophylla* and *H. crepitans*, respectively (Table 1). Intercorrelations ranged from 0.43 to 0.49, above the critical correlation of 0.3281 with a confidence level of 99% established by COFECHA. While the Rbar varied from 0.18 to 0.22 and the EPS from 0.80 to 0.94 (Fig. 3).



**Fig. 2.** Macroscopic cross-sectional images for species with ring boundaries marked by fiber wall thickness and marginal parenchyma from the tropical humid forest Southern Amazon región. Ring boundaries are marked by black triangles.

**Table 1.** Chronologies statistics for six species from Southern Amazon región. COR = average of the correlation between the series. Rbar = inter-series between the correlation trees. EPS = express population signal. Minimum and maximum age. Span = Start and end year of the chronology.

Species	# (series)	Tres	COR	Rbar	EPS	Age range (mim-max)	Span
<i>Jacaranda copaia</i>	23 (47)		0.49	0.18	0.87	24-67	1952-2019
<i>Myroxylon balsamum</i>	24 (50)		0.45	0.21	0.90	57-92	1927-2019
<i>Drypetes sp.</i>	22 (42)		0.45	0.19	0.89	64-131	1888-2019
<i>Cedrela odorata</i>	52 (124)		0.48	0.22	0.94	37-231	1787-2018
<i>Swietenia macrophylla</i>	34 (96)		0.46	0.20	0.90	32-237	1781-2018
<i>Hura crepitans</i>	11 (28)		0.43	0.20	0.80	44-274	1744-2018

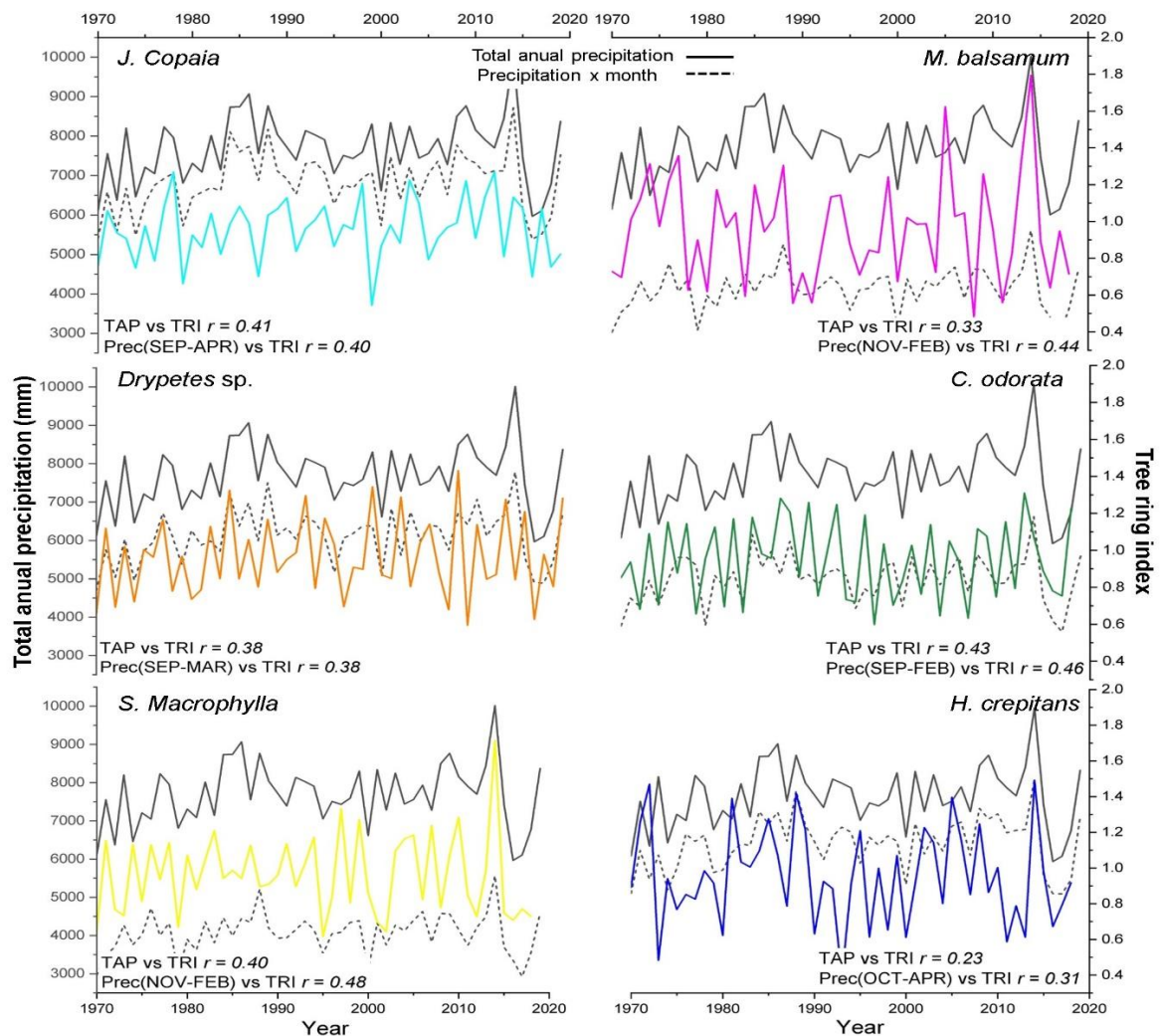


**Fig. 3.** Dated single ring width index series (gray lines); medium index standard series (colored lines) and depth of samples (red dashed lines).

#### 4.3.2. Climate-tree growth relationship

We found a significant positive relationship between the chronologies of the growth rings of the six species and the total annual rainfall *J. copaia* ( $r = 0.41$ ;  $p < 0.0001$ ), *M. balsamum* ( $r = 0.33$ ;  $p < 0.0001$ ), *Drypetes* sp. ( $r$

= 0.38;  $p < 0.0001$ ), *C. odorata* ( $r = 0.43$ ;  $p < 0.0001$ ), *S. macrophylla* ( $r = 0.40$ ;  $p < 0.0001$ ), and *H. crepitans* ( $r = 0.23$ ;  $p < 0.0001$ ) (Fig. 4). The reconstruction of the local precipitation data during the months with the highest correlations with the growth of the trees of the six species were compared with the interannual growth variations for the period from 1970 to 2019, the six species being positively related to the precipitation during the season current growing season for *J. copaia* (September to April;  $r = 0.40$ ;  $p < 0.0001$ ), *M. balsamum* (November to February;  $r = 0.44$ ;  $p < 0.0001$ ), *Drypetes* sp. (September to March;  $r = 0.38$ ;  $p < 0.0001$ ), *C. odorata* (September to February;  $r = 0.46$ ;  $p < 0.0001$ ), *S. macrophylla* (November to February;  $r = 0.48$ ;  $p < 0.0001$ ) and *H. crepitans* (October to April;  $r = 0.31$ ;  $p < 0.0001$ ) (Fig. 4), showing that the growth of the six species is influenced by rainfall in the rainy season in the tropical humid forest of Madre de Dios.

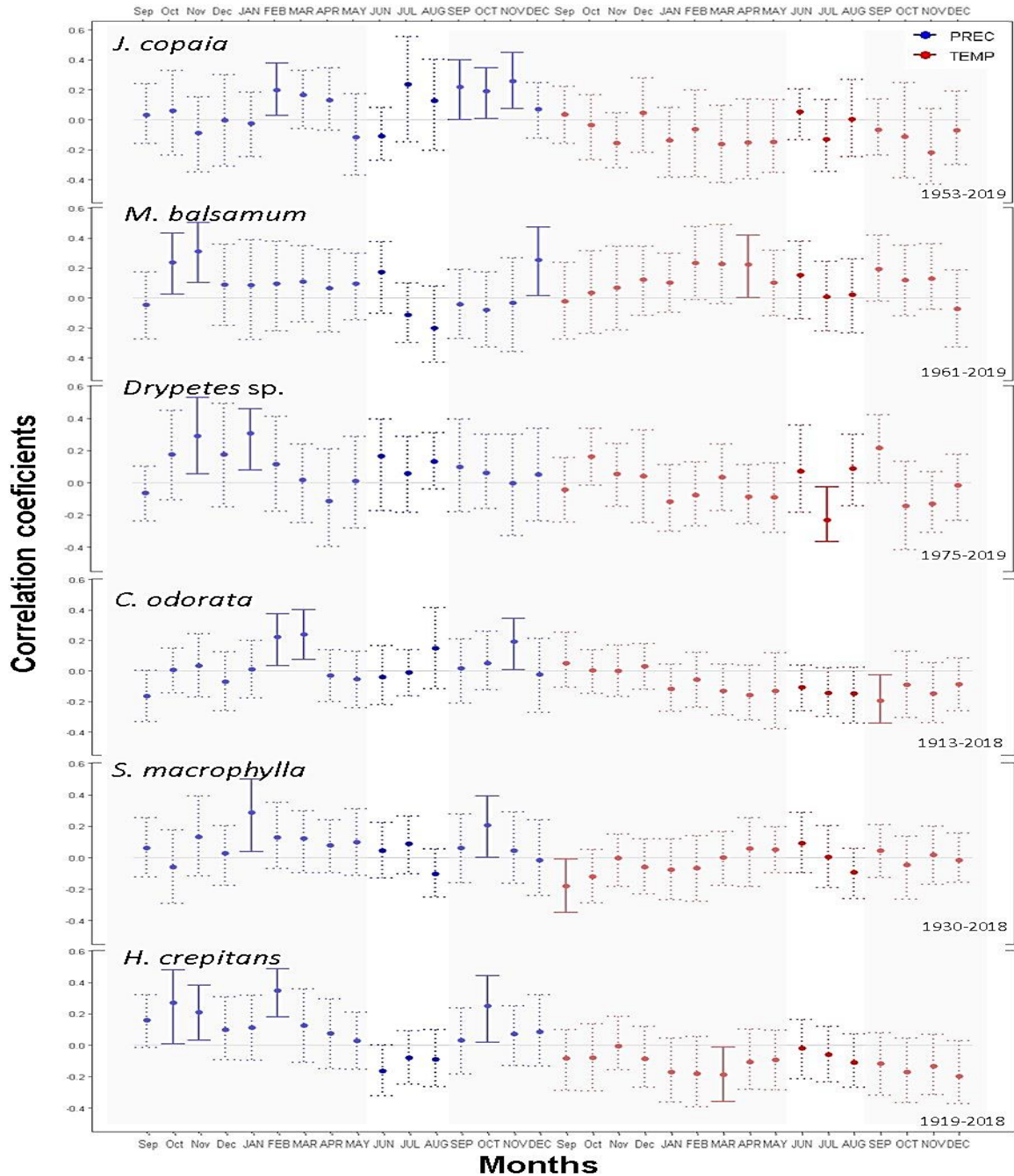


**Fig. 4.** Temporal relationship between standard chronologies and total annual precipitation for six species in the Southern Amazon region. Tree ring width chronology (colored lines), total annual precipitation = TAP (black line), precipitation by months = PREC (dashed line), tree ring index = TRI. Pearson correlations  $r$  provided for the years 1970–2019.

