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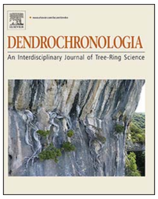

Original Article

Evaluating the robustness of three ring-width measurement methods for growth release reconstruction

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ABSTRACT

Growth release analysis on tree rings can be used to validate forest disturbances from the known past or reconstruct those beyond the time line or resolution of documentary evidence. Differences in ring-width measurements may result in incorrect disturbance reconstruction. Yet, little is known about how growth release detection is influenced by the ring-width measurement method. Methodological comparisons mostly do not take into account the ultimate objective of the measurements nor their practicalities, such as time consumption or sample preparation. We assessed differences in ring-width measurements between three methods (Lintab, measuRing, and DHXCT), in a ring-porous (*Quercus robur*) and diffuse-porous (*Fagus sylvatica*) species, and evaluated whether detection of growth releases was consistent among methods We also comprehensively compared the methods, including quantitative and qualitative criteria. Growth releases were consistent among methods despite small, but significant differences in ring-width values. The apparent robustness of the methods suggests that they may be substitutable in future growth release studies, although the highlighted drawbacks and necessary improvements may advocate combined approaches. Furthermore, we propose an evaluation framework for quantitative and qualitative methodological decision-making and advocate the need for similar methodological comparisons within other fields of dendrochronology.

1. Introduction

Ring-width (RW) series contain highly valuable and versatile information to monitor and understand a variety of natural (e.g. succession dynamics) and anthropogenic (e.g. forest management) processes (Speer, 2010). In dendroecology, growth release analyses allow the detection of historical forest disturbance events (e.g. Nowacki and Abrams, 1997; Altman et al., 2013). A growth release is an abrupt increase in radial growth in a tree which experienced improved light or nutrient conditions after mortality of a neighbouring tree (Oliver and Larson, 1990).

Obtaining reliable RW series is essential in growth release studies, since measurement or crossdating (CD) errors in RW series may give rise to incorrect disturbance reconstruction (Cook and Kairiukstis, 1990; Stokes and Smiley, 1996; Speer, 2010). In literature, three types of RW measurement methods are often used. First, a measuring stage which combines a sliding table with a microscope and software package (e.g. Lintab + TSAP-Win) is considered the conventional method (Stokes and Smiley, 1996). Second, semi-automatic image analysis on scanned digital images has gained interest and popularity thanks to increased availability and improved performance of affordable Flatbed scanners and software for image analysis (Speer, 2010; Maxwell et al., 2011). Commercial (e.g. CooRecorder) or user-created image analysis programs (e.g. *measuRing*, Lara et al., 2015) allow manual or automatic detection of ring boundaries based on properties of scanned images such as colour or light intensity (Maxwell et al., 2011). Third, semi-

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automatic image analysis on micro-focus X-ray computed tomography (XCT)-scanned images is a recent, innovative application for tree-ring analysis (Okochi et al., 2007; Grabner et al., 2009; Van den Bulcke et al., 2014; De Mil et al., 2016; Vannoppen et al., 2017).

Measurement methods have been compared in terms of accuracy of the resulting ring widths (Levanič, 2007; Maxwell et al., 2011; Nutto et al., 2012; Lara et al., 2015; Arenas-Castro et al., 2015). The majority of these comparative studies evaluated whether a more recent method measured RWs as accurately as a more conventional method (i.e. the "reference" for accuracy), and thus could substitute the latter.

However, the final objective of the measurements has mostly been ignored. Hence, to date, it remains for example unknown to what extent the employed method for RW measurement affects growth release results. Yet, it is highly relevant to investigate which methods are (more) robust for certain tree-ring analysis types, and thus might be more suited to use when performing that type of analysis. Firstly because an increasing number of available methods currently exist and are being used, without a thorough understanding of how the measurement method used influences the measurements and subsequent tree-ring analysis. Secondly because the resolution of measurements, for instance, might be a bigger issue in dendroclimatological studies (precise annual dating necessary for linking with climate events) than in growth release studies. That is, in growth release analyses, mean growth rates around a year of interest are *relatively* compared along the tree-ring series to identify growth increases above a critical level, so that the precise RW values might not be of key importance in the release detection process. Also, minor dating errors that can arise from using a lower resolution might be less of an issue in growth release analyses, since the timing and duration of a release is often allowed to differ with a number of years and still be considered "the same". This accounts for the fact that growth responses of trees following the same disturbance can be delayed in time as well as differ between trees or even within cores of the same tree (e.g. Copenheaver et al., 2009; Šamonil et al., 2015; Müllerová et al., 2016).

