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MAPPING WOOD DENSITY VARIATION USING QGIS: AN INNOVATIVE APPROACH FOR CHARACTERIZATION OF *OCHROMA PYRAMIDALE*, *ACACIA MANGIUM*, *EUCALYPTUS GRANDIS*, AND *PINUS* SP.

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ABSTRACT

This study explores the innovative application of QGIS for mapping radial wood density variation across the entire cross-section of selected native and non-native forest species, aiming to enhance wood characterization. Using samples from *Ochroma pyramidale*, *Acacia mangium*, *Eucalyptus grandis*, and *Pinus* sp., we applied X-ray densitometry to obtain high-resolution images, which were then analyzed with QGIS to create detailed density maps. These maps provided a clear visualization of radial density variation, offering insights into the internal structure of the wood. The integration of QGIS with X-ray densitometry proved to be an effective tool for assessing wood density variation, supporting more precise and sustainable forest management practices.

KEYWORDS: Density variability, QGIS analysis, sustainable forest management, wood properties, X-ray densitometry.

INTRODUCTION

Wood density is the most important technological property of wood, defined as the amount of dry matter per unit volume of fresh wood. This property significantly influences mechanical characteristics, natural durability, and various industrial applications of wood, serving as a key indicator of its quality (Mascarenhas et al. 2021; Qumruzzaman et al. 2012; Xue et al. 2022). Wood density also plays an essential role in tree biomechanics and hydraulic function, crucial for assessing plant carbon stocks by linking volume recovery to mass estimation (Yang et al. 2024). Furthermore, wood density exhibits considerable variability both within individual trees and among different trees in a forest (Ortega Rodriguez and Tomazello-Filho 2019; Petrea et al. 2024; Sousa et al. 2019; Takoudjou et al. 2020) owned to environmental conditions, tree age, growth strategies, and tree size, impacting ecological processes such as tree growth, resilience to disturbances, and carbon stock estimation (Arra'd et al. 2024; Fajardo 2022; Van Leeuwen et al. 2011; Yang et al. 2024). Accurate wood density estimates are essential for optimizing value chains in the forestry sector (Cahuana et al. 2023; Chavesta et al. 2022; Gaitan et al. 2019; Moya et al. 2009; Portal et al. 2019).

Both traditional and innovative non-destructive methods are used to measure wood density. Traditional methods involve drying standardized wood samples until a constant weight is achieved (ATSM 2017; NTP N°251.011 2016). Innovative methods include extracting wood chips with drills (Francis 1994; Olale et al. 2019; Martínez et al. 2020a,b), using Pressler and motorized borers for wood cores (Mahari et al. 2024; Portal-Cahuana et al. 2023; Bobadilla et al. 2018; Krottenthaler et al. 2015), and tools like the Pilodyn for assessing standing tree density (Gao et al. 2018; Gough and Barnes 1984; Schimleck et al. 2019; Wu et al. 2010). Additionally, resistographs are used for resistance drilling tests (Arnič et al. 2022; Nowak et al. 2016; Todoroki et al. 2021), along with X-ray tomography, densitometry (Freyburger et al. 2009; Hervé et al. 2014), and the DiscBot, which combines various techniques to analyze wood properties and density variation (Gendvilas et al. 2022; Schimleck et al. 2019).

X-ray densitometry is an advanced and precise technique for the quantitative evaluation of wood properties and its derivatives (such as particleboard, MDF, and plywood) (Chavesta et al. 2022; Gaitan et al. 2019; Hervé et al. 2014; Moya and Filho 2009; Portal et al. 2019; Tomazello et al. 2008). This methodology allows for the accurate identification of growth ring boundaries, revealing intra-annual variations in wood density and providing detailed data on minimum, mean, and maximum density in earlywood and latewood (Cahuana et al. 2023; Ortega et al. 2022; Pagotto et al. 2017; Quintilhan et al. 2021). Although initially laborious and costly, technological advancements have enabled rapid data acquisition and simplified sample preparation, facilitating its application in the wood industry.