The correlation analysis between the monthly precipitation and the chronologies of the six species showed a positive and significant influence on the rainy season *J. copaia* February, September, October and November (current year);  $p < 0.0001$ , *M. balsamum* October and November (previous year) and December (current year);  $p < 0.0001$ , *Drypetes* sp. November (previous year) and January (current year);  $p < 0.0001$ , *C. odorata* February, March and November (current year);  $p < 0.0001$ , *S. macrophylla* January and October (current year);  $p < 0.0001$  and



*H. crepitans* October and November (previous year) and February and October (current year);  $p < 0.0001$  (Fig. 5). The analysis of the monthly temperature and the chronologies of the six species showed a negative and significant influence on *Drypetes* sp. July (current year);  $p < 0.0001$ , *C. odorata* September (current year);  $p < 0.0001$ , *S. macrophylla* September (previous year);  $p < 0.0001$  and *H. crepitans* March (current year);  $p < 0.0001$ . The radial growths of the six species are positively associated with the precipitation in the rainy season of the previous and current year but inversely with the temperature showing significant negative relationships, however, *M. balsamum* was the only species that presented a significant correlation with the temperature in April (current year) and finally, *J. copaia* showed no correlation with temperature (Fig. 5). Using multiple linear regressions, we identified that the rainfall in March, April, August, September, October, November and December (previous year) and January, March, April, May, August, October and December (current year) were the months strongest determinants of growth (Appendix Table A3).



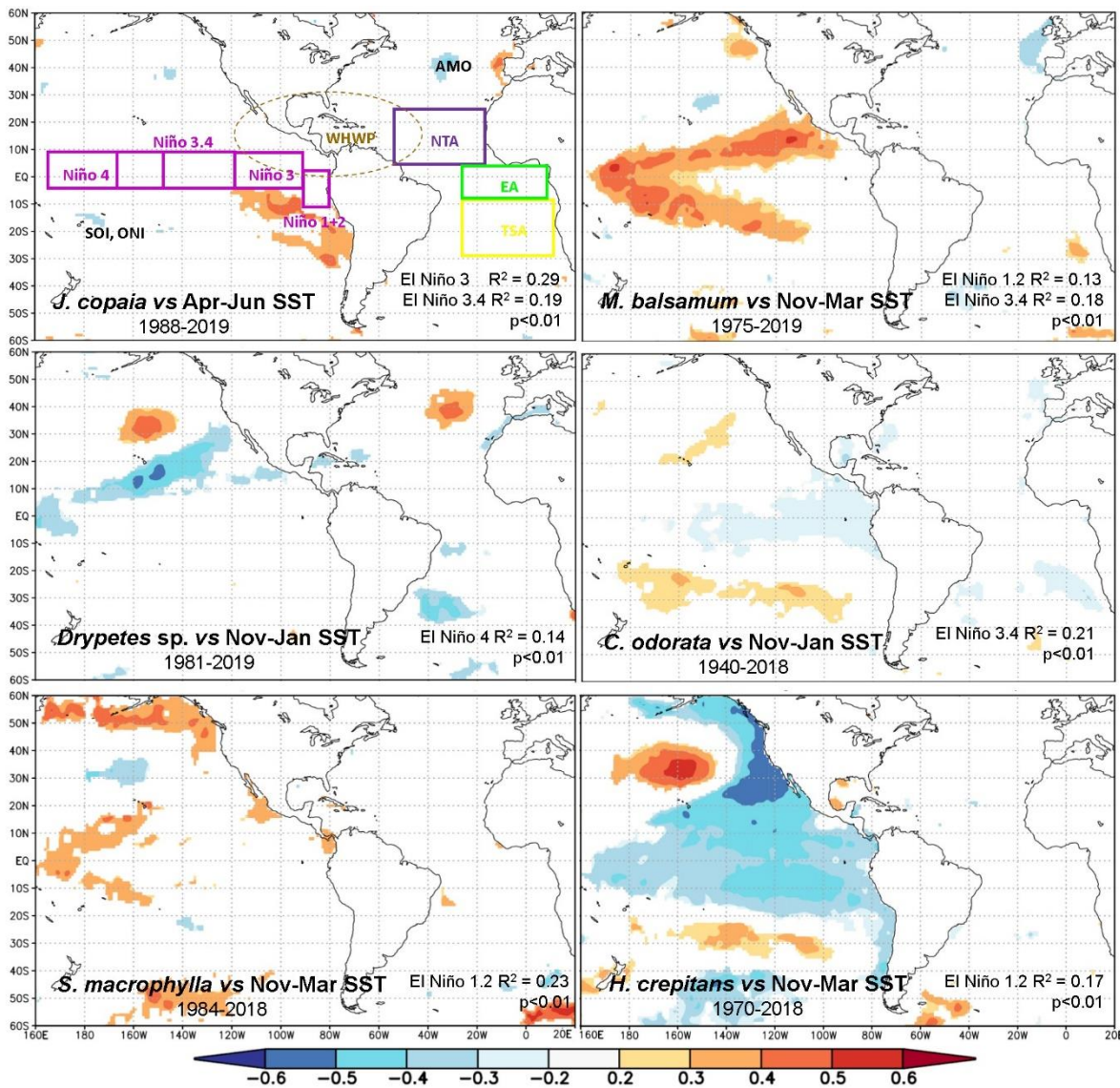
**Fig. 5.** Pearson's correlation coefficient for the relationship between the ring-width indices and the climatic variables (temperature and precipitation), the period of the analysis is in the lower right part of each species. The light gray vertical box includes the rainy months in the study area. The abbreviated months of the previous year (lowercase) and those of the current year (uppercase). A significance level of 0.05.

### 4.3.3. Atmospheric sensitivity

A global spatial correlation pattern was observed between tree ring chronologies and sea surface temperature (SST) anomalies (Fig. 6).

The correlation maps of the chronologies of the six studied species with the global sea surface temperature (SST) showed that the Equatorial Pacific Ocean affects the growth of the studied species, being the main area of the oceanic (Fig. 6). The species *M. balsamum* and *H. crepitans* presented higher correlation coefficients in

larger areas of the SSTs of the tropical Pacific Ocean (Fig. 6), and for the species *J. copaia* and *C. odorata* the correlations were weaker (Fig. 6). In general, the correlations with the El Niño index corroborated the correlation maps of the six species, presenting negative correlations for the six species. The El Niño index was a factor that significantly affected tree growth observed in the multiple linear regressions (Fig. 6; Table 2). There were also relations with SOI, AMO, ONI, TSA, EA, and WHWP confirmed by multiple linear regression analyzes (see Appendix Table A4).



**Fig. 6.** Spatial correlations between the chronologies of the growth ring width index and the monthly sea surface temperatures (SST) in the Pacific and Atlantic oceans of the 6 species in the eastern Amazon of Peru. The 5-month periods with the highest correlations are shown. Colors indicate Pearson's correlation coefficients. The spatial correlation map of the species *J. copaia* shows the areas of occurrence of SST anomalies: El Niño, Southern Oscillation-SOI, Atlantic Multidecadal Oscillation-AMO, Tropical Southern Atlantic-TSA, North Tropical Atlantic-NTA, Eastern Asia-EA and Western Hemisphere Warm Pool-WHWP. The analyses were performed using the KNMI Climate Explorer (<http://climexp.knmi.nl>).

**Table 2.** Result of the multiple regression analysis for the chronology of each species (dependent variable) and the values of the global (El Niño) environmental variables monthly. R<sup>2</sup> = coefficient of determination.

Species	Variables	b±SE	R <sup>2</sup>	Species	Variables	b±SE	R <sup>2</sup>	
<i>J. copata</i>	El Niño 3		0.29	<i>C. odorata</i>	El Niño 3.4		0.21	
	Intercept	3.8813 ± 1.4001 **			Intercept	3.9208 ± 1.8936 *		
	El Niño 3 FEB	0.1963 ± 0.0567 ***			El Niño 3.4 AUG	-0.2452 ± 0.0983*		
	El Niño 3 APR	-0.2061 ± 0.0523 ***			El Niño 3.4 OCT	0.4601 ± 0.1595**		
	El Niño 3 feb	-0.2792 ± 0.0828 **			El Niño 3.4 NOV	-0.2962 ± 0.1301*		
	El Niño 3 mar	0.3095 ± 0.1004 **			El Niño 3.4 feb	-0.0718 ± 0.0331*		
	El Niño 3 aug	-0.1380 ± 0.0416 **			El Niño 3.4 jul	0.2311 ± 0.0998*		
	El Niño 3.4		0.19		El Niño 3.4 sep	-0.1927 ± 0.0819*		
	Intercept	6.1341 ± 1.4643 ***						
	El Niño 3.4 JAN	0.3006 ± 0.0824 ***						
El Niño 3.4 MAR	-0.3499 ± 0.0951 ***							
El Niño 3.4 aug	-0.1351 ± 0.0633 *							
<i>M. balsamum</i>	El Niño 1.2		0.13	<i>S. macrophylla</i>	El Niño 1.2		0.23	
	Intercept	1.2068 ± 0.5147 *			Intercept	1.1903 ± 0.5009 *		
	El Niño 1.2 APR	-0.1268 ± 0.0453 **			El Niño 1.2 jul	-0.2381 ± 0.0625 ***		
	El Niño 1.2 MAY	0.1233 ± 0.0395 **			El Niño 1.2 aug	0.2529 ± 0.0771**		
	El Niño 3.4		0.18		El Niño 1.2 nov	0.2265 ± 0.0944 *		
	Intercept	-2.0129 ± 0.8930 *			El Niño 1.2 dec	-0.2293 ± 0.0907*		
El Niño 3.4 FEB	-0.2877 ± 0.0887 **							
El Niño 3.4 MAR	0.3926 ± 0.1085 ***							
<i>Drypetes</i> sp.	El Niño 4		0.14	<i>H. crepitans</i>	El Niño 1.2		0.17	
	Intercept	1.0339 ± 0.0493 ***			Intercept	1.4283 ± 0.5075 **		
	El Niño 4 NOV	0.2591 ± 0.1272 *			El Niño 1.2 may	0.0824 ± 0.0298 **		
El Niño 4 DEC	-0.2633 ± 0.1273 *		El Niño 1.2 aug	-0.1189 ± 0.0327 ***				

b = multiple linear regression coefficient, SE = standard error, significance levels are indicated as (\* p<0.05; \*\* p<0.01 and \*\*\* p<0.001). acronym for months with lowercase letters (previous year), an acronym for months with capital letters (current year). Acronym for months: uppercase = current year, lowercase = previous year.