Comparative studies, besides generally ignoring the final measurement objective, usually do not consider more practical aspects of the measurement methods, such as time or cost efficiency, required sample preparation steps, or the user-friendliness of a method, either (Maxwell et al., 2011; Lara et al., 2015; Arenas-Castro et al., 2015). However, besides resolution, these practical aspects may influence the results as well, and may be well-worth considering when choosing a method, since there are often important trade-offs involved. For instance, if a large number of cores has to be measured, greater financial investments to use a specific method with a higher time efficiency may be justified. On the other hand, when cost price is a cut-off criterion, scientists may opt for the method that involves the lowest financial investment, both in terms of hardware and software as well as salaries. Nevertheless, resolution/accuracy remains a key characteristic to consider, and one should not accept a lower accuracy in a method, if this leads to unreliable measurements and thus compromises inferences drawn from any estimates.

This study aims to address these knowledge gaps by (i) evaluating the robustness of three RW measurement methods with a specific objective in mind, i.e. growth release analyses, and (ii) taking into account all relevant criteria of the methods involved during this evaluation. Furthermore, anatomical differences in ring visibility are accounted for by performing this assessment for a ring-porous (*Quercus robur* L.) as well as a diffuse-porous (*Fagus sylvatica* L.) hardwood species. An important note concerning our first study objective should be made. Our evaluation of robustness should not be confused with comparative studies that assess the accuracy of RW measurements with a newer method compared to a reference method. Contrastingly, we want to evaluate whether expected differences in RW measurements, measured with three methods as commonly implemented, actually lead to different results of the ultimate growth release analysis. Therefore, we first evaluate how large or important these differences are, and next, whether these differences result in different release detection.

2. Material and methods

2.1. Study area

Increment cores were collected from *Quercus robur* trees in Skåne (S Sweden) and *Fagus sylvatica* in Lyons-la-forêt (N France). The trees were sampled in 20 × 20 m^2 forest plots from the European PASTFORWARD project (ERC Consolidator Grant; Grant Agreement Number 614839): 9 plots in Skåne (55.81°N, 13.58°E, 79 masl), and 10 plots in Lyons-la-forêt (49.44°N, 1.48°E, 149 masl). The climate of the Swedish study site is temperate/subhumid (mean annual precipitation 550 mm, mean annual temperature 7.6 °C), the French site has a temperate climate (MAP 580 mm, MAT 10.0 °C, WorldClim, 2016).

2.2. Increment cores

We cored dominant trees to extract the longest possible tree-ring series. In each plot, we sampled two trees (max 14.1 m apart); while only one dominant tree was present in two plots in Lyons-la-forêt. Two trees per plot is a sufficient sample size for reconstructing (past) local disturbance events based on growth release analyses and historical plot records (for the ERC-project PASTFORWARD). From each tree, two perpendicular cores were taken at breast height to enable crossdating (CD) per tree and to increase the reliability of the detected releases, following Woodall (2008) and Buchanan and Hart (2011). In total, we collected 72 cores (18 trees of each species, 2 cores per tree), which was considered sufficient for an in-depth methodological evaluation (cf. Maxwell et al., 2011; Nutto et al., 2012; Lara et al., 2015; Arenas-Castro et al., 2015).

2.3. Sample processing

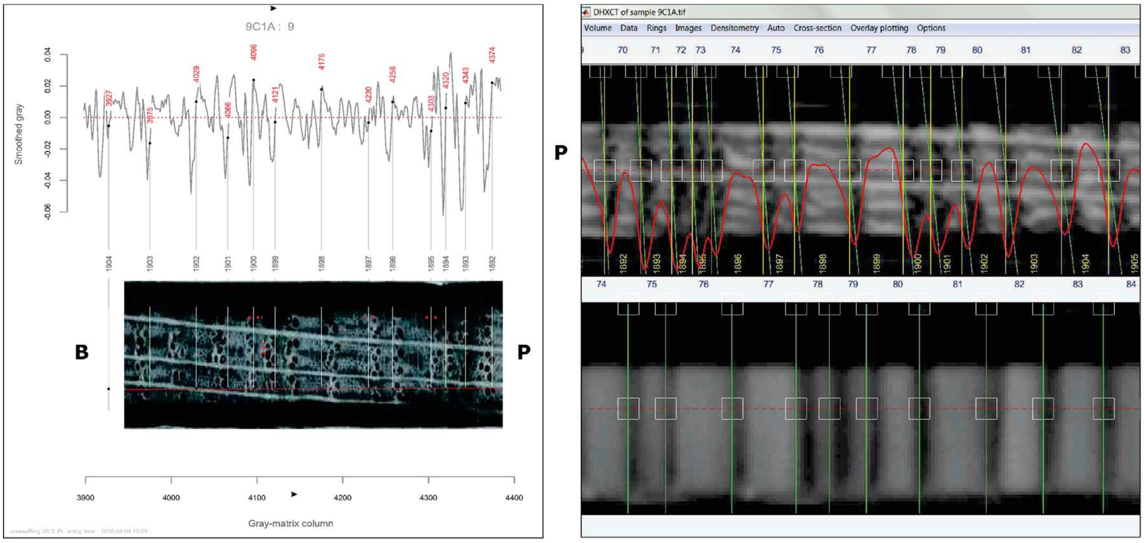
The samples were stored in paper straws. Before the X-ray Computed Tomography (XCT) scanning, the samples were dried for 24 h at 103 °C to ensure correct density estimates and then mounted in custom-made cardboard holders which can contain 33 intact cores of variable length (De Mil et al., 2016). The cores were scanned in batch at 110 μm resolution using NanoWood XCT facility, developed by Woodlab in collaboration with XRE (www.xre.be) (Dierick et al., 2014; Van den Bulcke et al., 2014; De Mil et al., 2016). After reconstruction with the Octopus Reconstruction software licensed by InsideMatters (www.insidematters.eu), core image extraction, tilt and tangential alignment of the 3D volumes was done (De Mil et al., 2016). To make the rings visible on the Lintab and the Flatbed scans, all cores were unwrapped and planed with a Core Microtome (Gärtner and Nievergelt, 2010). For *F. sylvatica*, additional sanding with two grades of sandpaper (320 and 400 grit) was needed to facilitate ring boundary demarcation. All cores were scanned with an Epson Perfection Photo (Flatbed) scanner and the 2D core images were cropped from the scanned images using the open-source software package ImageJ (Schindelin et al., 2015). The Lintab and Flatbed measurements were performed at equilibrium moisture content (i.e. air-dry) since this is custom procedure when using these methods. Table S2 provides a workflow including all steps for the three methods.