The free and open-source Geographic Information System (QGIS) software has gained popularity across various fields due to its versatility and user-friendly interface. Its widespread use for spatial data analysis and visualization makes it a valuable tool in both academic and professional contexts (Duarte et al. 2021). The open-source nature of QGIS facilitates continuous improvement and customization, fostering a collaborative environment among users and developers (Rosas-Chavoya et al. 2022). In the field of forestry engineering, QGIS plays a crucial role by enabling spatial analysis and more effective management of forest resources. It has been shown to enhance forest inventory processes by allowing more efficient data collection and analysis, which is essential for sustainable forest management (Bastos et al. 2024). Additionally, QGIS supports the integration of various data types, such as remote sensing and ground measurements, which optimizes forest modeling and decision-making regarding forests (Podolskaia 2022). Furthermore, QGIS has established itself as a powerful tool for creating variation maps in fields such as environmental sciences, urban planning, and agriculture, facilitating the visualization of spatial variations through the integration of diverse datasets (Duarte et al. 2021).

Wood density analysis can be improved by creating high resolution wood density maps of cross section using QGIS. This tool could allows detailed analysis of whole cross section of wood, supporting wood characterization of forest species for production of high-quality wood products (Ortega et al. 2022; Quintilhan et al. 2021; Santini et al. 2019).

This study aims to evaluate the capability of using QGIS for mapping wood density variation within the whole cross-section in four tree species: *Ochroma pyramidale*, *Acacia mangium*, *Eucalyptus grandis*, and *Pinus* sp. The results of this study will contribute to the knowledge of a new tool for wood characterization supporting sustainable and efficient practices in forest management and the wood industry.

MATERIAL AND METHODS

Wood sampling

We sampled four forest species: one native species, *O. pyramidale* (Cav. ex Lam.) Urb. from Peru, and three non-native species, *A. mangium* Willd, *E. grandis*, and *Pinus* sp., commonly used in tropical forest plantations in Brazil (Tab. 1). These samples were available at the Wood Anatomy and Identification Laboratory of the University of São Paulo, located on the Luiz de Queiroz College of Agriculture campus in Piracicaba, Brazil (LAIM/USP/ESALQ). For each species, one tree was selected, and a sample was taken per tree. Whole cross-sections, half cross-sections, or wood wedges approximately 2 inches thick were cut and mounted in a wooden cube to facilitate sample acquisition.

Tab. 1: Forest species sampled.

Species	Botanical family	Sampling location
Acacia mangium Willd.	Fabaceae	Ipameri, Goiás, Brazil
Eucalyptus grandis W. Mill ex Maiden	Myrtaceae	Estación Experimental Itatinga, São Paulo, Brazil
Ochroma pyramidale (Cav. ex Lam.) Urb.	Malvaceae	Tambopata, Madre de Dios, Perú
Pinus sp.	Pinaceae	Piracicaba, São Paulo, Brazil

Sample preparation

Wood slices and wedges were glued with synthetic adhesive to a wooden cube to allow the cube to hold the sample securely during cutting. The samples were then cut using an Invicta® band saw with an aluminum base and fence to aid in cutting. Prior to cutting, the cutting thickness was calibrated to obtain a thin and homogeneous sample. The thickness ranged from 1.84 mm to 2.35 mm among species. To ensure uniform cutting, a digital vernier caliper was used to take three measurements on each sample to assess the quality of sample preparation.

X-ray Imaging and xRing analysis

Subsequently, wood samples were conditioned in a Memmert® HPP110 climate chamber at 20°C and 60% relative humidity for approximately 48 h to reach a moisture content of 12%.

The samples were digitally radiographed using an X-ray system with the Faxitron MX-20 Cabinet X-Ray Imaging System (Faxitron X-Ray Corporation, Lincolnshire, IL, USA) (Cahuana et al. 2023; Quintilhan et al. 2021), employing a stepped cellulose acetate wedge of known density with eight thicknesses to cover all gray scale values (Campelo et al. 2019; Tomazello et al. 2008). Images were captured with an exposure time of 19 s at a voltage of 30 kV, with a resolution of 513 dpi, and saved in "tif" and "jpg" formats. Using RStudio software and the xRing package (Campelo et al. 2019) X-ray images were analyzed. The stepped acetate wedge was used to generate a density-thickness calibration curve, enabling determination of wood density based on grayscale values. Each pixel in the X-ray image of the wood sample was analyzed for density, and thus the thickness of each sample was measured with a digital vernier caliper. A conversion factor of 0.828 was used to calculate basic density from average apparent density values per species (Vieilledent et al. 2018).

