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Variability of vessel diameter, growth ring width and wood density in Paulownia (*Paulownia tomentosa*)

Variabilität des Gefäßdurchmessers, der Jahrringbreite und der Holzdichte bei Paulownia (*Paulownia tomentosa*)

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Schlüsselbegriffe: Gefäße, Xylem, Holzanatomie, Holzqualität, raschwüchsige Baumarten, Aufforstungen

Abstract

Paulownia tomentosa is a fast-growing broadleaf species of increasing interest for timber and bioenergy production. This study examined the interactions between the microscopic structure of the wood — specifically the vessel element size, wood density, and growth ring width — in samples collected from a five-year-old plantation in Vasilika, Thessaloniki. The results indicated significant variability in anatomical characteristics across growth rings. Vessel diameter increased toward the outer growth rings, while it consistently decreased from earlywood to latewood. The average wood density was 0.285 g/cm^3, and it was negatively correlated with vessel diameter. In conclusion, vessels play a critical role in determining the wood quality of *Paulownia tomentosa*, a ring-porous species that displays semi-diffuse porosity in its early developmental stages.

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Zusammenfassung

Paulownia tomentosa ist eine schnell wachsende Laubbaumart, die zunehmend für die Holz- und Bioenergieproduktion von Interesse ist. In dieser Studie wurden die Wechselwirkungen zwischen der mikroskopischen Holzstruktur – insbesondere der Größe der Gefäßelemente, der Holzdichte und der Jahrringbreite – an Proben aus einer fünf Jahre alten Plantage in Vasilika, Thessaloniki, untersucht. Die Ergebnisse zeigten eine erhebliche Variabilität der anatomischen Merkmale zwischen den Jahrringen. Der Gefäßdurchmesser nahm zu den äußeren Jahrringen hin zu, während er vom Frühholz zum Spätholz hin kontinuierlich abnahm. Die durchschnittliche Holzdichte betrug 0.285 g/cm^3 und stand in negativer Korrelation zum Gefäßdurchmesser. Zusammenfassend lässt sich sagen, dass die Gefäße eine entscheidende Rolle für die Holzqualität von *Paulownia tomentosa* spielen, einer ringporigen Art, die in ihren frühen Entwicklungsstadien eine semi-diffuse Porosität aufweist.

1 Introduction

Paulownia species are widely distributed, fast-growing forest trees native to East Asia. Commonly known as the "miracle tree", "princess tree," "dragon tree," or "Kiri" in Japan, *Paulownia* has been cultivated for over 2,300 years in China and almost 1,000 years in Japan and Korea. Besides its high carbon sequestration potential, even in the case of small rotation cultivations (Magar *et al*., 2018), *Paulownia* holds considerable economic value due to its multiple uses, particularly in timber production (Van de Hoef & Hill, 2003; Esteves *et al*., 2022). In Greece, it is grown in plantations for the production of technical and construction timber, biomass for energy, and for environmental applications (Spanos & Gaitanis, 2021). Cultivated hybrids are mainly *Paulownia tomentosa* and *Paulownia elongata*, while research on these and new hybrids is being conducted by the Forest Research Institute (FRI) (Spanos & Gaitanis, 2021).

The wood of *Paulownia* is suitable for many applications due to its favorable properties, fast growth rate, and high biomass yield in a short period. It is light-colored, low-density wood with relatively good strength-to-weight characteristics (Zhu *et al*., 1986; Yadav *et al*., 2013; Icka *et al*., 2016; Koman & Feher, 2020). Every part of the Paulownia plant can be used as an energy source, including pellet production, offering an energy yield of 4211.1 kcal/kg (Rodríguez-Seoanea *et al*., 2020; Linnik, 2020). High-quality timber is used in solid wood products, veneers, and pulp, while lower-quality wood is utilized in biofuels, pellets, and particleboards (OSB, MDF) (Bergmann, 1998; Bee *et al*., 2005; Clatterbuck & Hodges, 2004; Hua *et al*., 2022; Jakubowski, 2022). It is also used for furniture, woodcarvings, doors and frames, molds, picture frames, canoes, toys, fishing rods, posts, pallets, crates, *etc*. (Zhao-Hua *et al*., 1986; Akyildiz & Kol, 2010a, 2010b; Jakubowski, 2022). It should be noted that during the last decades, reforestation with fast growing species for biomass production is an effective treatment of degraded forest areas, contributing to the stability of environmental conditions (García-Morote *et al*., 2014).