#### 4.4. Discussion

This is one of the first evaluations of dendrochronological potential in the tropical moist forest of the department of Madre de Dios in the eastern Amazon of Peru. The six species studied form annual rings and we found good delimitation of the growth rings, acceptable statistics and the variations in radial growth of the species are associated with precipitation and with anomalies in sea surface temperature (SST), we highlight a strong influence of the El Niño phenomenon on our species. Several investigations were carried out on the Bolivian Amazon (Pando) border with Peru (Madre de Dios) where they not only showed the annuality and potential of the species, but also became a reference in dendrochronology studies in the tropics (Brienen and Zuidema, 2005; Brienen et al., 2006; Brienen and Zuidema, 2006), and since the climate and diversity of forest species in the department of Madre de Dios are similar, and with the results, we confirm the potential of these species for dendroclimatological studies in these tropical forests.

##### 4.4.1. Tree-ring boundaries and dendrochronology potentiality

We observed different growth ring boundary types for the six species (Fichtler and Worbes, 2012; Schöngart et al., 2017), the visibility and type of growth rings agree with descriptions from other studies of the same

species or other species of the same genus (Dünisch et al., 2002; López et al., 2012; Portal et al., 2020; Menezes et al., 2022; Rebollar et al., 1993; Lisi et al., 2008). Of the six species studied, three species (*M. balsamum*, *Drypetes* sp. and *H. crepitans*) the construction of their chronologies are presented for the first time, since in other investigations their potential was only described based on the marking of the limits of the growth rings (Lisi et al., 2008; López et al., 2012; Schöngart et al., 2017). For the species *J. copaia* there was a chronology (Portal et al., 2020) and with our study, we corroborate its potential, finally, although *C. odorata* and *S. macrophylla* are species widely studied in tropical dendrochronology, it is important to continue studying them because they are threatened species and are found in Appendix II of the Convention on International Trade in Endangered Species of Fauna and Wild Flora (CITES, 2020).

#### 4.4.2. Chronology building

It was important to carry out a correct anatomical characterization of the limits of the growth rings and the false rings of the six species that helped in the construction of the chronologies (Schöngart et al., 2017; Worbes and Fichtler, 2010), the characteristics of false rings in tropical species have also been reported in other investigations (Brienen et al., 2016; Brienen Zuidema, 2005; Dünisch et al., 2002), these problems are common and must be taken into account, they can result from occasional short-duration rainy (dry season) and drought (rainy season) events that are common in humid tropical forests (Schöngart et al., 2002; Worbes, 1995).

The statistics of the chronologies that we used to evaluate the quality of the growth ring data indicate that the trees of the six species have a common signal in the growth trees (Brienen and Zuidema, 2005; López et al., 2022), where *J. copaia* presented higher correlations between series within the tree (0.49). It is a very widespread pioneer tree in the Peruvian Amazon with fast growth and has a deciduous leaf habit (Maués et al., 2008), this phenological characteristic associated with the anatomy of the limits of the growth rings helps to explain their correlation between the series (Stahle et al., 1999). Of all the species studied, the species *C. odorata* presented the highest correlation between series between the trees (0.22) and expressed population signal (0.94), although the EPS threshold for non-tropical species is 0.85 (Wigley et al., 1984). We highlight that all the species presented an expressed population signal  $\geq 0.80$  being well reproduced, which demonstrates the potential of the six tropical species for studies in dendroclimatology (Mendivelso et al., 2014; Venegas-González et al., 2018).

The diversity of species studied, with different phenological behaviors (Reynel et al., 2003), characteristics of the growth rings (Marcelo-Peña et al., 2020), basic density (low to very high) of the wood (Acevedo and Kikata, 1994), dendrochronological statistics, we observed that they behave differently, using different functional strategies to face climate change (Singh and Fetzer, 2022; Staal et al., 2018).

#### 4.4.3. Growth and climate correlations

The six species studied presented variations in their radial growth determined by local precipitation, correlating in a significantly positive way during the rainy season both in the previous year and in the current year of growth, this limitation of growth is due to the availability of water during the wet season in tropical forests, is consistent with our findings (Brienen and Zuidema, 2005; Pereira et al., 2018; Zuidema et al., 2022). Where variations

in precipitation influence radial growth patterns of tropical trees and induce the formation of annual rings (Brienen et al., 2016; Schöngart et al., 2007; Worbes and Schöngart, 2019).

The phenology of the six species studied helps to understand how tropical trees cope with the dry season, for example, the species *J. copaia*, *M. balsamum*, *C. odorata*, *S. macrophylla* and *H. crepitans* have their flowering in the dry season and fruiting in the middle or at the end of the dry season and the beginning of the rainy season (Reynel et al., 2003). In addition, the species *J. copaia*, *C. odorata*, *S. macrophyllas* and *H. crepitans* use a strategy of adaptation to the dry season through the fall of its leaves (Kallarackal et al., 2013; Reynel et al., 2003), this physiological strategy of acting against water stress and reducing the radial growth of trees in the dry season *seca* is frequent in tropical forests (Angoboy et al., 2021; Fétéké et al., 2016; Millar et al., 2007).

#### 4.4.4. SST teleconnections

The climate in South America is strongly dependent on SST patterns in the Pacific and Atlantic (Haylock et al., 2006; Nobre and Shukla, 1996) and any climate change will have collateral effects on vegetation (Pereira et al., 2017). For example SSTs anomalies and asymmetric wind stress relative to the equator is the dominant mode of interannual variability in large-scale anomalous rainfall patterns over South America, where the maximum precipitation point is in southern Amazonia It occurs in the austral summer due to the southern migration of the Intertropical Convergence Zone, which is the physical cause (Marengo et al., 2018; Nobre and Shukla, 1996). In addition, the droughts and floods in the Amazon can be explained as a result of the combined effect of the anomalous circulation associated with changes in the SST of the tropical Pacific and Atlantic oceans (Marengo and Espinoza, 2016) for the aforementioned that the radial growth of the six species studied was also positively and/or negatively influenced by Pacific and Atlantic Ocean SST anomalies. The influences of SSTs on the growth of tropical species in South America have already been shown in other studies (Aragão et al., 2022; Granato et al., 2019; Layme et al., 2018; Menezes et al., 2022).

We highlight the El Niño phenomenon that had a significant influence that affected the growth of the six species studied, mainly in the rainy season and that according to research on the El Niño-Southern Oscillation (ENSO) in the forests of South America shows precipitation deficits. widespread over the Amazon during the austral summer (Jimenez et al., 2019) and that reductions in precipitation in the Amazon are associated with surface warming in the central and eastern equatorial Pacific and that it occurs in El Niño events or the opposite during La Niña (Sulca et al., 2018). Finally, the diversity of species studied acquires various adaptation mechanisms over time that make them resilient and adapt to their forest ecosystem to face various climatic changes (Singh and Fetzer, 2022).

Finally, one of the first chronologies with multispecies for this part of the Peruvian Amazon is presented, which presented sensitivity for local and global climatic variables, future studies should evaluate the influences of these micro and macro climatic variables due to climate change in the tropics, being that for other regions it was observed that as of 1980 there is an increase in air temperature during the dry season over the southeast of the Amazon and that it is bringing changes in the structure of our forests, it is for this reason that understanding the functional strategies of the forest species will be important to apply it in the conservation and forest management of tropical forests (Jimenez et al., 2019; Marengo et al., 2018; Zuidema et al., 2022).

We conclude that working with diverse tropical species, the six species presented distinct growth rings and annual formations for the six species studied in the southeastern Amazon of Peru, revealing their potential for

dendrochronology in the tropics. The local precipitation influences the radial growth of the species, mainly in the rainy season in a positive way, being the limiting factor of growth for these species. The growth rings were also influenced by the global macroclimate due to the surface temperature of the Atlantic and Pacific seas, specifically the influence of the El Niño phenomenon on the growth of the six species. Finally, as three of the species had longevity greater than 200 years, this work enables studies of local climatic and macro-climate reconstruction through climatic changes in this part of Peru, as well as studies of different ecological responses of tropical species to dry conditions.

### **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.

### **Acknowledgments**

We thank the Concession of the company Corporación Forestal Tres Fronteras S.R.L., Conservation Concession “Rodal Semillero Tahuamanu”, Forest Concession of the Native Community of Bélgica. To the forest manager Ing. Demetrio Enrique Pacheco Villanueva for his support in the collection coordination, to the Forest Engineers Erick Grandez Piña and German Payeza Tuesta for their support in the collections. We also thank friends and colleagues from the Wood Anatomy and Identification Laboratory-LAIM of the University of São Paulo at the Luiz de Queiroz Higher School of Agriculture and the technician Aparecido Candido Siqueira for his support in preparing the samples. This study was made possible thanks to the support financed by the National Scholarship and Educational Credit Program (PRONABEC) of the Ministry of Education of Peru.