Visual classification of density in wood samples

QGIS version 3.26 open-source software was used for the visual classification of density in the wood slice. As a first step, a raster layer was added, and the X-ray image was located and added to the project. Subsequently, the raster menu was accessed, and the "Calculate Raster" option was selected. The equation generated from the stepped cellulose acetate wedge of known density with eight thicknesses was applied, adding the raster band to the equation and naming the output layer. Finally, the changes were confirmed by clicking "OK".

Next, the created layer was selected, and under Properties, the render type was set to Singleband pseudocolor. A color ramp was chosen, and custom color shades were selected to display variations in densities within the sample. After making the desired adjustments, the changes were saved by clicking "OK". Lastly, the resulting image was exported at a resolution of 1000 dpi.

RESULTS AND DISCUSSION

This study focuses on the measurement and visualization of the apparent density of four tree species: *O. pyramidale* (native species), *A. mangium*, *E. grandis*, and *Pinus* sp. (non-native species), using X-ray densitometry and QGIS geographic information system software. Wood density, a key technological property, significantly influences the mechanical characteristics, durability, and various industrial applications of wood, as well as playing a crucial role in tree biomechanics and the estimation of plant carbon stocks. This work not only contributes to scientific knowledge about the variability of wood density but also proposes an innovative and precise methodology for its analysis and visualization.

Apparent wood density via X-ray densitometry

The average minimum and maximum apparent density values, along with the calculated basic density of the wood log samples, are presented in Tab. 2. Apparent density profiles generated by the xRing package in the whole cross-section samples are shown in Fig. 1, illustrating the wood cross-section or wedge with apparent density profiles.

Tab. 2: Apparent density and calculated basic density of the studied species using X-ray densitometry.

Species	Apparent density ($g.cm^{-3}$)			Basic average density ($g.cm^{-3}$)
	Maxima	**Minimum**	**Average**	
Acacia mangium Willd.	0.93	0.13	0.50	0.42
Eucalyptus grandis W. Mill ex Maiden	0.92	0.13	0.55	0.45
Ochroma pyramidale (Cav. ex Lam.) Urb.	0.52	0.07	0.17	0.14
Pinus sp.	0.73	0.31	0.48	0.39