Although *Paulownia* wood is not ideal for high-load structural applications, it is widely used in beams for house construction. Its low density and natural decay resistance without warping or cracking make it ideal for aircraft models, gliders, plywood furniture, and packaging (crates) (Akyildiz & Kol, 2009). Recent studies aim to further develop its use in plastics, composite wood materials, and biopolymers (Jakubowski, 2022), as well as in wood-based panels, such as OSB and particleboards, especially in dry conditions and in structures with low loads (Fauziyyah *et al*., 2025). Such research aligns with the view that product selection should be tailored to the species' mechanical limitations.

However, to fully capture the utilization potential of *Paulownia*, we must also consider its biomass productivity, as expressed by the product of stem volume and wood density (Biomass = Volume × Wood density). Merriman *et al*. (2025) tried to estimate the annual biomass production of a *Paulownia* plantation over a 10-year rotation, which may range from 0.5 to 25.4 oven-dry tones per hectare per year (t/ha/yr). This range can be considered as typical for fast-grown species, having, according to the same authors, a wood utilization potential. Unfortunately, data scarcity hinders causal inference of growth factors (*e.g.* genetic factors, site conditions and management) on *Paulownia*'s biomass production. For example, in Bulgaria, the main cultivated hybrids are *Paulownia tomentosa* and *Paulownia elongata x fortunei*, with the first to show higher productivity and survival percentage in different locations (Gyuleva *et al*., 2021).

The structure of *Paulownia tomentosa* wood significantly affects its quality, playing a key role in its properties and utilization. It is characterized by large-diameter vessels, which facilitate the transport of water and nutrients (Jiang & Yang, 2010). Macroscopically, on a cross-sectional section, *Paulownia* appears as a ring-porous or semi-diffuse porous hardwood, with clearly defined growth ring boundaries. Growth ring width is usually around 2 cm and may exceed 4 cm during the first years of growth. Furthermore, the transition from heartwood to sapwood is hardly noticeable (Fos *et al*., 2023).

Previous studies have shown that annual ring width varies with geographic origin. Paulownia wood from Serbia had an average ring width of 1.7 cm, while samples originating from Spain and Bulgaria showed greater widths of 2.83 cm and 4.6 cm, respectively (Bardarov & Popovska, 2017; Komán & Vityi, 2017). These variations are linked to soil and climate conditions, tree age, and height. In a trial plot at Souroti area in Thessaloniki (Greece), the average growth ring width of five-year-old *Paulownia* logs ranged between 2.23 cm and 2.83 cm, indicating a growth rate comparable to other internationally cultivated *Paulownia* species. The samples were collected from five, approximately one meter long, logs taken from the base of five coppice trees (Chavenetidou & Foti, 2023).

Studies have shown that larger vessel diameters may result in lower wood density, as they occupy more space, leaving less room for other wood cell structures (Hacke & Sperry, 2001). Conversely, smaller vessels are associated with higher wood density due to more solid wood mass. However, this relationship may vary, depending on cultivation conditions and genetic factors (Baas & Schweingruber, 1987).

This study aims to examine the variability in vessel element width in *Paulownia tomentosa* and investigate its relationship with (a) wood density and (b) growth ring width. The research seeks to explore how variations in vessel dimensions may affect wood density. Understanding these factors will support more efficient management and cultivation of *Paulownia tomentosa*, promoting high-quality wood production and improving silvicultural practices. Finally, the study aims to expand scientific knowledge on the microscopic characteristics of this important forestry species and explore their links to the physical and mechanical properties of its wood.

2 Materials and Methods

The study material was obtained from five five-year-old *P. tomentosa* trees (regenerated by coppicing), with a root system aged 10 years, located in an experimental *Paulownia* plantation of the FRI in the Vasilika area of Thessaloniki (Fig. 1). Logging and sample preparation were conducted on 1/2/2023. The plantation comprised five consecutive tree rows, each containing 13 individuals, planted with a 3 x 3 m spacing pattern which results in a stem density of 1110 stems/ha. The basal area and growing stock were estimated at 18 m^2/ha and 87 m^3/ha, respectively. The biometric data of the studied trees are presented in Table 1.