2.4. Ring-width measurements

Ring widths were measured with three different methods: (i) a Lintab measuring stage with TSAP-Win software *(the "Lintab" method)*, (ii) Flatbed-scanned image analysis with *measuRing* in R *("Flatbed")* and (iii) XCT-scanned image analysis with the software program *DHXCT* in Matlab *("XCT")*. These methods differ in (i) resolution, (ii) ring demarcation procedure, and (iii) fibre structure correction. First, the resolution was determined for each method as a compromise between

***Quercus robur*: 9C1A (1892-1904)**

(a) Flatbed:*measuRing* (b) XCT: *DHXCT*



***Fagus sylvatica*: LF5C1B (1948-1960)**

(c) Flatbed:*measuRing* (d) XCT: *DHXCT*

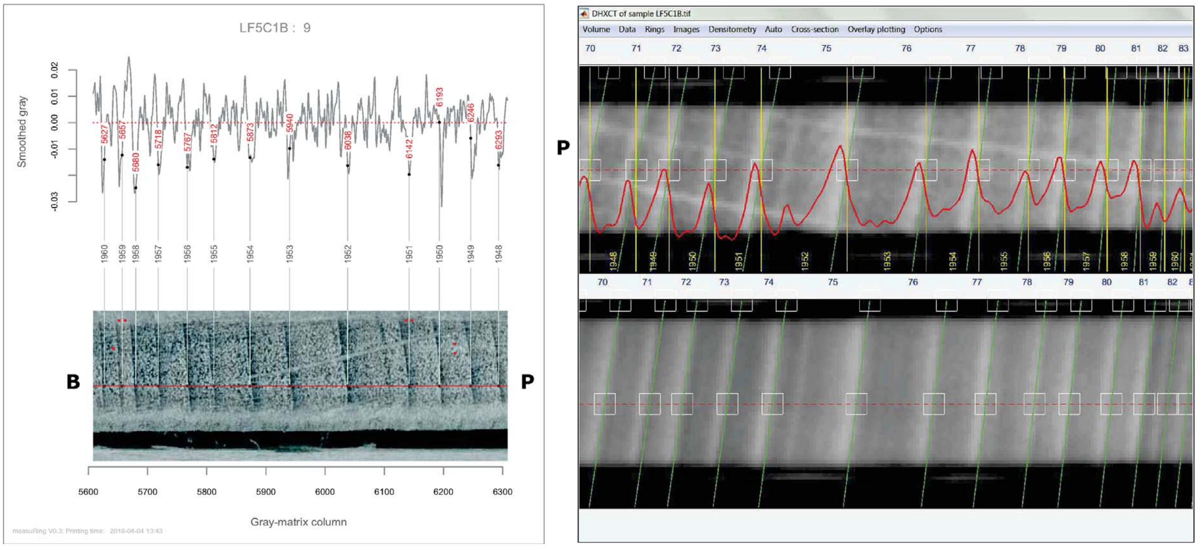


Fig. 1. Visual illustration of the digital measurements for a core section of *Quercus robur* (top) and *Fagus sylvatica* (bottom) in the graphical interface of *measuRing* in the R-programming environment (Flatbed: a, c, Lara et al., 2015) and the graphical interface of DHXCT in the MATLAB environment (XCT: b, d, De Mil et al., 2016). In *measuRing* (a, c), the smoothed gray curve (upper part) is combined with the image section (lower part). We manually indicated rings along the horizontal red line. In DHXCT (b, d), the transversal (upper part) and radial planes (lower part) of the 3D core volume are shown as well as the structure indication lines (green), the ring indications (yellow years and lines) and the estimated density curve (red). The rings were automatically detected, based on the density inflection points for *Q. robur* and the points of density maxima for *F. sylvatica*. The locations of bark (B) and pith (P) are indicated. (For interpretation of the references to color in this figure legend and text, the reader is referred to the web version of this article.)