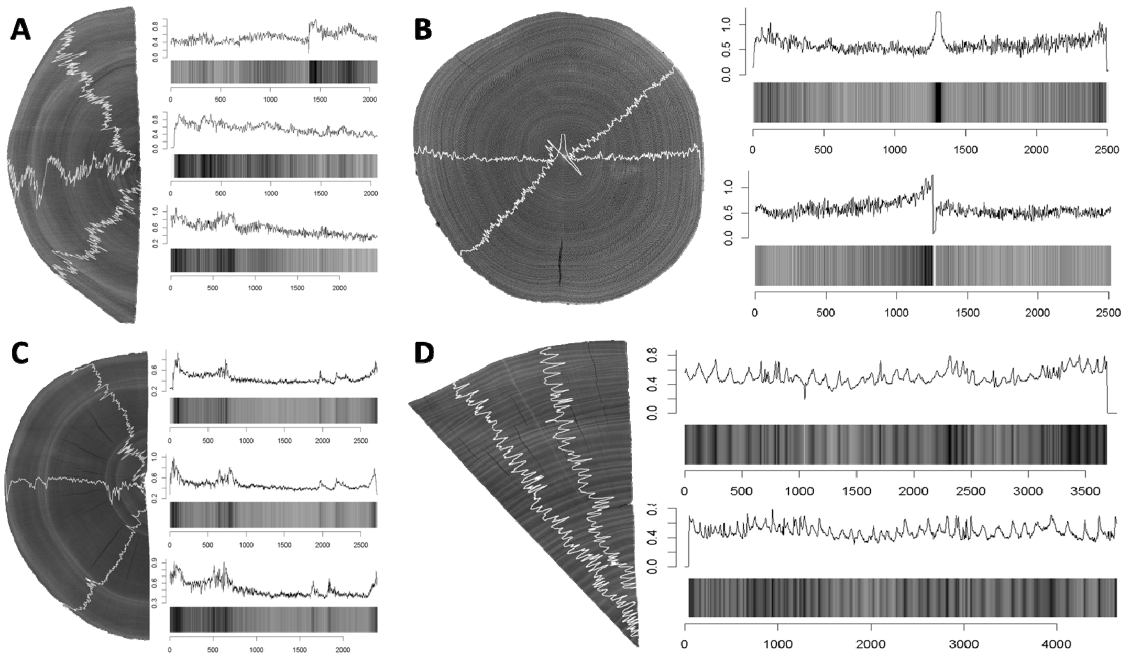

Fig. 1: Apparent density profile of wood logs from X-ray samples: a) A. mangium, b) E. grandis, c) O. pyramidale, d) Pinus sp. and the apparent density profiles generated by the xRing package.

In the analysis of the apparent densities of the studied species, consistent patterns were observed that reflect the inherent differences between native and non-native species. The average apparent density varied considerably among the species, with *O. pyramidale* showing the lowest density and *E. grandis* the highest. These variations align with the scientific literature, highlighting how factors such as species and growth environment influence wood density (Lira-Martins et al. 2022; MacFarlane 2020; Petrea et al. 2024; Takoudjou et al. 2020). Additionally, the application of X-ray densitometry, along with visual analysis in QGIS, proved to be an effective tool for revealing fine details of the internal wood structure, providing a clear and detailed visualization of density variations. This approach not only enhances our understanding of wood properties but also offers significant implications for forest management and the wood industry, promoting more sustainable and efficient practices.

Images of visual classification of density in wood samples

The results of this study (Fig. 2) highlight the capability of combining X-ray densitometry with QGIS software to map and visualize in detail the density variations in the wood of four tree species: *A. mangium*, *E. grandis*, *O. pyramidale*, and *Pinus* sp. The images generated allow for a clear observation of how wood density varies in the radial direction from the pith to the bark, revealing specific growth patterns and internal structure in each species. This detailed visualization of density is crucial for wood characterization, as it directly influences its mechanical properties and suitability for various industrial applications.

Furthermore, the methodology used not only provides an accurate view of the intrinsic differences in wood density between native and non-native species, but also highlights the practical applications in forest management. The ability to visualize and analyze these density variations contributes to more sustainable and efficient forest management practices, optimizing wood product quality and improving decision-making in the forestry industry. This innovative approach holds great potential for enhancing wood quality assessments and strengthening sustainable management practices in the forestry sector.

The visual classification of X-ray images using QGIS allowed to build high resolution maps of wood density variation along whole cross section (Fig. 2).