Table 1: Properties of the sampled trees.

Tabelle 1: Eigenschaften der untersuchten Bäume.

Tree	Base diameter (cm)	DBH (Diameter at breast height) (cm)	Top diameter (before crown crown) (cm)	Total height (m)	Trunk height (Stump to crown start) (m)	Stump height (cm)
2	17.0	13.5	10.5	8.35	3.45	5.0
3	21.0	16.0	10.3	9.30	4.65	5.0
7	16.0	12.5	9.0	8.80	3.80	5.0
10	19.0	14.5	11.5	9.0	3.60	5.0
13	19.0	15.0	9.0	8.10	4.35	5.0

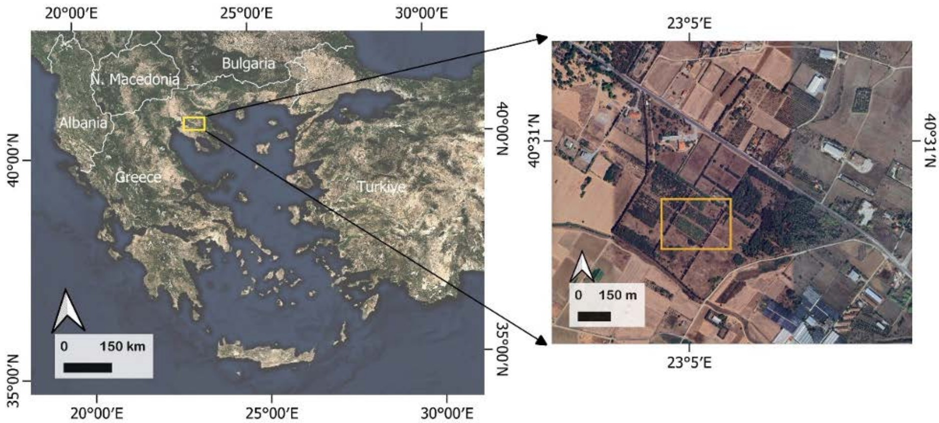

Figure 1: Location of the study site in Greece (left) and detailed view of the sampling area (right). Background imagery: Sentinel-2 satellite image (© ESA/Copernicus). Administrative boundaries: Natural Earth.

Abbildung 1: Lage des Untersuchungsgebietes in Griechenland (links) und Detailansicht des Probenahmebereichs (rechts). Hintergrundbild: Sentinel-2-Satellitenbild (© ESA/Copernicus). Verwaltungsgrenzen: Natural Earth.

The samples were collected from a row near the edge of the plantation, oriented to the east. The felled trees were the 2., 3., 7., 10. and 13. individuals in the row.

Figure 2: The studied Paulownia plantation in 2020.

Abbildung 2: Die untersuchte *Paulownia*-Plantage im Jahr 2020.

From the five tree trunks, cross-sectional discs were collected from the base and at 1 m intervals along the stem, up to the point where the crown began. The discs were placed under controlled humidity conditions in the laboratory to allow gradual moisture loss, thus preventing cracking or splitting. The second disc, taken at 1 m height, was selected for further analysis. From this disc, cubes dimensioned 1.5 x 1.5 x 1.5 cm were prepared in such a way as to represent the transverse, tangential, and radial planes of the wood (Fig. 2a). The samples were then softened by boiling in deionized water and stored in a solution containing glycerin, ethyl alcohol, and water for a specified period, to facilitate easier handling during microtome sectioning.

From each sample, 15 μm thick sections were prepared using a portable WSL-type microtome (Fig. 3a). The sections were stained with safranin (Fig. 3b). The stained preparations were mounted on glass slides and permanently fixed using Canada balsam (Pasialis, 1997; Chavenetidou, 2009).

Microscopic observation and vessel measurements were carried out using a Nikon Eclipse 50i optical microscope. The samples were photographed with a Nikon DS-Fi1-L2 digital camera mounted on the microscope at 40x magnification. Vessel diameters were measured through digital imaging and analysis of the photographs, using the microscope‘s proprietary software (Fig. 3a & 3b).