processing time and ring visibility: 10 µm (Lintab), 28 or 42 µm (corresponds to 900 or 600 dpi for *Q. robur* and *F. sylvatica* with Flatbed), and 110 µm (XCT). Second, measurements were performed manually (Lintab, Flatbed) or automatic (XCT). For the Flatbed method, we measured the RWs manually using the graphical user interface of *measuRing* (Lara et al., 2015) as the automatic procedure over-detected false boundaries in both study species (Fig. 1). For XCT, the automatic detection procedure of *DHXCT* based on the densitometry profile (De Mil et al., 2016) was successfully applied for both species (Fig. 1). After manually and automatically indicating the rings with *measuRing* and respectively *DHXCT*, a visual inspection was performed to attain exact boundary locations and in- or exclude missing or falsely indicated rings. Third, in the case of deviating fibre structures, one can correct for the non-parallel ring boundaries with Lintab by manually rotating the core and by indicating the structure direction prior to ring detection with *DHXCT* (see Van den Bulcke et al., 2014) (Fig. 1, green lines). In the graphical interface of *measuRing*, ring boundaries are manually marked along a horizontal line; at present only straight lines can be drawn and thus correction for non-parallel ring boundaries is not possible (Lara et al., 2015) (Fig. 1, red lines).

2.5. Crossdating

To ensure correctly dated tree-ring series, we crossdated the two cores per tree, the four cores per plot and ultimately all cores per study site. To allow comparison of the results, we performed CD in a similar way for all methods, following a graphical and statistical crossdating procedure in TSAP-Win. The CD was considered acceptable if the *gleichläufigkeit* (percentage of simultaneous RW increases or decreases, Buras and Wilmking, 2015), CD index (index of possible best match positions for two or more series) and t-value after Ballie-Pilcher were > 65, > 30 and > 6 (see Table S1 for CD details). We omitted four series of *Q. robur* and four of *F. sylvatica* with bad CD results due to narrow and unclear rings from further analyses.

2.6. Data analysis

Because a growth release can be expressed on only one side of the tree (Copenheaver et al., 2009), they are not necessarily detected in both cores of a sampled tree. Therefore, we performed all further analyses on the individual series and not on average series per tree.

2.6.1. Measurement differences

To assess the differences in RW measurements among methods, distributions of all RWs were first graphically and then statistically compared by evaluating boxplots and performing two-sample Kolmogorov-Smirnoff tests (ks.test function in R-package “stats”) for both species (R Development Core Team, 2016).

To reveal systematic methodological biases, the difference in paired RWs between two methods was plotted against the average of these paired RWs (Bland and Altman, 1986, 1999). In these Bland and Altman graphs, the overall mean RW difference is compared with the equality line (i.e. zero difference) and the observed RW differences are compared with the limits of agreement (mean RW difference ± 1.96 times the standard deviation of the differences) (Bland and Altman, 1999; Giavarina, 2015; Bland and Altman, 1986). Histograms and QQ plots determined quite heavy-tailed distributions of differences, violating the assumption of normality of differences to calculate the limits of agreement in a correct way (Bland and Altman, 1999). However, following Bland and Altman (1999), this violation is not an issue to interpret the plots.

To test for significant differences in RWs among methods, we used univariate Repeated Measures ANOVA (factor “method” with 3 levels). To create a sensible sample size to perform this statistical test (the total S.S. of ca. 3600 RWs resulted in very low *p*-values, thus always significant results), 10.000 tests of 32 randomly chosen RWs (one RW measurement per core, same measured ring in all methods) were performed and the resulting *p*-value histograms and frequency of significant results were assessed. At the same time, random selection removed any dependencies in the RW data of each method due to interrelatedness of rings from the same core (i.e. autocorrelation), of cores from the same tree and cores from the same plot. All assumptions for the Repeated Measures ANOVA were evaluated, including normal data distributions (with QQ plots), homoscedasticity (with variance tests), independence of measurements per method (solved by random selection) and sphericity (with Mauchly’s test). Mauchly’s test results were used to determine per test result whether the sphericity assumed *p*-value (if Mauchley’s $p > 0.05$) or the Greenhouse-Geisser corrected *p*-value (if $p < 0.05$) reflected the Repeated Measures result (Park et al., 2009).

Finally, to assess which methods were different from each other, post-hoc pairwise comparison tests were performed for each test dataset of the 10.000 replicates for which a significant difference among the three methods was found. This was done with the function *pairwise.t.test* using the Bonferroni correction in R (R Development Core Team, 2016) and both assumptions of normality and homoscedasticity were fulfilled.