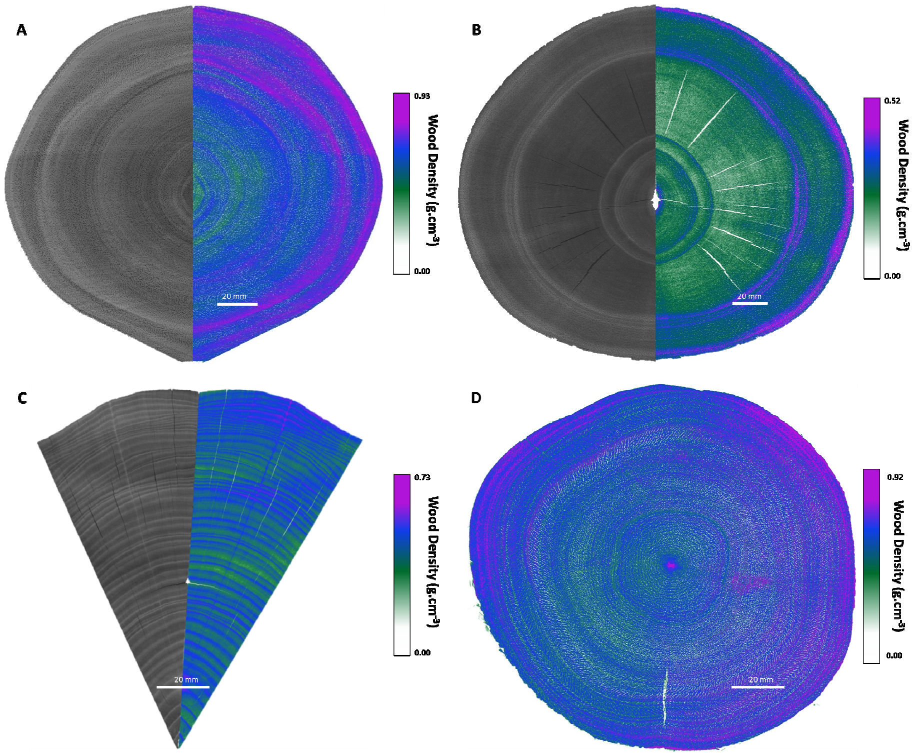

Fig. 2. X-ray densitometry samples of the studied species, visually classified by apparent density using QGIS software: a) Acacia mangium, b) Ochroma pyramidale, c) Pinus sp., d) Eucalyptus grandis.

Numerous studies have been conducted on X-ray densitometry in wood samples, both destructive and non-destructive, using small samples to analyze the wood density profile in the radial direction: bark-to-pith or bark-to-bark (Cahuana et al. 2023; Gaitan et al. 2019; Moya et al. 2009; Ortega et al. 2022; Pompa-García et al. 2024; Quintilhan et al. 2021). Although some scientific articles have presented images of the complete cross-section of a wood slice

(Chambi-Legoas et al. 2023; Del Valle et al. 2012), until now, samples have not been used for the analysis of wood density in a significant part or the entire cross-section, allowing the density to be visualized on the transverse surface with the help of geographic information system software. Few studies have combined X-ray densitometry with geographic information system software, such as performing an interpolation analysis to evaluate the longitudinal and radial variation of X-ray density (Moraes et al. 2023).

DiscBot, developed by Scion (The New Zealand Forest Research Institute Limited), integrates multiple non-destructive evaluation techniques (NIR hyperspectral imaging, radial acoustics, densitometry, and fiber angle scanning) into a single platform. This provides a multidimensional and detailed characterization of the physical, mechanical, and chemical properties of wood at a cubic centimeter scale (Schimleck et al. 2019). DiscBot offers an integrated and holistic approach, enhancing the ability to predict and manage the performance of wood products (Gendvilas et al. 2022). However, combining different technologies into a single device is pricey costly. In contrast, X-ray densitometry combined with QGIS allows for precise evaluation of the apparent density of wood and a clear visualization of its distribution, facilitating the identification of intrinsic variations within a sample. This method is highly effective for detailed and specific studies of wood density.

Understanding wood density in the complete cross-section of a tree using X-ray densitometry images combined with geographic information system (GIS) software like QGIS can assist in several ways: it allows for a precise evaluation of wood quality, crucial for determining its potential use in various industrial applications; it facilitates the identification of intrinsic variations, defects, and deteriorated zones, improving wood management and utilization; it assists forest managers in making informed decisions about sustainable forest management; it provides precise data for scientific studies on wood structure and properties; it optimizes log processing, reducing waste and enhancing production efficiency; it enables continuous monitoring of tree growth and health, allowing for early detection of problems; it contributes to the analysis of tree biomass and biomechanics, helping to better understand structural resistance and tree stability; it allows the study of the relationship between wood density and climatic conditions, providing valuable information on how environmental factors affect tree growth and development. Finally, integration with QGIS facilitates clear and comprehensible visualization of wood density and its distribution, making it useful for communicating findings to scientists, forest managers, and the general public.

CONCLUSIONS

We conclude that measuring the apparent density of wood using X-ray densitometry and analyzing it with geographic information system software like QGIS provides a powerful and precise tool for evaluating the quality and structural properties of different tree species. In this study, average densities ranged from 0.17 g/cm^3 in *Ochroma pyramidale* to 0.55 g/cm^3 in *Eucalyptus grandis*, reflecting both intrinsic species differences and the environmental conditions affecting their growth. This approach allows for a detailed visualization of wood density variation, identifying zones of high and low density that influence mechanical properties. The integration of these innovative methods enhances decision-making in forest management, improves the quality of wood products, and promotes the sustainable and efficient use of forest resources, contributing to the overall sustainability of the sector.