The collected data concerned the diameters of earlywood and latewood vessels in the growth rings (radially and tangentially for each vessel), which were statistically analyzed to identify any relationships between variables. Data entry was done in Excel (Microsoft Office 365), and statistical analyses were conducted using IBM SPSS version 23 (IBM, 2015). Normality was tested using the Kolmogorov-Smirnov test, while statistically significant differences between earlywood and latewood were assessed using a t-test.

Wood density was determined according to ASTM D143-94 standards. In each wood strip taken from the selected discs, individual growth rings were separated with the help of a blade and used for determining oven-dry density (Fig. 5a). The dry samples were weighed using a high-precision balance to determine their mass (Fig. 5b). Sample volume was calculated either by direct measurement of dimensions (for geometrically regular shapes) or by water displacement using Archimedes’ principle (for irregular shapes) (Tsoumis, 1991).

3 Results and Discussion

Measurements were carried out along the bark-to-pith direction, with growth ring A representing the outermost ring and ring E representing the innermost, closest to the pith. In the outer growth rings, a strong presence of paired vessel elements was observed, gradually decreasing toward the inner rings. Additionally, a progressive reduction in vessel width from earlywood to latewood was recorded within each growth ring—characteristic of semi-diffuse porous species. However, this pattern may be related to the presence of juvenile wood, likely due to the young age of the samples. This trend appeared to diminish as the rings moved further away from the pith.

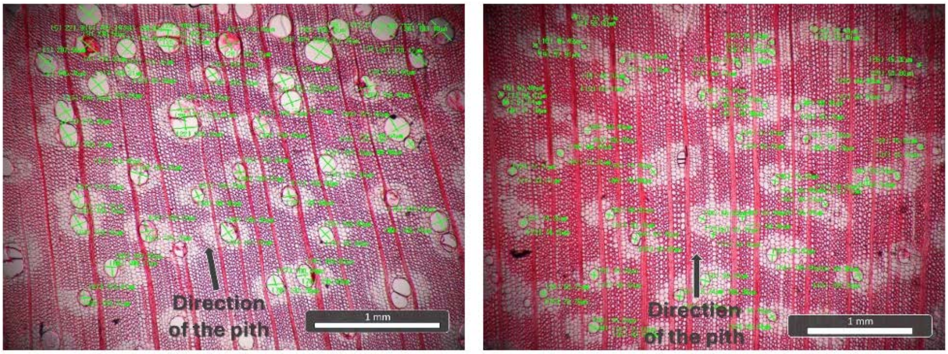

Figure 3: Earlywood transverse Paulownia section (left panel 3a), Latewood Paulownia section (right panel 3b, both sections taken from the same sample).

Abbildung 3: Querschnitt durch Frühholz von *Paulownie* (links, 3a), Querschnitt durch Spätholz von *Paulownie* (rechts, 3b, beide Schnitte stammen aus derselben Probe).

According to Table 2, earlywood vessel diameter ranged from 53.765 to 293.565 µm, with a mean value of 167.233 µm based on 1,692 cell measurements. Latewood vessel diameter ranged from 15.940 to 119.825 µm, with a mean value of 62.397 µm from a total of 1,663 measurements. In both cases, the data followed a normal distribution. Mean vessel width was statistically lower in earlywood compared to latewood ($t(3354) = -105.30$, $p < 0.001$ 95%; CI: -115.94 to -111).

Table 2: Descriptive statistics of earlywood and latewood vessel diameters of Paulownia.

Tabelle 2: Beschreibende Statistiken der Gefäßdurchmesser von Frühholz und Spätholz von *Paulownie*.

Parameter	Sample Size (N)	Range (µm)	Mean (µm)	Standard Deviation
Earlywood vessel width	1692	53.765 – 293.565	167.233	43.860
Latewood vessel width	1663	15.940 – 119.825	62.397	17.654

As for wood density, it ranged from 0.154 to 0.265 g/cm^3, with an average of 0.354 g/cm^3 and a standard deviation of 0.041. Compared to our result, Akyildiz and Kol (2010a) reported a lower average density of 0.272 g/cm^3 for *Paulownia tomentosa* wood from Turkey, which has also been the case for Komán and Feher (2020) who reported a density of 0.246 g/cm^3 for *Paulownia tomentosa* from Hungary. However, the lowest density values having reported for Spanish *Paulownia* wood at 0.215 g/cm^3 (Lachowicz & Giedrowicz 2020) and 0.216 g/cm^3 (Lachowicz *et al*., 2020). In contrast, Esteves *et al*. (2022) determined a density of 0.460 g/cm^3 for *Paulownia* (COTEVISA-2) wood in Portugal—higher than the average density of spruce (430 kg/m^3) (Grosser, 2007).