### **References**

- Acevedo, M., & Kikata, Y. (1994). *Atlas de Maderas del Perú.: Vol. I (I, I)* [Computer software]. UNALM – Universidad de Nagoya.
- Aguirre, J., Guerrero, E., & Campana, Y. (2021). How effective are protected natural areas when roads are present? An analysis of the Peruvian case. *Environmental Economics and Policy Studies*. <https://doi.org/10.1007/s10018-021-00304-y>
- Angoboy, B., Beeckman, H., Van Acker, J., Van den Bulcke, J., Fayolle, A., Couralet, C., Hubau, W., Kafuti, C., Rousseau, M., Kaka di-Makwala, A., Bourland, N., Deklerck, V., Kasongo Yakusu, E., Ewango, C., & De Mil, T. (2021). Variation in Onset of Leaf Unfolding and Wood Formation in a Central African Tropical Tree Species. *Frontiers in Forests and Global Change*, 4, 673575. <https://doi.org/10.3389/ffgc.2021.673575>
- Aragão, J. R., Groenendijk, P., & Lisi, C. (2019). Dendrochronological potential of four neotropical dry-forest tree species: Climate-growth correlations in northeast Brazil. *Dendrochronologia*, 53, 5-16. <https://doi.org/10.1016/j.dendro.2018.10.011>

- Aragão, J. R. V., Zuidema, P. A., & Groenendijk, P. (2022). Climate-growth relations of congeneric tree species vary across a tropical vegetation gradient in Brazil. *Dendrochronologia*, *71*, 125913. <https://doi.org/10.1016/j.dendro.2021.125913>
- Araujo, A., Parada, A., Terán, J., Baker, T., Feldpausch, T., Phillips, O., & Brien, R. (2011). Necromasa de los bosques de Madre de Dios, Perú; una comparación entre bosques de tierra firme y de bajos. *Revista Peruana de Biología*, *18*(1), 113-118. <https://doi.org/10.15381/rpb.v18i1.155>
- Blasing, T. J., Solomon, A. M., & Duvick, D. N. (1984). *Response functions revisited*. 16.
- Brançalion, P. H. S., Broadbent, E. N., de-Miguel, S., Cardil, A., Rosa, M. R., Almeida, C. T., Almeida, D. R. A., Chakravarty, S., Zhou, M., Gamarra, J. G. P., Liang, J., Crouzeilles, R., Hérault, B., Aragão, L. E. O. C., Silva, C. A., & Almeyda-Zambrano, A. M. (2020). Emerging threats linking tropical deforestation and the COVID-19 pandemic. *Perspectives in Ecology and Conservation*, *18*(4), 243-246. <https://doi.org/10.1016/j.pecon.2020.09.006>
- Brien, R. J., & Zuidema, P. A. (2006). The use of tree rings in tropical forest management: Projecting timber yields of four Bolivian tree species. *Forest Ecology and Management*, *226*(1-3), 256-267. <https://doi.org/10.1016/j.foreco.2006.01.038>
- Brien, R., P.A., & During, H. J. (2006). Autocorrelated growth of tropical forest trees: Unraveling patterns and quantifying consequences. *Forest Ecology and Management*, *237*(1-3), 179-190. <https://doi.org/10.1016/j.foreco.2006.09.042>
- Brien, R., Schöngart, J., & Zuidema, P. A. (2016). Tree Rings in the Tropics: Insights into the Ecology and Climate Sensitivity of Tropical Trees. En G. Goldstein & L. S. Santiago (Eds.), *Tropical Tree Physiology* (Vol. 6, pp. 439-461). Springer International Publishing. [https://doi.org/10.1007/978-3-319-27422-5\\_20](https://doi.org/10.1007/978-3-319-27422-5_20)
- Brien, R. W., & Zuidema, P. A. (2005). Relating tree growth to rainfall in Bolivian rain forests: A test for six species using tree ring analysis. *Oecologia*, *146*(1), 1-12. <https://doi.org/10.1007/s00442-005-0160-y>
- Cardoso, D., Särkinen, T., Alexander, S., Amorim, A., Bittrich, V., Celis, M., Daly, D., Fiaschi, P., Funk, V., Giacomini, L., Goldenberg, R., Heiden, G., Iganci, J., Kelloff, C., Knapp, S., Cavalcante de Lima, H., Machado, A., dos Santos, R., Mello-Silva, R., ... Forzza, R. (2017). Amazon plant diversity revealed by a taxonomically verified species list. *Proceedings of the National Academy of Sciences*, *114*(40), 10695-10700. <https://doi.org/10.1073/pnas.1706756114>
- CITES, 2020. (2020). *Apéndices I, II y III. CONVENCIÓN SOBRE EL COMERCIO INTERNACIONAL DE ESPECIES AMENAZADAS DE FAUNA Y FLORA SILVESTRES*. <https://cites.org/sites/default/files/esp/app/2020/S-Appendices-2020-08-28.pdf>



- Cook, E. (1985). *A time series analysis approach to tree ring standardization* [University of Arizona]. <http://ltrr.arizona.edu/sites/ltrr.arizona.edu/files/bibliodocs/CookER-Dissertation.pdf>
- Détienne, P. (1989). Appearance and Periodicity of Growth Rings in some Tropical Woods. *IAWA Journal*, 10(2), 123-132. <https://doi.org/10.1163/22941932-90000480>
- Dünisch, O., Bauch, J., & Bracamonte, L. (2002). FORMATION OF INCREMENT ZONES AND INTRAANNUAL GROWTH DYNAMICS IN THE XYLEM OF SWIETENIA MACROPHYLLA, CARAPA GUIANENSIS, AND CEDRELA ODORATA (MELIACEAE). *IAWA Journal*, 23(2), 101-119. <https://doi.org/10.1163/22941932-90000292>
- Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of Tropical Forests in the Anthropocene. *Current Biology*, 29(19), R1008-R1020. <https://doi.org/10.1016/j.cub.2019.08.026>
- Exbrayat, J., Liu, Y., & Williams, M. (2017). Impact of deforestation and climate on the Amazon Basin's above-ground biomass during 1993–2012. *Scientific Reports*, 7(1), 15615. <https://doi.org/10.1038/s41598-017-15788-6>
- Fétéké, F., Fayolle, A., Dainou, K., Bourland, N., Dié, A., Lejeune, P., Doucet, J.-L., & Beeckman, H. (2016). VARIATIONS SAISONNIÈRES DE LA CROISSANCE DIAMÉTRIQUE ET DES PHÉNOLOGIES FOLIAIRE ET REPRODUCTIVE DE TROIS ESPÈCES LIGNEUSES COMMERCIALES D'AFRIQUE CENTRALE. *BOIS & FORETS DES TROPIQUES*, 330(330), 3. <https://doi.org/10.19182/bft2016.330.a31315>
- Fichtler, E., & Worbes, M. (2012). Wood anatomical variables in tropical trees and their relation to site conditions and individual tree morphology. *IAWA Journal*, 33(2), 119-140. <https://doi.org/10.1163/22941932-90000084>
- Foster, R., Parker, T., & Gentry, A. (Eds.). (1994). *The Tambopata-Candamo reserved zone of southeastern Perú: A biological assessment*. Conservation International, Department of Conservation Biology.
- Golar, G., Malik, A., Muis, H., Herman, A., Nurudin, N., & Lukman, L. (2020). The social-economic impact of COVID-19 pandemic: Implications for potential forest degradation. *Heliyon*, 6(10), e05354. <https://doi.org/10.1016/j.heliyon.2020.e05354>
- Granato, D., Barbosa, A., & Ferreira, H. (2019). Drivers of growth variability of *Hymenaea stigonocarpa*, a widely distributed tree species in the Brazilian Cerrado. *Dendrochronologia*, 53, 73-81. <https://doi.org/10.1016/j.dendro.2018.12.001>
- Granato, D., Stahle, D., Barbosa, A., Feng, S., Torbenson, M., de Assis Pereira, G., Schöngart, J., Barbosa, J., & Griffin, D. (2019). Tree rings and rainfall in the equatorial Amazon. *Climate Dynamics*, 52(3-4), 1857-1869. <https://doi.org/10.1007/s00382-018-4227-y>

- Harris, I., Jones, P. D., Osborn, T. J., & Lister, D. H. (2013). Updated high-resolution grids of monthly climatic observations - the CRU TS3.10 Dataset: updated high-resolution grids of monthly climatic observations. *International Journal of Climatology*, *34*(3), 623-642. <https://doi.org/10.1002/joc.3711>
- Haylock, M. R., Peterson, T. C., Alves, L. M., Ambrizzi, T., Anunciação, Y. M. T., Baez, J., Barros, V. R., Berlato, M. A., Bidegain, M., Coronel, G., Corradi, V., Garcia, V. J., Grimm, A. M., Karoly, D., Marengo, J. A., Marino, M. B., Moncunill, D. F., Nechet, D., Quintana, J., ... Vincent, L. A. (2006). Trends in Total and Extreme South American Rainfall in 1960–2000 and Links with Sea Surface Temperature. *Journal of Climate*, *19*(8), 1490-1512. <https://doi.org/10.1175/JCLI3695.1>
- Holmes, R. (1983). Computer-assisted quality control in tree-ring dating and measurement. *Tree-ring bulletin*, *11*.
- Hubau, W., Lewis, S. L., Phillips, O. L., Affum-Baffoe, K., Beeckman, H., Cuní-Sanchez, A., Daniels, A. K., Ewango, C. E. N., Fauset, S., Mukinzi, J. M., Sheil, D., Sonké, B., Sullivan, M. J. P., Sunderland, T. C. H., Taedoumg, H., Thomas, S. C., White, L. J. T., Abernethy, K. A., Adu-Bredu, S., ... Zemagho, L. (2020). Asynchronous carbon sink saturation in African and Amazonian tropical forests. *Nature*, *579*(7797), 80-87. <https://doi.org/10.1038/s41586-020-2035-0>
- IAWA. (1989). *IAWA list of microscopic features for hardwood identification* (Vol. 10). IAWA Bull.
- Jimenez, J. C., Marengo, J. A., Alves, L. M., Sulca, J. C., Takahashi, K., Ferrett, S., & Collins, M. (2019). The role of ENSO flavours and TNA on recent droughts over Amazon forests and the Northeast Brazil region. *International Journal of Climatology*, *41*(7), 3761-3780. <https://doi.org/10.1002/joc.6453>
- Kallarackal, J., Otieno, D. O., Reineking, B., Jung, E.-Y., Schmidt, M. W. T., Granier, A., & Tenhunen, J. D. (2013). Functional convergence in water use of trees from different geographical regions: A meta-analysis. *Trees*, *27*(3), 787-799. <https://doi.org/10.1007/s00468-012-0834-0>
- Köppen, W. (1948). *Climatología: Con un estudio de los climas de la tierra*.
- Lakerveld, R. P., Lele, S., Crane, T. A., Fortuin, K. P. J., & Springate-Baginski, O. (2015). The social distribution of provisioning forest ecosystem services: Evidence and insights from Odisha, India. *Ecosystem Services*, *14*, 56-66. <https://doi.org/10.1016/j.ecoser.2015.04.001>
- Land, A., Remmele, S., Schönbein, J., Küppers, M., & Zimmermann, R. (2017). Climate-growth analysis using long-term daily-resolved station records with focus on the effect of heavy precipitation events. *Dendrochronologia*, *45*, 156-164. <https://doi.org/10.1016/j.dendro.2017.08.005>