REFERENCES

1. Anten, N., & Schieving, F. (2010). The role of wood mass density and mechanical constraints in the economy of tree architecture. The American Naturalist, 175(2), 250-260 pp.
2. Arnič, D., Krajnc, L., Gričar, J., & Prislan, P. (2022). Relationships between wood-anatomical features and resistance drilling density in Norway spruce and European beech. Frontiers in Plant Science, 13, 1-13 pp.
3. Arra'd, I., Dwianto, W., Sudarmanto, Narto, Adi, D.S., Triwibowo, D., Darmawan, T., Amin, Y., Bahanawan, A., Sejati, P.S., Damayanti, R., Djarwanto, Rahmanto, R.G.H., Agustiningrum, D.A., Pari, R., Dewi, L.M., Kusumah, S.S., Augustina, S., & Marbun, S.D. (2024). Application of near-infrared spectroscopy for predicting the wood density of teakwood stands by increment cores and thin wood surface sampling. International Wood Products Journal 0(0) 8 pp.
4. ASTM D2395 (2017). Standard test methods for density and specific gravity (relative density) of wood and wood-based material.
5. Cahuana, L.A.P., Piña, E.A.G., Tuesta, G.P., & Tomazello-Filho, M. (2023). Radial variation of wood density and fiber morphology of two commercial species in a tropical humid forest in Southeastern Peru. Cerne, 29, 9 pp.
6. 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 pp.
7. Chambi-Legoas, R., Tomazello-Filho, M., Vidal, C., & Chaix, G. (2023). Wood density prediction using near-infrared hyperspectral imaging for early selection of *Eucalyptus grandis* trees. Trees, 37(3), 981-991 pp.
8. Chavesta, M., Montenegro, R., Romero, J., Tomazello-Filho, M., Carneiro, M., & Nisgoski, S. (2022). Colorimetría y densitometría en madera de *Guazuma crinita*. Maderas. Ciencia y Tecnología, 24(32), 1-12 pp.
9. Del Valle, J. I., Ramirez, J.A., & Herrera, D.A. (2012). Experiencias dendroclimáticas con árboles de ecosistemas contrastantes de Colombia. Cuadernos de Geografía: Revista Colombiana de Geografía, 21(2), 117-126 pp.
10. Fajardo, A. (2022). Wood density relates negatively to maximum plant height across major angiosperm and gymnosperm orders. American Journal of Botany, 109(2), 250-258 pp.
11. Francis, J.K. (1994). Simple and inexpensive method for extracting wood density samples from tropical hardwoods. Tree Planter's Notes, 45(1), 10-12 pp.
12. Freyburger, C., Longuetaud, F., Mothe, F., Constant, T., & Leban, J.M. (2009). Measuring wood density by means of X-ray computer tomography. Annals of Forest Science, 66(8), 804-804 pp.