When comparing these values to those of Balsa wood, which has a density of approximately 160 kg/m^3 (Byrne & Nagle, 1997; Borrega & Gibson, 2015), it becomes clear that Paulownia wood has a higher density than *Balsa* but lower than other lightweight woods, such as poplar, which has a density of 440 kg/m^3 (Grosser, 2007; Ciftci & Kaya, 2019).

Based on a previous study in Greece (Chavenetidou & Foti, 2023), the oven-dry density of *Paulownia tomentosa* wood ranged from 0.32 to 0.39 g/cm^3, while the apparent density ranged from 0.30 to 0.44 g/cm^3. The average oven-dry density was 0.35 g/cm^3 and the average apparent density 0.38 g/cm^3—values that were comparable to other studied species.

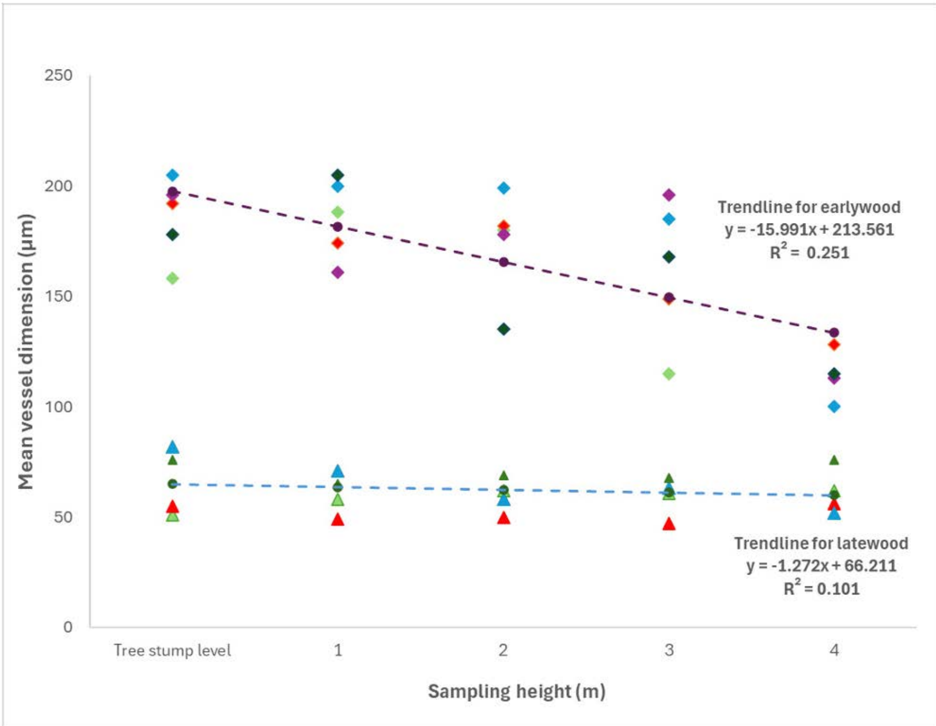

Figure 4: Variation of mean vessel dimension in relation to sampling height for earlywood and latewood tissues. Data points represent individual measurements taken at 1-m intervals, from tree stump level to 4 meters above stump.

Abbildung 4: Variation der mittleren Gefäßdurchmesser in Abhängigkeit von der Probennahmehöhe für Früh- und Spätholzgewebe. Die Datenpunkte repräsentieren Einzelmessungen im Abstand von 1 m, vom Baumstumpf bis 4 m über Wurzelstock.

Figure 4 shows the variability of vessel diameter in earlywood and latewood across trees and growth rings. According to Fos *et al*. (2023), this variability is expected, since *Paulownia* is a ring-porous broadleaf species. However, the first five years of growth are considered to belong to the juvenile wood zone, which tends to exhibit semi-diffuse porosity.