2.6.2. Growth release analyses

Release events were determined with Radial Growth Averaging (RGA), i.e. one of the most common “running mean release identification” methods using the “TRADER” package (Altman et al., 2014) in R (R Development Core Team, 2016; Rubino and McCarthy, 2004). This technique computes the percentage growth change (%GC) for each target year as $\%GC = [(M2 - M1)/M1]*100$, with $M1$ and $M2$ being the average radial growth over the preceding and subsequent 10-year period, including (M1) and excluding (M2) the target year (Nowacki and Abrams, 1997). TRADER detects a release as a sustained period of increased growth by running comparisons of the sequential%GC values. We selected a 10-year span for the GC calculation since this tends to average out short-term growth responses related to climate (Nowacki and Abrams, 1997). Furthermore, a release was only detected if the period of increased growth (i) exceeded the threshold of 25%GC and 50%GC for a moderate and a major release; (ii) was sustained for at least seven years; and (iii) if the release was a minimum of ten years apart from another detected release. Within a *release*, or the time period in which all criteria are fulfilled, TRADER identifies the *release year* as the year with the maximum% GC. Since we were interested in whether release detection results would be different among measurement methods, we used fixed criteria for our analysis.

To examine the differences in release detection observed among measurement methods, we considered differences in *magnitude* or *timing* of the observed releases. A difference in magnitude was defined if a release was detected by one method but not by another, or if a release was classified as a major release by one method and moderate by another. A difference in timing occurred when the release year differed between methods.

2.7. Comprehensive evaluation of the three methods

The following (i) quantitative and (ii) qualitative criteria were evaluated for each method: (i) *time consumption, cost, data storage, sample length, RW resolution,* and (ii) *fibre structure correction, wood anatomy, availability of hard- and software, core destructiveness, core drying, verifiability/repeatability, added value* and *user-friendliness*. All criteria were scored from 1 (best) to 3 (worst) for each method, based on real values or orders of magnitude for the quantitative criteria and on personal experience for the qualitative ones.

3. Results & discussion

3.1. Measurement differences

The majority of the ring widths measured with the three methods was quite similar (Figs. 2 and 3), and no method showed an extreme measurement bias (Fig. 3). However, the ring-width distributions did differ significantly between XCT and Flatbed ($p < 0.001$ for *Q. robur* and *F. sylvatica*) and Lintab ($p = 0.02$, $p = 0.005$), but not between Lintab and Flatbed ($p = 0.06$, $p = 0.6$). Flatbed also tended to overestimate ring widths compared to Lintab or XCT for *Q. robur* (Fig. 3a, c: more outliers below than above the limits of agreement). For both species, RW measurements were smallest with XCT (Figs. 2 and 3), reflected also by the lower median RW of 1.88 and 2.02 mm for *Q. robur* and *F. sylvatica* with XCT compared to 1.96 and 2.12 mm with Lintab and 1.99 and 2.14 mm with Flatbed. Although not statistically significant, Flatbed measured slightly bigger RWs than Lintab in both species (Figs. 2 and 3). Overall, RW measurements increased from XCT to Lintab to Flatbed (Figs. 2 and 3, Table 1).

These differences might be explained by a combination of the following factors. First, XCT scanning was performed on oven-dry cores to enable correct density estimates, whereas Lintab and Flatbed measurements were performed on cores at equilibrium moisture content. As a result, a dimensional wood shrinkage factor likely led to narrower rings in XC Vannoppen et al. (2017), investigating the same study

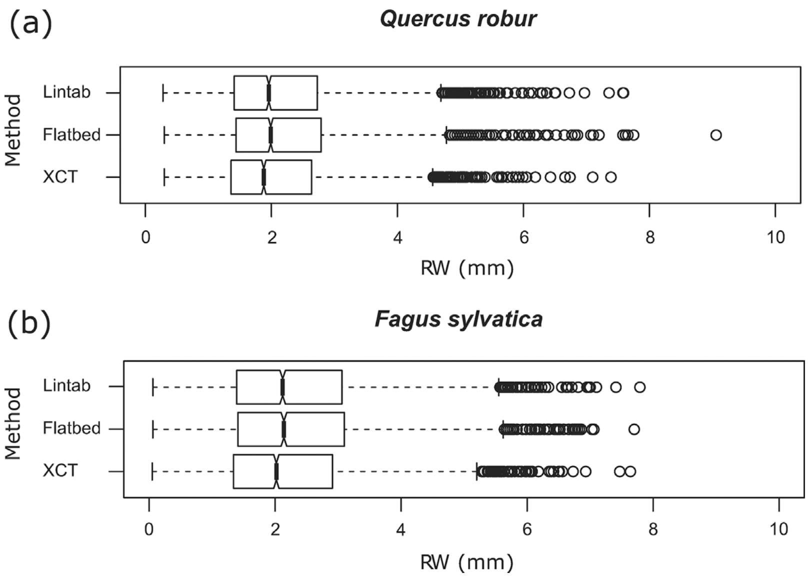


Fig. 2. The range of variation in raw ring-width measurement values in the three methods (Lintab, Flatbed, XCT) for the 32 tree-ring chronologies of (a) *Quercus robur* (n = 3584) and (b) *Fagus sylvatica* (n = 3570).