13. 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 pp.
14. Gao, J., Kim, J.S., Terziev, N., Cuccui, I., & Daniel, G. (2018). Effect of thermal modification on the durability and decay patterns of hardwoods and softwoods exposed to soft rot fungi. International Biodeterioration & Biodegradation, 127, 35-45 pp.
15. Gendvilas, V., Neyland, M., Rocha-Sepúlveda, M.F., Downes, G.M., Hunt, M., Jacobs, A., Williams, D., Vega, M., & O'reilly-Wapstra, J. (2022). Effects of thinning on the longitudinal and radial variation in wood properties of *Eucalyptus nitens*. Forestry: An International Journal of Forest Research, 95(4), 504-517 pp.
16. Gough, G., & Barnes, R.D. (1984). A comparison of three methods of wood density assessment in a *Pinus elliottii* progeny test. South African Forestry Journal, 128(1), 22-25 pp.
17. Hervé, V., Mothe, F., Freyburger, C., Gelhaye, E., & Frey-Klett, P. (2014). Density mapping of decaying wood using X-ray computed tomography. International Biodeterioration & Biodegradation, 86, 358-363 pp.
18. Lehnebach, R., Bossu, J., Va, S., Morel, H., Amusant, N., Nicolini, E., & Beauchêne, J. (2019). Wood density variations of legume trees in French Guiana along the shade tolerance continuum: Heartwood effects on radial patterns and gradients. Forests, 10(80), 22 pp.
19. Lira-Martins, D., Quesada, C.A., Strekopytov, S., Humphreys-Williams, E., Herault, B., & Lloyd, J. (2022). Wood nutrient-water-density linkages are influenced by both species and environment. Frontiers in Plant Science, 13, 15 pp.
20. Macfarlane, D.W. (2020). Functional relationships between branch and stem wood density for temperate tree species in North America. Frontiers in Forests and Global Change, 3, 16 pp.
21. Mahari, A., Eshete, G., & Watson, A.T. (2024). Efficient and sustainable wood density assessment in tropical trees: A comparative analysis of increment borer and destructive methods in timber logging hotspots. 40(01), 1529-1534 pp.
22. Mascarenhas, A.R.P., Sccoti, M.S.V., Melo, R.R., Corrêa, F.L., Souza, E.F.M. De, & Pimenta, A.S. (2021). Quality assessment of teak (*Tectona grandis*) wood from trees grown in a multi-stratified agroforestry system established in an Amazon rainforest area. Holzforschung, 75(5), 409-418 pp.
23. Moraes, L.G., Lima, M.D.R., Assis-Pereira, G., De Almeida Gonçalves, D., Vidaurre, G. B., Bufalino, L., Guedes, F.T.P., Tomazello-Filho, M., & De Paula Protásio, T. (2023). Forking and planting spacing impacts on wood density, X-ray density, and heartwood proportion of *Tachigali vulgaris*. Trees, 37(5), 1567-1581 pp.
24. Moya, R., Berrocal, A., Serrano, J.R., & Tomazello, M. (2009). Radial variation of anatomical features, wood density and decay resistance in teak (*Tectona grandis*) from two qualities of growing sites and two climatic regions of Costa Rica. Forest Systems, 18(2), 1-19 pp.

25. Moya, R., & Tomazello, M.T. (2009). Trees using X-ray densitometry. Cerne, 15(1), 9.
26. Nock, Ch., Geihofer, D., Grabner, M., Baker, P., Bunyavejchewin, S., & Hietz, P. (2009). Wood density and its radial variation in six canopy tree species differing in shade-tolerance in western Thailand. Annals of Botany, 104(2), 297-306 pp.
27. Nowak, T. P., Jasieńko, J., & Hamrol-Bielecka, K. (2016). In situ assessment of structural timber using the resistance drilling method – Evaluation of usefulness. Construction and Building Materials, 102, 403-415 pp.
28. NTP N°251.011. (2016). Maderas. Método de Determinación de Densidad. 14pp.
29. Olale, K., Yenesew, A., Jamnadass, R., Sila, A., & Shepherd, K. (2019). A simple field based method for rapid wood density estimation for selected tree species in Western Kenya. Scientific African, 5, 7 pp.
30. Ortega, D.R., Hevia, A., Sánchez-Salguero, R., Santini, L., Carvalho, H.W.P. De, Roig, F. A., & Tomazello-Filho, M. (2022). Exploring wood anatomy, density and chemistry profiles to understand the tree-ring formation in Amazonian tree species. Dendrochronologia, 71, 17 pp.
31. Ortega Rodriguez, D.R., & Tomazello-Filho, M. (2019). Clues to wood quality and production from analyzing ring width and density variabilities of fertilized *Pinus taeda* trees. New Forests, 50(5), 821-843 pp.
32. 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 pp.
33. Petrea, S., Radu, G.R., Braga, C.I., Cucu, A.B., Serban, T., Zaharia, A., Pepelea, D., Ienasoiu, G., & Petritan, I.C. (2024). The role of wood density variation and biomass allocation in accurate forest carbon stock estimation of European beech (*Fagus sylvatica* L.) mountain forests. Forests, 15(3), 20 pp.
34. Pompa-García, M., Vivar-Vivar, E.D., Hornink, B., Martínez-Rivas, J.A., Ortega-Rodriguez, D.R., & Tomazello-Filho, M. (2024). Tree-ring wood density reveals differentiated hydroclimatic interactions in species along a bioclimatic gradient. Dendrochronologia, 85, 10 pp.
35. 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 pp.
36. Portal-Cahuana, L.A., Kohagura-Arrunátgui, J.A.H., Flores, C.E.M., Frías-Quiñones, T., & Tomazello-Filho, M. (2023). Wood anatomical structure and density of *Tachigali aubl* species occurring in the southeastern Peruvian Amazon forest. Revista Floresta, 53(2), 174-183 pp.
37. 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, 10 pp.

