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TECHNICAL COMMUNICATION

CONSIDERATIONS ON IMAGE RESOLUTION, MEASUREMENT ACCURACY, AND CROSSDATING IN THE DIGITAL ERA

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ABSTRACT

The field of dendrochronology is currently undergoing a transition, with an increasing reliance on digital analysis. Recent advances in hardware and software have enabled the rapid acquisition of information from wood in ways that were previously unattainable. However, the variety of digitization tools and the high resolutions achievable present a challenge in maintaining replicability and comparability of results. In addition, the high speed at which data are collected can lead to overlooking important aspects of dendrochronological techniques. For example, awareness of resolution of images for tree-ring measurements or even crossdating may play a minor role when setting tree-ring boundaries or may be biased towards the first samples measured.

This commentary addresses potential sources of error in the novel advances of digital techniques and highlights the suitability of combining digital advances with traditional data-control procedures that maintain the robustness and replicability of dendrochronological methods.

Keywords: crossdating, digitization, hardware, imaging, resolution.

COMMENTARY

The current widespread use of digital tools for data acquisition in dendrochronology has changed how dendrochronologists collect information from wood samples. In recent years, there have been discussions about maintaining classical measuring table-based methods or "going digital" with image-based techniques in the specialized forums (*e.g.* congresses, ITRDB forum). Advancements in sample digitation are pushing dendrochronology into the digital world, speeding up costly traditional workflows with remarkable results but also requiring the adaptation of the classic control points to the digital framework. Here, we remark and discuss some basic aspects to consider in the new era of digitization in the tree-ring science.

Hardware and software developments in image acquisition and data collection are significantly accelerating tree-ring measurements. Sample digitization is not something new; indeed, scanners or camera systems attached to a binocular lens were applied in recent decades (Aniol 1987; Guay *et al.* 1992; Levanič 2007). However, the image resolution was insufficient for analyzing samples that present challenging narrow rings or unclear tree-ring limits. Consequently, these technical constraints typically compelled the technical staff to revisit the physical sample under a stereo microscope.

Recent achievements in hardware tools for image acquisition have addressed those limitations (Griffin *et al.* 2021; García-Hidalgo *et al.* 2022; WSL 2023; Rydval *et al.* 2024). New digitization systems provide high-resolution images and allow for the collection of dendrochronological measurements, even for very narrow rings or other relevant structures (*e.g.* inter-annual density fluctuations, resin ducts). These digitization tools, along with the development of different dedicated user-friendly software (*e.g.* García-Hidalgo *et al.* 2021; Maxwell and Larsson 2021; Rademacher *et al.* 2021), have

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Table 1. Standard limit of resolution of different digitization devices with published documentation.

Dots per inch (dpi)	pixel size (μm)	Device	Hardware	Reference
2400 × 4800	10.58 × 5.29	12000XL Epson	CCD	Epson America 2024
6502	3.9	Skippy	CMOS	WSL 2023
6920	3.7	CaptuRING	CMOS	García-Hidalgo *et al.* 2022, Olano *et al.* 2023
19,812	1.28	Gigapixel	CMOS	Griffin *et al.* 2021
74,700	0.34	UHR reflected Light*	CCD attached to microscope	Rydval *et al.* 2024

*Requires microsectioning procedures.

significantly reduced the process of revisiting physical samples. Meanwhile, these technical innovations are decreasing the traditional reliance on the number of measuring facilities, as the images are stored as accessible files on personal computers, removing the restriction of available measuring stations in the lab. This new era of digitization and analysis of dendrochronological samples is putting aside the use of measurement tables and binocular lenses, which were essential to the field in the last century.