- Layme, E. T., Ferrero, M. E., Palacios, K. S., & Requena, E. J. (2018). *Cedrela nebulosa*: A novel species for dendroclimatological studies in the montane tropics of South America. *Dendrochronologia*, *50*, 105-112. <https://doi.org/10.1016/j.dendro.2018.06.004>
- Layme, E. T., Ferrero, M. E., Palacios-Lazaro, K. S., & Requena-Rojas, E. J. (2018). *Cedrela nebulosa*: A novel species for dendroclimatological studies in the montane tropics of South America. *Dendrochronologia*, *50*, 105-112. <https://doi.org/10.1016/j.dendro.2018.06.004>
- Lisi, C. S., Fo, M. T., Botosso, P. C., Roig, F. A., Maria, V. R., Ferreira-Fedele, L., & Voigt, A. R. (2008). Tree-ring formation, radial increment periodicity, and phenology of tree species from a seasonal semi-deciduous forest in southeast Brazil. *Iawa Journal*, *29*(2), 189-207.
- Locosselli, G. M., Brienen, R. J. W., Leite, M. de S., Gloor, M., Krottenthaler, S., Oliveira, A. A. de, Barichivich, J., Anhof, D., Ceccantini, G., Schöngart, J., & Buckeridge, M. (2020). Global tree-ring analysis reveals rapid decrease in tropical tree longevity with temperature. *Proceedings of the National Academy of Sciences*, *117*(52), 33358-33364. <https://doi.org/10.1073/pnas.2003873117>
- Locosselli, G. M., Buckeridge, M. S., Moreira, M. Z., & Ceccantini, G. (2013). A multi-proxy dendroecological analysis of two tropical species (*Hymenaea* spp., Leguminosae) growing in a vegetation mosaic. *Trees*, *27*(1), 25-36. <https://doi.org/10.1007/s00468-012-0764-x>
- Locosselli, G. M., Krottenthaler, S., Pitsch, P., Anhof, D., & Ceccantini, G. (2019). Impact of temperature on the growth of a Neotropical tree species (*Hymenaea courbaril*, Fabaceae) at its southern distribution limit. *International Journal of Biometeorology*, *63*(12), 1683-1692. <https://doi.org/10.1007/s00484-019-01786-y>
- López, L., Villalba, R., & Peña-Claros, M. (2012). Determining the annual periodicity of growth rings in seven tree species of a tropical moist forest in Santa Cruz, Bolivia. *Forest Systems*, *21*(3), 508. <https://doi.org/10.5424/fs/2012213-02966>
- López, L., Villalba, R., & Stahle, D. (2022). High-fidelity representation of climate variations by *Amburana cearensis* tree-ring chronologies across a tropical forest transition in South America. *Dendrochronologia*, *72*, 125932. <https://doi.org/10.1016/j.dendro.2022.125932>
- Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., & Nobre, C. A. (2008). Climate Change, Deforestation, and the Fate of the Amazon. *Science*, *319*(5860), 169-172. <https://doi.org/10.1126/science.1146961>
- Marcelo-Peña, J., Roig, F., Goodwin, Z., & Tomazello, M. (2020). Characterizing growth rings in the trees of Perú: A wood anatomical overview for potential applications in dendroecological-related fields. *Dendrochronologia*, 125728. <https://doi.org/10.1016/j.dendro.2020.125728>

- Marengo, J. A., & Espinoza, J. C. (2016). Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. *International Journal of Climatology*, 36(3), 1033-1050. <https://doi.org/10.1002/joc.4420>
- Marengo, J., Souza, C., Thonicke, K., Burton, C., Halladay, K., Betts, R., Alves, L., & Soares, W. (2018). Changes in Climate and Land Use Over the Amazon Region: Current and Future Variability and Trends. *Frontiers in Earth Science*, 6, 228. <https://doi.org/10.3389/feart.2018.00228>
- Mariaux, A. (1967). Les cernes dans les bois tropicaux africains, nature et periodicite. *Rev. Bois For. Trop.*, 113, 3-14.
- Maués, M., Oliveira, P., & Kanashiro, M. (2008). Pollination biology in *Jacaranda copaia* (Aubl.) D. Don. (Bignoniaceae) at the «Floresta Nacional do Tapajós», Central Amazon, Brazil. *Revista Brasileira de Botânica*, 31(3), 517-527. <https://doi.org/10.1590/S0100-84042008000300015>
- Mendivelso, H., Camarero, J., Gutiérrez, E., & Zuidema, P. (2014). Time-dependent effects of climate and drought on tree growth in a Neotropical dry forest: Short-term tolerance vs. long-term sensitivity. *Agricultural and Forest Meteorology*, 188, 13-23. <https://doi.org/10.1016/j.agrformet.2013.12.010>
- Menezes, I. R. N., Aragão, J. R. V., Pagotto, M. A., & Lisi, C. S. (2022). Teleconnections and edaphoclimatic effects on tree growth of *Cedrela odorata* L. in a seasonally dry tropical forest in Brazil. *Dendrochronologia*, 72, 125923. <https://doi.org/10.1016/j.dendro.2022.125923>
- Millar, C. I., Stephenson, N. L., & Stephens, S. L. (2007). CLIMATE CHANGE AND FORESTS OF THE FUTURE: MANAGING IN THE FACE OF UNCERTAINTY. *Ecological Applications*, 17(8), 2145-2151. <https://doi.org/10.1890/06-1715.1>
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, 403(6772), 853-858. <https://doi.org/10.1038/35002501>
- Nobre, P., & Shukla, J. (1996). Variations of sea surface temperature, wind stress, and rainfall over the Tropical Atlantic and South America. *Journal of Climate*, 9(10), 2464-2479.
- Nogueira, F., Pagotto, M., Aragão, J., Roig, F., Ribeiro, A., & Lisi, Cl. (2019). The hydrological performance of *Prosopis juliflora* (Sw.) growth as an invasive alien tree species in the semiarid tropics of northeastern Brazil. *Biological Invasions*, 21(8), 2561-2575. <https://doi.org/10.1007/s10530-019-01994-y>
- Pan, Y., Birdsey, R. A., Fang, J., Houghton, R., Kauppi, P. E., Kurz, W. A., Phillips, O. L., Shvidenko, A., Lewis, S. L., Canadell, J. G., Ciais, P., Jackson, R. B., Pacala, S. W., McGuire, A. D., Piao, S., Rautiainen, A., Sitch, S., & Hayes, D. (2011). A Large and Persistent Carbon Sink in the World's Forests. *Science*, 333(6045), 988-993. <https://doi.org/10.1126/science.1201609>

- Pereira, G., Barbosa, A., Torbenson, M., Stahle, D., Granato, D., Santos, R., & Barbosa, J. (2018). The Climate Response of *Cedrela Fissilis* Annual Ring Width in the Rio São Francisco Basin, Brazil. *Tree-Ring Research*, 74(2), 162-171. <https://doi.org/10.3959/1536-1098-74.2.162>
- Pereira, M., Costa, M. H., Justino, F., & Malhado, A. C. M. (2017). Response of South American Terrestrial Ecosystems to Future Patterns of Sea Surface Temperature. *Advances in Meteorology*, 2017, 1-16. <https://doi.org/10.1155/2017/2149479>
- Portal, L., Cardozo, J., Santos, L., Saavedra, G., & Huamán, B. (2020). Dendrocronología de Jacaranda copaia que contiene registro ENSO en Madre de Dios, Perú. *Nativa*, 8(4), 572-578. <https://doi.org/10.31413/nativa.v8i4.10082>
- Puzzi, A., Herndon, K., Flores-Anderson, A., & Griffin, R. (2019). A spatial pattern analysis of forest loss in the Madre de Dios region, Peru. *Environmental Research Letters*, 14(12), 124045. <https://doi.org/10.1088/1748-9326/ab57c3>
- Qin, Y., Xiao, X., Dong, J., Zhou, Y., Wang, J., Doughty, R., Chen, Y., Zou, Z., & Moore, B. (2017). Annual dynamics of forest areas in South America during 2007–2010 at 50-m spatial resolution. *Remote Sensing of Environment*, 201, 73-87. <https://doi.org/10.1016/j.rse.2017.09.005>
- Quéré, C., Andrew, R. M., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P. A., Korsbakken, J. I., Peters, G. P., Canadell, J. G., Arneeth, A., Arora, V. K., Barbero, L., Bastos, A., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., Doney, S. C., ... Zheng, B. (2018). Global Carbon Budget 2018. *Earth System Science Data*, 10(4), 2141-2194. <https://doi.org/10.5194/essd-10-2141-2018>
- Quesada, C. A., Lloyd, J., Schwarz, M., Patiño, S., Baker, T. R., Czimczik, C., Fyllas, N. M., Martinelli, L., Nardoto, G. B., Schmerler, J., Santos, A. J. B., Hodnett, M. G., Herrera, R., Luizão, F. J., Arneeth, A., Lloyd, G., Dezzeo, N., Hilke, I., Kuhlmann, I., ... Paiva, R. (2010). Variations in chemical and physical properties of Amazon forest soils in relation to their genesis. *Biogeosciences*, 7(5), 1515-1541. <https://doi.org/10.5194/bg-7-1515-2010>
- Rebollar, S., De la Paz-Pérez Olvera, C., & Quintanar, A. (1993). Anatomía de la madera de cinco especies de Quintana Roo, México. *Botanical Sciences*, 53, 113. <https://doi.org/10.17129/botsci.1418>
- Reynel, C., Pennington, T. D., & Pennington, R. T. (2003). *Arboles útiles de la Amazonía peruana y sus usos*. Lima Tarea Gráfica Educativa.
- Román, F., Huayllani, M., Michi, A., Ibarra, F., Loayza, R., Vázquez, T., Rodríguez, L., & García, M. (2015). Reforestation with four native tree species after abandoned gold mining in the Peruvian Amazon. *Ecological Engineering*, 85, 39-46. <https://doi.org/10.1016/j.ecoleng.2015.09.075>