species, also found narrower widths for XCT than for Lintab, and showed that up to 48% of the difference in RWs could be explained by drying of the cores. Second, the methods differed in the ability to correct for deviating structure directions in the cores (see 2.4). Since *measuRing* does not yet allow to measure non-parallel ring boundaries correctly – i.e. perpendicular to the boundary (Fig. S1) – ring widths were overestimated with Flatbed in parts of the cores with structure deviations. Indeed, the most extreme outliers in Fig. 3a and c comprised rings that were far from parallel (e.g. Fig. S1a, c). Although this is a clear drawback of *measuRing* under its current settings, it is noteworthy that it did not lead to huge differences: a mean difference of 0.05 mm between Lintab-Flatbed and 0.12 mm between XCT-Flatbed, and the latter probably also included a shrinkage effect. Third, the higher resolution with Lintab and Flatbed, providing a more precise location of the ring boundaries, might have resulted in more similar RW measurements compared to those measured with XCT. Interestingly, although the lack of structural deviation correction was expected to cause the largest measurement bias, it appears that the shrinkage effect from drying the cores for XCT scanning caused the strongest RW differences in the measurements.

When comparing the study species, wider limits of agreement (thus larger standard deviations) between paired methods for *F. sylvatica* (Fig. 3d–f) suggested larger measurement differences among all methods for this species. This is supported by the pairwise comparison tests (Table 1): for all paired method comparisons where a significant difference was found, the median mean difference was larger for *F. sylvatica*: 0.16 (Flatbed-Lintab), 0.17 (Lintab-XCT) and 0.19 (Flatbed-XCT) compared to 0.11, 0.10 and 0.15 for *Q. robur*. The lower agreement among RW measurements for *F. sylvatica* can probably be explained by species-specific (i) wood anatomy and (ii) shrinkage effects. First, early-wood vessels in ring-porous species such as *Q. robur* are easy to recognize, making the detection of ring boundaries less problematic and thus facilitating measurement. In contrast, diffuse-porous species such as *F. sylvatica* have vessels evenly distributed in size across the early- and latewood, making their ring borders less distinct and measurements more difficult, resulting in less similar measurements in this species. Second, since *F. sylvatica* had overall wider rings than *Q. robur* (Fig. 2), a higher absolute shrinkage might have caused larger

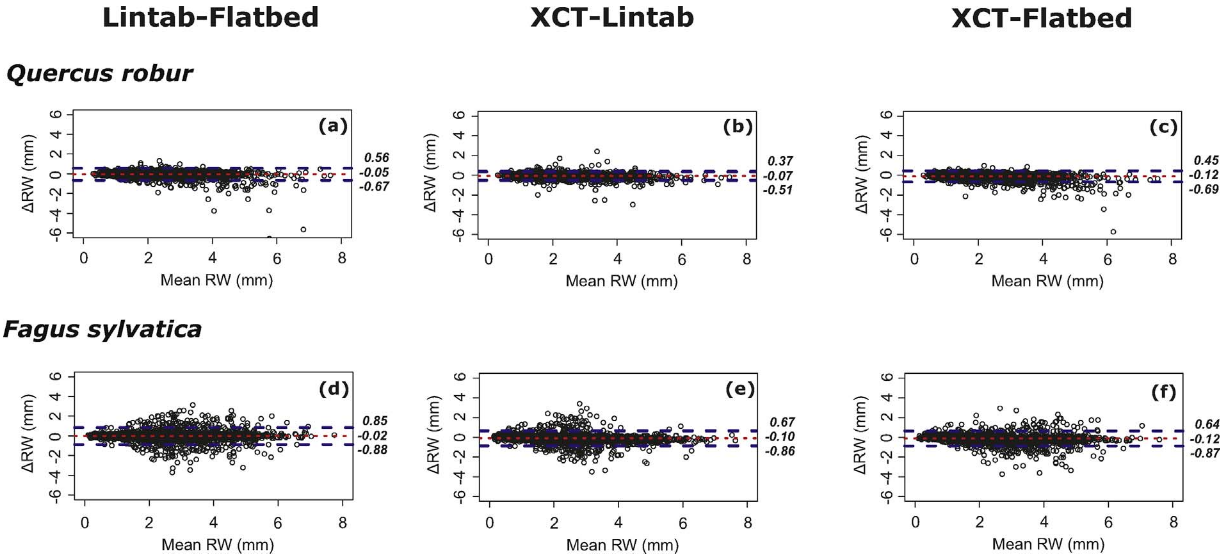


Fig. 3. Differences between paired ring-width values against the average of these RWs for *Quercus robur* (top) and *Fagus sylvatica* (bottom). Comparisons between Lintab and Flatbed (n(a) = 3589; n(d) = 3602), XCT and Lintab (n(b) = 3585; n(e) = 3598) and XCT and Flatbed (n(c) = 3585; n(f) = 3605) are shown from left to right. The red line indicates the mean difference between the two methods ('bias'), and the blue line the 95% confidence interval ('limits of agreement': mean diff ± 1.96 SD). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Post-hoc pairwise comparison tests (Bonferroni correction) for significant differences of RW values among the three methods as determined by Repeated Measures ANOVA (i.e. 7287 replicates of *Quercus robur* and 2771 of *Fagus sylvatica*).