The different private and open-source alternatives for wood digitization introduce varying levels of data quality, departing from the standard accuracy of 0.001 mm offered by the traditional measuring tables. At the same time, the hardware resolution limits have changed from optical and table accuracy to optical lenses and digitization sensors. The digital resolution limit results in specific pixel sizes that predetermine the accuracy of the ring border delimitations. For example, scanners (CCD sensor) reach modest optical resolutions without remarkable improvements in recent decades, compared to camera-based tools (CMOS sensor) (Table 1). Therefore, the current tendency regarding hardware tools for digitization is focused on digital cameras with CMOS sensors, following macrophotography principles to achieve impressive pixel sizes (ca. 3.4 μm) without photo stacking. These pixel sizes exceed the actual resolutions of scanners but limit subsequent measurements using current width software tools.

The versatility of camera-based methods, including varied camera and lenses models, could hinder image comparisons and reproducibility. Thus, because of changes in hardware models and focus distances, camera-based systems require the incorporation of physical scales during the shooting process. These serve as checkpoints to address any distortions in the autofocus or the subsequent stitching process to get the whole image of the sample. Similarly, recent techniques dependent on color depth (*e.g.* Blue Intensity) would also require color standardization (Campbell *et al.* 2007; García-Hidalgo *et al.* 2023). Obtaining precise and accurate measurements from images requires a robust and reliable process from the physical sample to the digital image to avoid artifacts and inaccuracies in the measurements, in the same way that calibration of measuring tables was common in the past.

Despite the change in data collection techniques, crossdating remains a foundational process in dendrochronology, demanding a significant amount of time. The assignment of tree rings to calendar years is the cornerstone for further dendrochronological analysis (Cook and Pederson 2011). Thus, crossdating prevails as an essential step in any analysis based on dendrochronological data (Black *et al.* 2016; Björklund *et al.* 2019). Nowadays, digital tools make it easier to handle and measure tree-ring samples. However, this convenience can sometimes lead researchers to overlook crucial factors that affect the accuracy of crossdating.

Tree-ring measurements from images often bypass the initial visual crossdating and the identification of tree-ring characteristics. The digital method tends to simplify the dating process into quick, mechanistic mouse clicks from bark to pith, measuring and dating rings in a simultaneous step. The speed and ease of digital methods might tempt researchers to take shortcuts in the dating process. As users, we might assume that previously dated tree-ring series are accurate and simply adjust new measurements to fit these existing records. This digital practice, unfeasible with traditional measuring tables, is faster than traditional protocols but can generate significant biases in some species. The issue lies in skipping an essential step in dendrochronology, *i.e.* the identification of characteristic rings and visual crossdating of all samples before measuring. This could be solved with an initial screening of samples to ensure visual crossdating before measuring, which can be accomplished as done in the past by assigning decadal points. This step would require more time before measurements but ensures accurate data collection for complex series, species, or environments. However, we currently lack software tools specifically designed for this purpose.

The standard protocol in which a few individuals are dated to create an average series for comparison with other samples may work for species with predictable growth variability or easily identifiable ring structures. However, this standard method becomes less reliable when applied to more challenging species. Trees with highly variable growth rates, for instance, may not be well represented by just a few samples. Similarly, species with complex anatomical features can make it difficult to consistently identify and measure ring boundaries (Maxwell *et al.* 2011). This is especially true for many tropical species, where growth rings may be indistinct or irregular because of the lack of strong seasonal changes (Stahle 1999).

Recent digital systems allow for accurate tree-ring border detection following anatomical hints, and novel developments in statistical crossdating interfaces simplify year assignments (Bunn 2008, 2010). Nevertheless, preliminary visual assessment remains important for ensuring dating quality. Overall, the time saved by rapid data collection is negligible compared to the time spent rectifying measurements during the subsequent crossdating validation. It is critical to emphasize best practices for new dendrochronologists in the digital age and highlight the importance of dating samples before measuring, especially for complex samples. In this sense, software developers could also consider creating options to facilitate visual crossdating using images to ensure the reliability of dendrochronological data.

Dendrochronology is undergoing a widespread digitization movement that requires the adaptation of classical protocols to the dedicated image analysis software. We advocate for reconciling digital measurement with traditional crossdating to enhance dendrochronology through reliable image analysis.

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