- Rozendaal, D. M. A., Phillips, O. L., Lewis, S. L., Affum-Baffoe, K., Alvarez-Davila, E., Andrade, A., Aragão, L. E. O. C., Araujo-Murakami, A., Baker, T. R., Bánki, O., Brienen, R. J. W., Camargo, J. L. C., Comiskey, J. A., Djuikouo Kamdem, M. N., Fauset, S., Feldpausch, T. R., Killeen, T. J., Laurance, W. F., Laurance, S. G. W., ... Vanderwel, M. C. (2020). Competition influences tree growth, but not mortality, across environmental gradients in Amazonia and tropical Africa. *Ecology*, *101*(7). <https://doi.org/10.1002/ecy.3052>
- RStudio Team. (2015). *RStudio: Integrated Development Environment for R*. <http://www.rstudio.com/>
- Sánchez-Cuervo, A. M., de Lima, L. S., Dallmeier, F., Garate, P., Bravo, A., & Vanthomme, H. (2020). Twenty years of land cover change in the southeastern Peruvian Amazon: Implications for biodiversity conservation. *Regional Environmental Change*, *20*(1), 8. <https://doi.org/10.1007/s10113-020-01603-y>
- Schöngart, J., Bräuning, A., Barbosa, A., Lisi, C., & de Oliveira, J. (2017). Dendroecological Studies in the Neotropics: History, Status and Future Challenges. En M. Amoroso, L. Daniels, P. Baker, & J. Camarero (Eds.), *Dendroecology* (Vol. 231, pp. 35-73). Springer International Publishing. [https://doi.org/10.1007/978-3-319-61669-8\\_3](https://doi.org/10.1007/978-3-319-61669-8_3)
- Schöngart, J., Piedade, M. T. F., Ludwigshausen, S., Horna, V., & Worbes, M. (2002). Phenology and stem-growth periodicity of tree species in Amazonian floodplain forests. *Journal of Tropical Ecology*, *18*(04), 581-597. <https://doi.org/10.1017/S0266467402002389>
- Schöngart, J., Wittmann, F., Worbes, M., Piedade, M. T. F., Krambeck, H.-J., & Junk, W. J. (2007). Management criteria for *Ficus insipida* Willd. (Moraceae) in Amazonian white-water floodplain forests defined by tree-ring analysis. *Annals of Forest Science*, *64*(6), 657-664. <https://doi.org/10.1051/forest:2007044>
- SERFOR. (2020). *Estado situacional del género Cedrela en Perú* (p. 130).
- Singh, C., & Fetzer, I. (2022). *Hydroclimatic adaptation critical to the resilience of tropical forests*. 10.
- Staal, A., Nes, E. H., Hantson, S., Holmgren, M., Dekker, S. C., Pueyo, S., Xu, C., & Scheffer, M. (2018). Resilience of tropical tree cover: The roles of climate, fire, and herbivory. *Global Change Biology*, *24*(11), 5096-5109. <https://doi.org/10.1111/gcb.14408>
- Stahle, D. W., Mushove, P. T., Cleaveland, M. K., Roig, F., & Haynes, G. A. (1999). Management implications of annual growth rings in *Pterocarpus angolensis* from Zimbabwe. *Forest Ecology and Management*, *124*(2-3), 217-229. [https://doi.org/10.1016/S0378-1127\(99\)00075-4](https://doi.org/10.1016/S0378-1127(99)00075-4)
- Sulca, J., Takahashi, K., Espinoza, J., Vuille, M., & Lavado, W. (2018). Impacts of different ENSO flavors and tropical Pacific convection variability (ITCZ, SPCZ) on austral summer rainfall in South America, with a focus on Peru. *International Journal of Climatology*, *38*(1), 420-435. <https://doi.org/10.1002/joc.5185>

- Sulca, J., Vuille, M., Silva, Y., & Takahashi, K. (2016). Teleconnections between the Peruvian Central Andes and Northeast Brazil during Extreme Rainfall Events in Austral Summer. *Journal of Hydrometeorology*, *17*(2), 499-515. <https://doi.org/10.1175/JHM-D-15-0034.1>
- Trouet, V., & Van Oldenborgh, G. (2013). KNMI Climate Explorer: A Web-Based Research Tool for High-Resolution Paleoclimatology. *Tree-Ring Research*, *69*(1), 3-13. <https://doi.org/10.3959/1536-1098-69.1.3>
- Venegas-González, A., Roig, F. A., Lisi, C. S., Junior, A. A., Alvares, C. A., & Tomazello-Filho, M. (2018). Drought and climate change incidence on hotspot Cedrela forests from the Mata Atlântica biome in southeastern Brazil. *Global Ecology and Conservation*, *15*, e00408. <https://doi.org/10.1016/j.gecco.2018.e00408>
- Walter, H., & Lieth, H. (1960). *Klimadiagram-Weltatlas*. Gustav Fisch. <https://donum.uliege.be/handle/2268.1/7079>
- Wigley, T. M. L., Briffa, K. R., & Jones, P. D. (1984). On the average value of correlated time-series, with applications in dendroclimatology and hydrometeorology. *J. Clim. Appl. Meteorol.*, *23*, 201-213. [https://doi.org/10.1175/1520-0450\(1984\)023<0201:otavoc>2.0.co;2](https://doi.org/10.1175/1520-0450(1984)023<0201:otavoc>2.0.co;2).
- Wigneron, J.-P., Fan, L., Ciais, P., Bastos, A., Brandt, M., Chave, J., Saatchi, S., Baccini, A., & Fensholt, R. (2020). Tropical forests did not recover from the strong 2015–2016 El Niño event. *SCIENCE ADVANCES*, *11*.
- Worbes, M. (1995). How to Measure Growth Dynamics in Tropical Trees a Review. *IAWA Journal*, *16*(4), 337-351. <https://doi.org/10.1163/22941932-90001424>
- Worbes, M. (2002). One hundred years of tree-ring research in the tropics – a brief history and an outlook to future challenges. *Dendrochronologia*, *20*(1-2), 217-231. <https://doi.org/10.1078/1125-7865-00018>
- Worbes, M., & Fichtler, E. (2010). Wood Anatomy and Tree-Ring Structure and Their Importance for Tropical Dendrochronology. En W. J. Junk, M. T. F. Piedade, F. Wittmann, J. Schöngart, & P. Parolin (Eds.), *Amazonian Floodplain Forests* (Vol. 210, pp. 329-346). Springer Netherlands. [https://doi.org/10.1007/978-90-481-8725-6\\_17](https://doi.org/10.1007/978-90-481-8725-6_17)
- Worbes, M., & Schöngart, J. (2019). Measures for sustainable forest management in the tropics – A tree-ring based case study on tree growth and forest dynamics in a Central Amazonian lowland moist forest. *PLOS ONE*, *14*(8), e0219770. <https://doi.org/10.1371/journal.pone.0219770>
- Xu, L., Saatchi, S. S., Yang, Y., Yu, Y., Pongratz, J., Bloom, A. A., Bowman, K., Worden, J., Liu, J., Yin, Y., Domke, G., McRoberts, R. E., Woodall, C., Nabuurs, G.-J., de-Miguel, S., Keller, M., Harris, N., Maxwell, S., & Schimel, D. (2021). Changes in global terrestrial live biomass over the 21st century. *Science Advances*, *7*(27), eabe9829. <https://doi.org/10.1126/sciadv.abe9829>

- Zang, C., & Biondi, F. (2015). treeclim: An R package for the numerical calibration of proxy-climate relationships. *Ecography*, *38*(4), 431-436. <https://doi.org/10.1111/ecog.01335>
- Zhang, X., Wang, Y.-P., Peng, S., Rayner, P. J., Ciais, P., Silver, J. D., Piao, S., Zhu, Z., Lu, X., & Zheng, X. (2018). Dominant regions and drivers of the variability of the global land carbon sink across timescales. *Global Change Biology*, *24*(9), 3954-3968. <https://doi.org/10.1111/gcb.14275>
- Zhou, X., Fu, Y., Zhou, L., Li, B., & Luo, Y. (2013). *An imperative need for global change research in tropical forests*. *33*, 10.
- Zuidema, P. A., Babst, F., Groenendijk, P., Trouet, V., Abiyu, A., Acuña-Soto, R., Adenesky-Filho, E., Alfaro-Sánchez, R., Aragão, J. R. V., Assis-Pereira, G., Bai, X., Barbosa, A. C., Battipaglia, G., Beeckman, H., Botosso, P. C., Bradley, T., Bräuning, A., Brienen, R., Buckley, B. M., ... Zhou, Z.-K. (2022). Tropical tree growth driven by dry-season climate variability. *Nature Geoscience*, *15*(4), 269-276. <https://doi.org/10.1038/s41561-022-00911-8>
- Zuidema, P. A., Heinrich, I., Rahman, M., Vlam, M., Zwartsenberg, S. A., & Sleen, P. (2020). Recent CO<sub>2</sub> rise has modified the sensitivity of tropical tree growth to rainfall and temperature. *Global Change Biology*, *26*(7), 4028-4041. <https://doi.org/10.1111/gcb.15092>



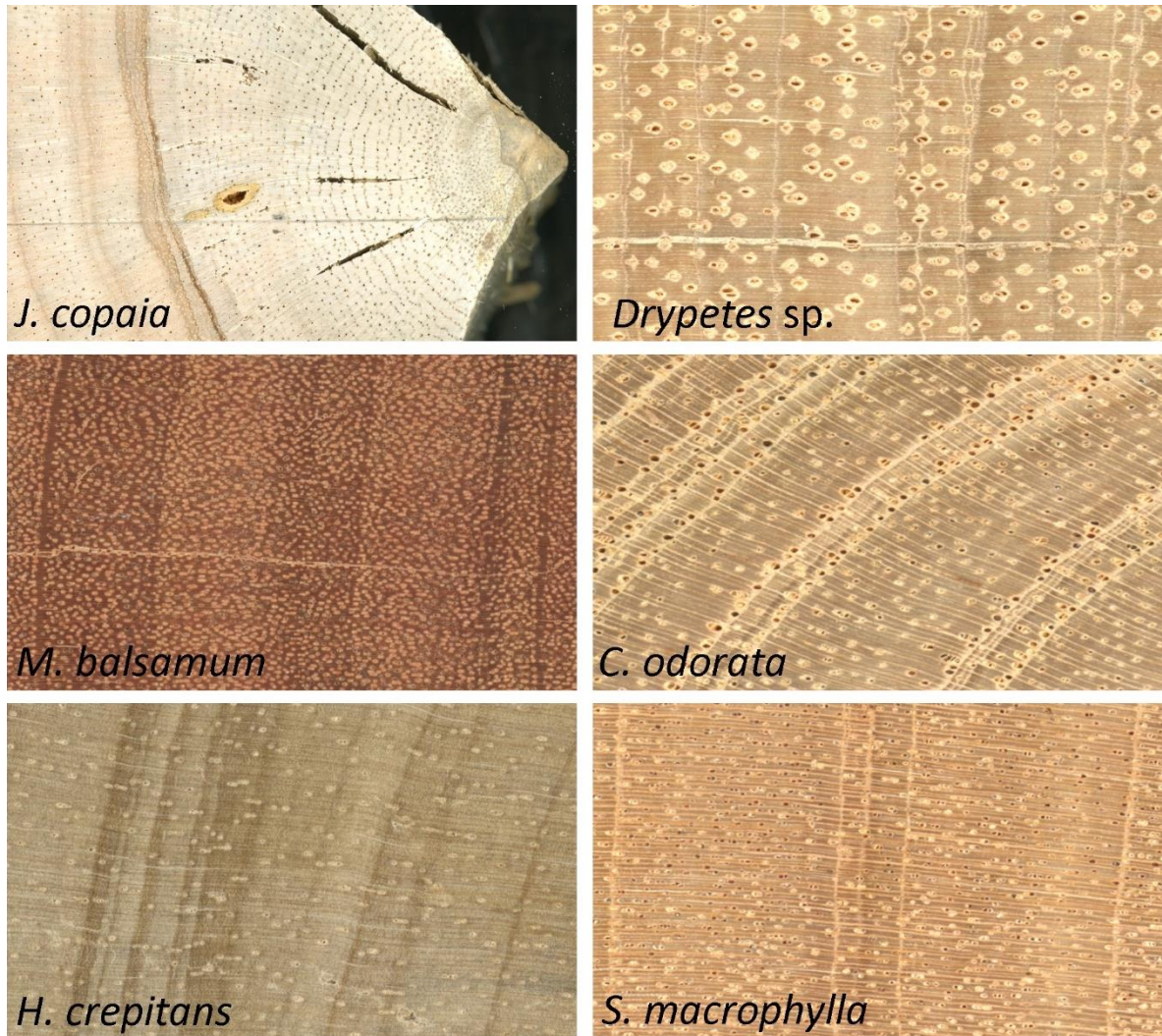
### Appendix. Supplementary material

**Table A1.** Tree species selected for dendrochronological analysis. Average diameter at breast height (DBH). Commercial Height (CH). Minimum Cutting Diameter (MCD). Conservation status (LC= Least Concern; VU= Vulnerable; NE= Not Evaluated). Type of the ring boundary (FWT= change in fiber wall thickness, MP= marginal parenchyma, SRP-MP= semi ring porosity combined with marginal parenchyma). Conservation status is consulted in the IUCN database.