38. Qumruzzaman, M., Ishiguri, F., Hiraiwa, T., Matsumoto, K., Takashima, Y., Iizuka, K., Yokota, Sh., & Yoshizawa, N. (2012). Variation in anatomical properties and correlations with wood density and compressive strength in *Casuarina equisetifolia* growing in Bangladesh. Australian Forestry, 75(2), 95-99 pp.
39. Roquette, J.G., Ortega-Rodriguez, D.R., Portal-Cahuana, L.A., De Almeida Lobo, F., Hevia, A., Sánchez-Salguero, R., Pereira De Carvalho, H.W., & Tomazello-Filho, M. (2023). Environmental forensics evaluation of residual soybean sludge using trees of Brazilian savannah. Environmental Nanotechnology, Monitoring & Management, 20, 11 pp.
40. Santini, L., Ortega, D., Quintilhan, M., Brazolin, S., & Tommasiello, M. (2019). Evidence to wood biodeterioration of tropical species revealed by non-destructive techniques. Science of The Total Environment, 672, 357-369 pp.
41. Schimleck, L., Dahlen, J., Apiolaza, L.A., Downes, G., Emms, G., Evans, R., Moore, J., Pâques, L., Van Den Bulcke, J., & Wang, X. (2019). Non-destructive evaluation techniques and what they tell us about wood property variation. Forests, 10(9), 50 pp.
42. Sousa, W.C.S.E, Barbosa, L. De J., Soares, A.A.V., Goulart, S.L., & Protásio, T. De P. (2019). Wood colorimetry for the characterization of Amazonian tree species: a subsidy for a more efficient classification. CERNE, 25(4), 451-462 pp.
43. Takoudjou, S., Ploton, P., Martin-Ducup, O., Lehnebach, R., Fortunel, C., Sagang, L. B. T., Boyemba, F., Couteron, P., Fayolle, A., Libalah, M., Loumeto, J., Medjibe, V., Ngomanda, A., Obiang, D., Pélissier, R., Rossi, V., Yongo, O., Preredd Collaborators, Bocko, Y., … Barbier, N. (2020). Leveraging signatures of plant functional strategies in wood density profiles of African trees to correct mass estimations from terrestrial laser data. Scientific Reports, 10(1), 11 pp.
44. Todoroki, C.L., Lowell, E.C., & Filipescu, C.N. (2021). Wood density estimates of standing trees by micro-drilling and other non-destructive measures. New Zealand Journal of Forestry Science, 51, 14 pp.
45. 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), 139-150 pp.
46. Van Leeuwen, M., Hilker, T., Coops, N.C., Frazer, G., Wulder, M.A., Newnham, G.J., & Culvenor, D.S. (2011). Assessment of standing wood and fiber quality using ground and airborne laser scanning: A review. Forest Ecology and Management, 261(9), 1467-1478 pp.
47. Vieilledent, G., Fischer, F. J., Chave, J., Guibal, D., Langbour, P., & Gérard, J. (2018). New formula and conversion factor to compute basic wood density of tree species using a global wood technology database. American Journal of Botany, 105(10), 1653-1661 pp.
48. Wu, S., Xu, J., Li, G., Risto, V., Lu, Z., Li, B., & Wang, W. (2010). Use of the Pilodyn for assessing wood properties in standing trees of eucalyptus clones. Journal of Forestry Research, 21(1), 68-72 pp.
49. Xue, J., Xu, W., Zhou, J., Mao, W., & Wu, S. (2022). Effects of high-temperature heat treatment modification by impregnation on physical and mechanical properties of poplar. Materials, 15(20), 19.

50. Yang, H., Wang, S., Son, R., Lee, H., Benson, V., Zhang, W., Zhang, Y., Zhang, Y., Kattge, J., Boenisch, G., Schepaschenko, D., Karaszewski, Z., Stereńczak, K., Moreno-Martínez, Á., Nabais, C., Birnbaum, P., Vieilledent, G., Weber, U., & Carvalhais, N. (2024). Global patterns of tree wood density. Global Change Biology, 30(3), 13 pp.

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