species	Pairwise comparison	% significant tests[a]	median sign level[b]	median mean Δ (mm)	interpretation
Quercus robur	Lintab-Flatbed	9%	*	−0.11	Flatbed > Lintab
	XCT-Lintab	39%	*	−0.10	Lintab > XCT
	XCT-Flatbed	60%	*	−0.15	Flatbed > XCT
Fagus sylvatica	Lintab-Flatbed	1%	*	−0.16	Flatbed > Lintab
	XCT-Lintab	15%	*	−0.17	Lintab > XCT
	XCT-Flatbed	19%	*	−0.19	Flatbed > XCT

[a] i.e. number of significant paired tests/significant repeated measures tests. Note that the sum of these can be > 100 per species since more than one pair can differ significantly within one three-way difference test.

[b] ns: p > 0.1, (*): (p < 0.1); *: p < 0.05; **: p < 0.01; ***: p < 0.001.

differences between XCT and the other methods in this species. This is supported by the higher mean difference between XCT and the other methods (0.10 mm Lintab, 0.12 mm Flatbed) than between Lintab-Flatbed (0.02 mm) (Fig. 3d–f).

3.2. Growth release analyses

The number of releases detected for *Q. robur* and *F. sylvatica* differed slightly among the three methods, for moderate and major releases as well as the total number of releases, with Lintab and Flatbed more similar than XCT (Table 3). This trend agrees with the higher similarity in RW measurements found between Lintab and Flatbed compared to those from XCT (see 3.1). While the majority of the detected releases in *Q. robur* were moderate (e.g. 25 moderate, 4 major for XCT), more major releases were detected for *F. sylvatica* (e.g. 23 moderate, 19 major) (Table 3).

Even though measurement method did not seem to influence the number of releases considerably, the release signals did differ among the three methods (Tables 4 and S3). Out of all the releases detected for *Q. robur* and *F. sylvatica*, 48 and 59% were equally detected in the series from the three methods. Of the remaining growth releases, their difference in detection between methods included differences in timing (10 for *Q. robur*, 8 for *F. sylvatica*), magnitude (5 *Q. robur*, 7 *F. sylvatica*), or both magnitude and timing (3 for *F. sylvatica*). The majority of the timing differences was less than 5 years (only 1 out of 21 releases differed with 6 years: Table S3b), and the majority of the magnitude differences were releases that remained undetected with one or two of the three methods (9 out of 15 releases: see Table S3b). Only a few releases were differently detected with all three methods.