Species	Family	DBH (cm)	CH (m)	MCD (cm)	Conservation status	Leaf habit	Type of boundaries	Previous tree-ring study?
<i>Jacaranda copaia</i>	Bignoniaceae	78	18	41	LC	Deciduous	FWT	Yes <sup>a</sup>
<i>Myroxylon balsamum</i>	Fabaceae	61	18	41	LC	Semideciduos	FWT	No
<i>Drypetes</i> sp.	Putranjivaceae	73	17	41	NE	Evergreen	MP	No
<i>Swietenia macrophylla</i>	Meliaceae	92	20	75	VU	Deciduous	MP	Yes <sup>b</sup>
<i>Cedrela odorata</i>	Meliaceae	63	18	65	VU	Deciduous	SRP-MP	Yes <sup>b</sup>
<i>Hura crepitans</i>	Euphorbiaceae	100	16	60	LC	Semideciduos	FWT	No

<sup>a</sup> (Portal et al., 2020)

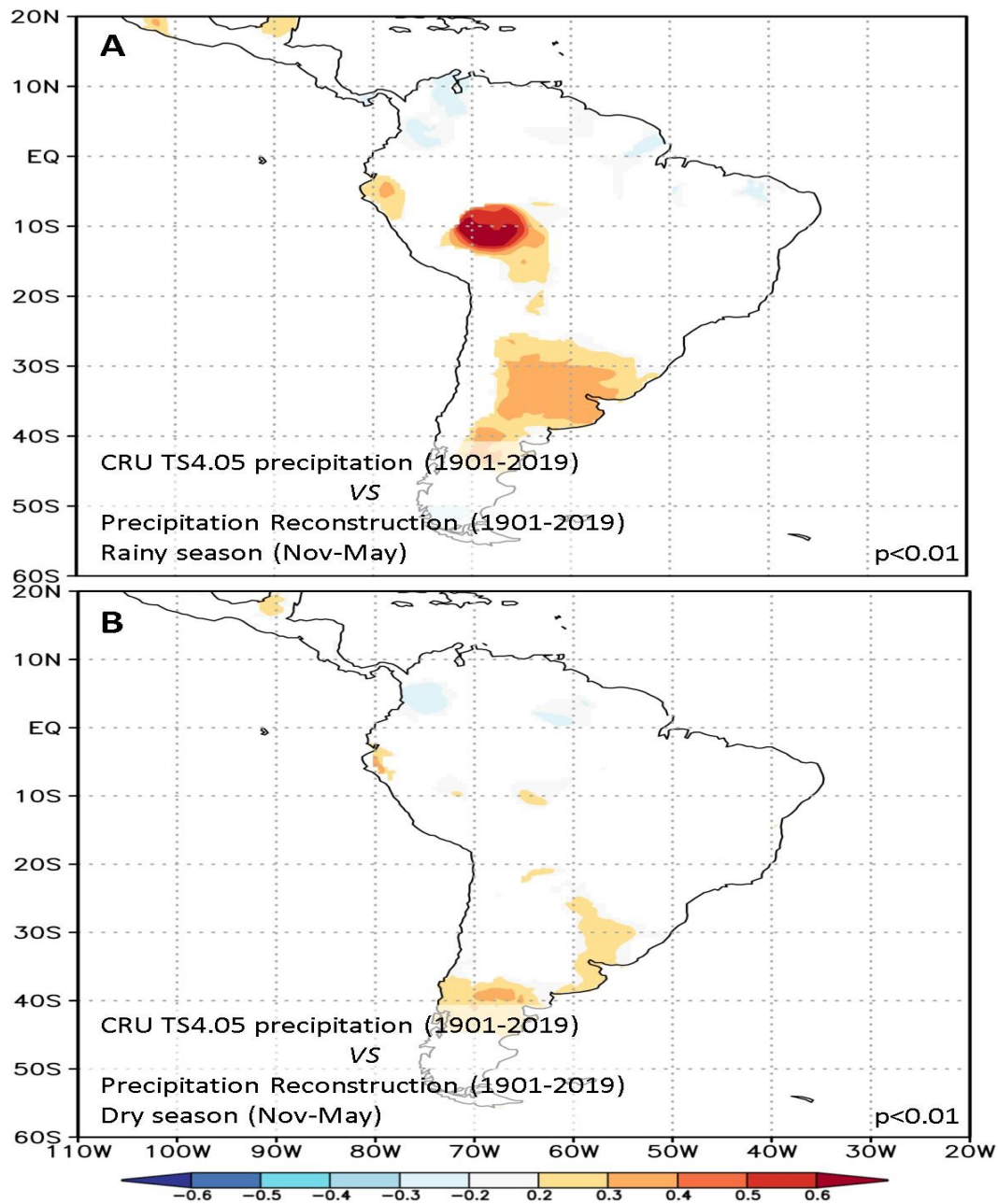
<sup>b</sup> (Dünisch et al., 2003)



**Fig. B1.** False rings in the six tropical species. For species with thick-walled latewood fiber growth rings and differences in vessel diameters (*J. copaia*, *M. balsamum*, and *H. crepitans*), faint false rings or difficulties in observing certain regions are observed. For species with marginal parenchyma growth rings (*Drypetes sp.*, *C. odorata* and *S. macrophylla*) growth rings are observed by dividing the marginal or discontinuous parenchyma.

*Validation of the quality of the precipitation data between the CRU TS4.05 precipitation versus the reconstruction of the local precipitation of the study area.*

Our analysis between CRU TS4.05 precipitation (Harris et al., 2013) versus local precipitation reconstruction of CRU, Rondonia, Brasilia, Rio Branco and Puerto Maldonado (Fig. B2). They indicate the strong correlations between the rainy season (November-May) precipitation in the study area (Fig. B2 A) and the low correlation between the dry season (June-August) precipitation in the study area (Fig. B2 B). Analyzes were performed using KNMI Climate Explorer (<http://climexp.knmi.nl>).



**Fig. B2.** Spatial correlations between CRU TS4.05 precipitation versus local precipitation reconstruction between the years 1901-2019. A) Spatial correlation for the rainy season of the study area. B) Spatial correlation for the dry season of the study area.

**Table A2.** Characteristics of the clean chronologies of the six commercial tree species selected in the eastern Amazon of Peru for analysis with the local climate (precipitation and temperature). The number of trees and the number of series are included in parentheses. COR = average of the correlation between the series. Rbar = interseries between the correlation trees. EPS = express population signal. Age. Span = Start and end year of the chronology.

Species	# Tres (series)	COR	Rbar	EPS	Age	Span
<i>Jacaranda copaia</i>	16 (23)	0.47	0.19	0.81	67	1952-2019
<i>Myroxylon balsamum</i>	14 (28)	0.45	0.25	0.70	70	1948-2018
<i>Drypetes</i> sp.	17 (31)	0.43	0.16	0.85	131	1888-2019
<i>Cedrela odorata</i>	32 (60)	0.46	0.20	0.98	199	1819-2018
<i>Swietenia macrophylla</i>	18 (30)	0.43	0.23	0.70	133	1885-2018
<i>Hura crepitans</i>	06 (12)	0.37	0.18	0.72	274	1744-2018

**Table A3.** Results of the multiple regression analysis for the chronology of each species (dependent variable) and the values of the local (precipitation) environmental variables monthly.  $R^2$  = coefficient of determination.

Species	Variables	b±SE	R <sup>2</sup>	Species	Variables	b±SE	R <sup>2</sup>
<i>J. copaia</i>	Precipitation		0.15	<i>C. odorata</i>	Precipitation		0.37
	Intercept	0.9574 ± 0.0883 ***			Intercept	1.3711 ± 0.1201 ***	
	Prec. OCT	0.0010 ± 0.0003 **			Prec. APR	-0.0007 ± 0.0003 *	
	Prec. nov	0.0008 ± 0.0003 *			Prec. MAY	-0.0016 ± 0.0005 **	
<i>Drypetes</i> sp.	Precipitation		0.28	Prec. DEC	-0.0013 ± 0.0003 ***		
	Intercept	0.8962 ± 0.1287 ***		Prec. dec	0.0008 ± 0.0003 *		
	Prec. JAN	0.0008 ± 0.0003 **		<i>S. macrophylla</i>	Precipitation		0.21
	Prec. MAR	-0.0007 ± 0.0003 *			Intercept	0.9325 ± 0.0540 ***	
	Prec. APR	-0.0008 ± 0.0003 *			Prec. AUG	-0.0016 ± 0.0006 *	
	Prec. OCT	-0.0008 ± 0.0003 *			Prec. aug	0.0021 ± 0.0006 **	
	Prec. apr	0.0007 ± 0.0003 *		<i>H. crepitans</i>	Precipitation		0.26
	Prec. oct	0.0011 ± 0.0004 **			Intercept	0.9675 ± 0.1243 ***	
		Prec. mar	0.0008 ± 0.0003 **				
		Prec. aug	-0.0016 ± 0.0006 *				
			Prec. sep	-0.0015 ± 0.0006 *			

b = multiple linear regression coefficient, SE = standard error, significance levels are indicated as (\*  $p < 0.05$ ; \*\*  $p < 0.01$  and \*\*\*  $p < 0.001$ ). acronym for months with lowercase letters (previous year), an acronym for months with capital letters (current year). Acronym for months: uppercase = current year, lowercase = previous year.