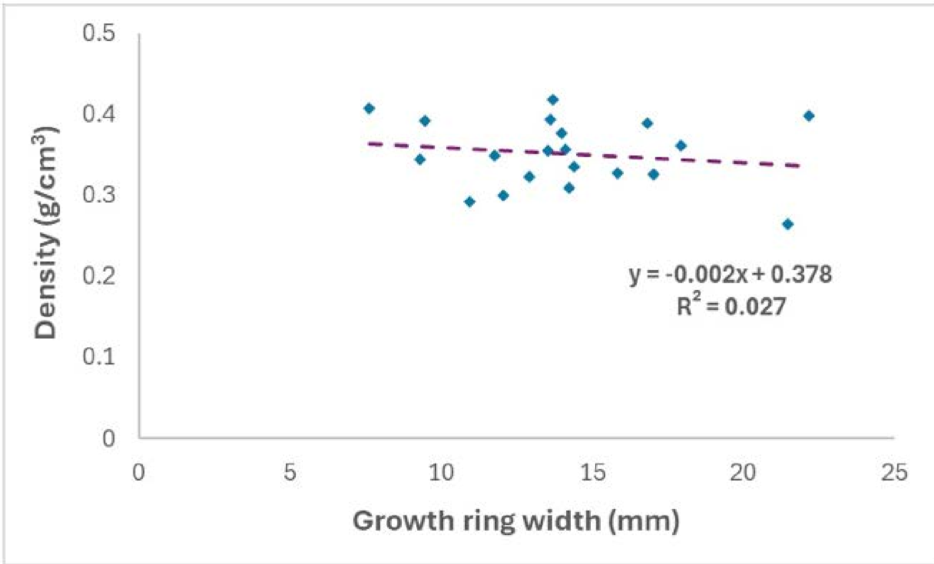

Figure 5: Linear correlation between growth ring width and density of Paulownia.

Abbildung 5: Lineare Korrelation zwischen Jahrringbreite und Dichte von *Paulownie*.

Figure 5 presents the linear relationship between growth ring width and wood density. A negative correlation between the two variables was observed, with a very low R^2 value (0.027) and a Pearson correlation coefficient of -0.156, indicating a weak linear correlation. Although it has been reported that wood density in ring-porous hardwoods often increases with growth ring width (Tsoumis, 1991), in *Paulownia tomentosa* the large vessel diameter and high proportion of parenchyma cells appear to be associated with a slight trend toward reduced density.

These findings are consistent with previous studies. Statistically significant linear correlations between density and growth ring width have been observed in other ring-porous hardwoods, such as chestnut and acacia (r = 0.563 for acacia and r = 0.234 for chestnut) (Adamopoulos *et al*., 2010). According to the same researchers, no statistically significant correlation was found between oven-dry density and growth ring width.

In all trees, earlywood was characterized by larger vessel diameters, highlighting the ring-porous structure of *Paulownia tomentosa* wood and its role in rapid water transport during the growing season. In contrast, latewood had smaller vessels, contributing to mechanical stability. Vessel width showed wide variability, indicating the functional adaptability of the wood to changing environmental conditions. In certain trees, such as Tree 13, a gradual decrease in vessel diameter was observed from the outer to the inner growth rings.

Growth ring width in most trees showed low variability, with average values reflecting stable growing conditions. Similarly, wood density showed less variation compared to vessel diameter, indicating greater structural stability. Although the negative correlation between density and growth ring width was statistically significant, it remained generally weak. Overall, earlywood differed from latewood in all trees, both in terms of physical and functional properties. This was confirmed by the results of the study, with earlywood exhibiting greater measurement variability compared to latewood.

4 Conclusions

This study investigated the variability in vessel element width and growth ring width in *Paulownia tomentosa* and examined their relationships with wood density. Wood density was significantly correlated with vessel width, even though the effect size was small to moderate. Density also exhibited a weak linear relationship with growth ring width. In most trees, mean growth ring width displayed low variability, suggesting relatively stable growing conditions.

Linking anatomical traits to wood density is important for improving genetic selection and guiding silvicultural practices aimed at producing high-quality technical timber. Further research should clarify how these anatomical characteristics interact with wood formation and density in *Paulownia*, supporting more effective cultivation and the production of high-value wood.

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