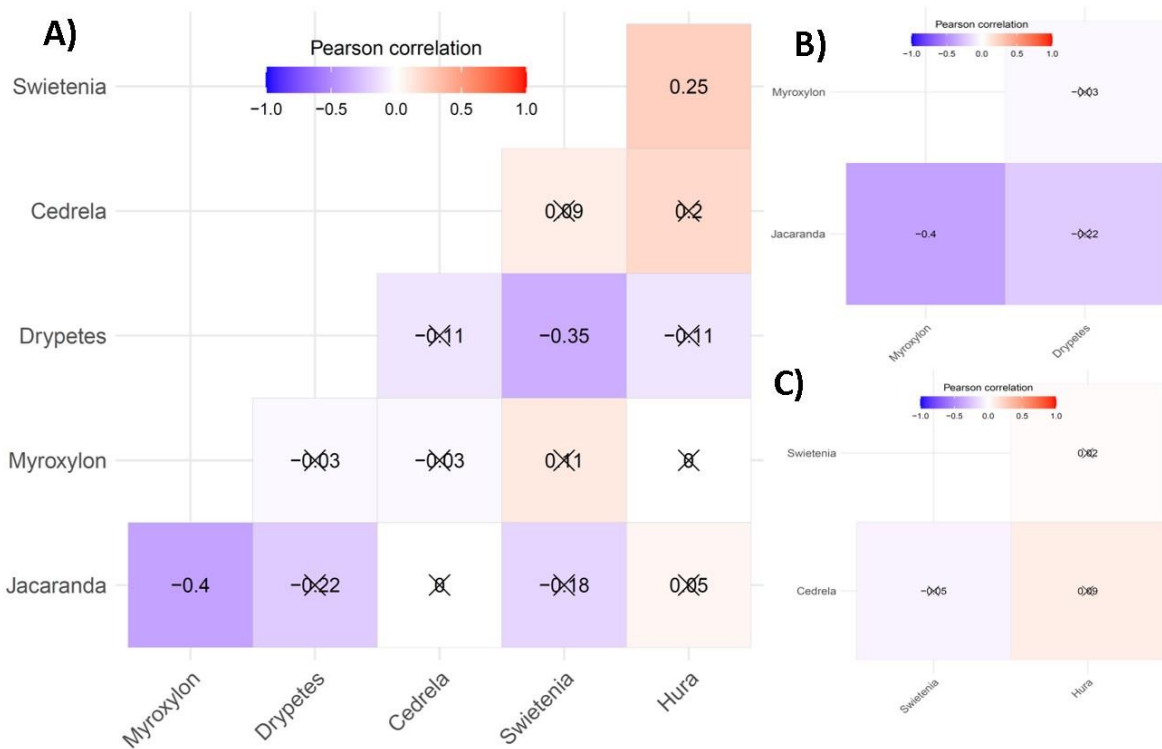
**Table A4.** Result of the multiple regression analysis for the chronology of each species (dependent variable) and the values of the global (Southern Oscillation-SOI, Atlantic Multidecadal Oscillation-AMO, Oceanic Niño-ONI, Eastern Asia-EA, Tropical Southern Atlantic-TSA and Western Hemisphere Warm Pool-WHWP) environmental variables monthly. R<sup>2</sup> = coefficient of determination.

Species	Variables	b±SE	R <sup>2</sup>	Species	Variables	b±SE	R <sup>2</sup>		
<i>J. copaia</i>	AMO		0.07	<i>C. odorata</i>	AMO		0.18		
	Intercept	0.9799 ± 0.0238 ***			Intercept	0.9033 ± 0.0283 ***			
	AMO NOV	0.7528 ± 0.3413 *			AMO OCT	1.0768 ± 0.3024 ***			
	AMO DEC	-0.8109 ± 0.3551 *			AMO NOV	-1.2366 ± 0.3336 ***			
	ONI		0.24		ONI			0.07	
	Intercept	0.9666 ± 0.0213 ***			Intercept	0.9558 ± 0.0263 ***			
	ONI JAN	0.0926 ± 0.0361 *			ONI feb	-0.6205 ± 0.2903 *			
	ONI MAY	-1.1722 ± 0.2659 ***			ONI mar	1.2287 ± 0.5787 *			
	ONI JUN	1.7668 ± 0.4264 ***			ONI apr	-0.6129 ± 0.2995 *			
	ONI JUL	-0.7484 ± 0.2113 ***			<i>S. macrophylla</i>	TSA		0.08	
	EA		0.08			Intercept	0.9714 ± 0.0246 ***		
	Intercept	0.9546 ± 0.0253 ***				TSA FEB	0.3078 ± 0.1443 *		
	EA JAN	0.5223 ± 0.2529 *				TSA MAR	-0.3089 ± 0.1356 *		
	EA FEB	-0.5993 ± 0.2648 *				EA			0.26
<i>M. balsamum</i>	SOI		0.33	Intercept		0.9709 ± 0.0274 ***			
	Intercept	0.9574 ± 0.0188 ***		EA mar		-0.4977 ± 0.1853 **			
	SOI FEB	-0.0509 ± 0.0230 *		EA may		1.4206 ± 0.6461 *			
	SOI APR	-0.0584 ± 0.0172 **		EA jun		-1.6937 ± 0.7599 *			
	SOI apr	-0.0403 ± 0.0155 *		EA aug		2.4975 ± 0.7436 **			
	SOI may	0.0653 ± 0.0208 **		EA sep		-2.3933 ± 0.6675 ***			
	SOI nov	0.0853 ± 0.0284 **		EA nov		1.4316 ± 0.5353 **			
	AMO		0.10	EA dec		-0.7820 ± 0.3731 *			
	Intercept	0.9690 ± 0.0213 ***		WHWP				0.18	
	AMO JAN	-0.3485 ± 0.1522 *		Intercept	0.9643 ± 0.02 36 ***				
	AMO NOV	0.3446 ± 0.1292 **		WHWP JUN	0.0887 ± 0.0247 ***				
	ONI		0.17	WHWP JUL	-0.0651 ± 0.0231 **				
	Intercept	0.9763 ± 0.0200 ***		<i>H. crepitans</i>	TSA		0.28		
	ONI MAR	-0.5547 ± 0.1966 **			Intercept	0.9527 ± 0.02438 ***			
ONI APR	1.1984 ± 0.4047 **		TSA JAN		0.3961 ± 0.1766 *				
ONI MAY	-0.5581 ± 0.2177 *		TSA FEB		-0.2825 ± 0.1348 *				
<i>Drypetes sp.</i>	TSA		0.16		TSA JUN	-0.2683 ± 0.1239 *			
	Intercept	0.9581 ± 0.0245 ***			TSA JUL	0.3629 ± 0.1403 *			
	TSA MAR	0.1886 ± 0.0624 **			TSA nov	0.3281 ± 0.1272 *			
	TSA mar	-0.1729 ± 0.0620 **			TSA dec	-0.4685 ± 0.1633 **			
	WHWP		0.12		WHWP			0.12	
	Intercept	0.9625 ± 0.0242 ***			Intercept	0.9650 ± 0.0259 ***			
	WHWP APR	0.1053 ± 0.0365 **			WHWP sep	0.0610 ± 0.0230 *			
	WHWP MAY	-0.0904 ± 0.0324 **			WHWP oct	-0.0698 ± 0.0241 **			

b = multiple linear regression coefficient, SE = standard error, significance levels are indicated as (\* p<0.05; \*\* p<0.01 and \*\*\* p<0.001). acronym for months with lowercase letters (previous year), an acronym for months with capital letters (current year). Acronym for months: uppercase = current year, lowercase = previous year.

*Correlations between chronologies of the six species studied.*

To observe and compare the similarities of the six forest species of the Peruvian Amazon in radial growth, we made correlations of their standard chronologies. For this, we used a correlation matrix organized hierarchically by the level of significance (less than 5%), correlating all the species in a common period (1952), for the three young species (*J. copaia*, *M. balsamum*, *Drypetes* sp.) in a common period (1952) and finally for three species with greater longevity (*C. odorata*, *S. macrophylla*, *H. crepitans*) for the common period of 1787. We used the corrplot package (Friendly, 2002), through the RStudio software (RStudio Team, 2015)



**Fig. B3.** A) Pearson correlations are organized hierarchically between the standard chronologies of the species of the South Amazon. A) For the six species in a common period (1952). B) For the 3 young species in a common period (1952). C) And for the three longest-lived species in a common period (1787). Colored frames represent a significant ratio of 95%.

## 5. FINAL CONSIDERATIONS

Through the analysis of the growth rings of tree species growing in a tropical humid forest in the southeast of the Peruvian Amazon, this doctoral thesis contributes to the dendrochronological and dendroclimatic knowledge of native species, helping to reduce the gaps in knowledge of growth rings in tropical forests.

Firstly, the state of the art of dendrochronology in Peru was carried out, which allowed compiling, systematizing, analyzing and making inferences about the knowledge accumulated from the beginning (end of the 1980s) to the present day. Analyzing not only scientific articles but also theses deposited in the various repositories of Peru and the world, allowed us to have a real overview of the progress and limitations of the study of growth rings in the country.

Subsequently, the potential of the growth rings of 34 forest species from the eastern Amazon of Peru was analyzed for dendrochronological studies, analyzing the macroscopic anatomy, growth rings, and delimitation of the growth rings by X-ray densitometry. In addition, it was used a subset will evaluate the trajectory and growth rate of 06 forest species. This allows scientific information on tropical species to be applied in more specific studies on dendrochronology.

Finally, using the subset of 06 species (*J. copaia*, *H. crepitans*, *Drypetes sp.*, *M. balsamum*, *C. odorata* and *S. macrophylla*), the chronologies were constructed and the associations with climatic and atmospheric variables were made. This allowed the construction of chronologies for the first time of 03 species (*H. crepitans*, *Drypetes sp.*, *M. balsamum*), where 03 species had ages greater than 200 years (*C. odorata* and *S. macrophylla*, *H. crepitans*), in addition, all the species showed correlations with the local precipitation in the rainy season and an influence of the El Niño phenomenon was also found in the growth of the 06 forest species.

Future studies that can be addressed with the information generated are i) use the measurements of the growth rings of the 06 species (*J. copaia*, *H. crepitans*, *Drypetes sp.*, *M. balsamum*, *C. odorata* and *S. macrophylla*) and apply them to forest management, determining, for example, the cutting cycle of these species, ii) using the 03 longest-lived species (*C. odorata* and *S. macrophylla*, *H. crepitans*), to carry out the climatic reconstruction in this part of Peru.

It is evident that the study of growth rings in the tropical humid forest of the department of Madre de Dios considered the capital of biodiversity in Peru, is feasible and the results of this doctoral thesis show great potential for studies in dendrochronology and dendroclimatology in Madre de Dios.