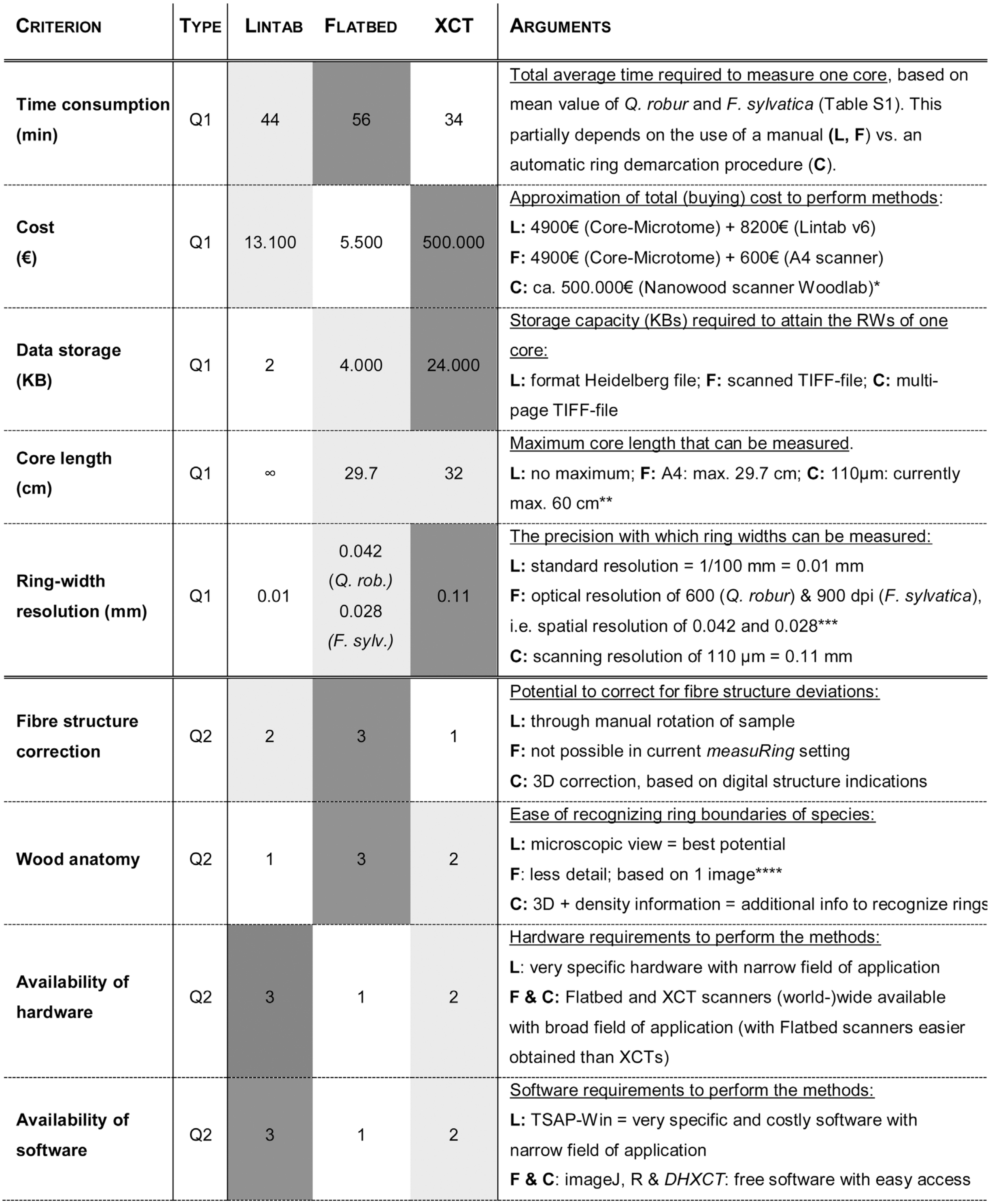
Examining the differences in detail revealed two causes. Different lengths of the measured tree-ring series caused one magnitude difference; while all others originated from the differences in absolute RW values between methods (see Fig. S2 for examples). First, the detection difference caused by different lengths of the measured tree-ring series, even though measuring the exact same core, arose because the microscopic and scanned images with Lintab and Flatbed were unclear before 1899. We could not reliably demarcate ring boundaries with these methods anymore before 1899, while the XCT images were clear enough to measure until 1880. Because of this, a 1900 release that was detected with XCT remained undetected with the other two methods (i.e. the magnitude difference). Of course, measuring different lengths with a chosen method would not be an issue in a "real" tree-ring study since one measures only one core, thus creating one tree-series (length). However, this example nicely illustrates a specific advantage of the XCT method over Flatbed or Lintab here, related to "how" each method visualizes the tree rings. Namely, the XCT measurements are based on 3D volumes coupled with density values to aid with tree-ring demarcation, thus unclear core sections on the 2D volume might still be reliably measured with XCT compared to Lintab or Flatbed. Second, the more frequent differences in detection caused by different RW values between methods ensued from the subtle differences in calculated growth change values along the time series leading to variations in timing, number and magnitude of identified releases (Fig. S2). For instance, the 1924 release detected with Flatbed and XCT remained undetected with Lintab because of small differences in absolute measured values resulting in different% growth change values (Fig. S2). Specifically, the growth change was not sustained for long enough above the threshold (only 6 years > 25% instead of 7) to be detected as a moderate release by TRADER. Similarly, the 1960 release detected with Lintab remained undetected with Flatbed and XCT.

When interpreting the graphical growth release output for all cores, however, all the aforementioned different growth releases among methods could be identified as the same releases. Specifically, depending on the exact detection technique used for the growth release analysis, these differences could ultimately be interpreted as the same results. First, for the timing differences, all but one consisted of a < 5-year difference in release year. If we accept here a buffer of 6 years around the exact timing of a release as is commonly accepted in growth release studies, all the differences between measurement methods can be considered the same. In growth release studies, this timing buffer is used to account for delayed growth responses following a disturbance event or variation in individual tree growth (e.g. Šamonil et al., 2015; Müllerová et al., 2016; Copenheaver et al., 2009). Nevertheless, we reason that it is suitable to use this buffer in this context, since we are assessing which releases would ultimately be considered as the result of individual disturbance events when interpreting the results for disturbance reconstruction. Second, when reassessing the magnitude differences graphically, we found that these can also be tackled, but through a more thorough evaluation of the parameter values during the release analysis (in TRADER). Here, we used fixed criteria, since we were primarily interested in whether detection would be different among methods. However, changing the criteria to characterize releases – a process referred to as adjusting their sensitivity (Altman et al., 2014) – is common in growth release studies and might be appropriate depending on the study objectives. For instance, by lowering the number of years that the growth increase needs to be sustained, one might detect the "undetected" releases that were graphically visible with that method, but just did not reach all fixed criteria. Also, by editing the thresholds for a major or moderate release, one could detect the releases with a different magnitude. Finally, even with a sensitivity analysis of the criteria, a visual inspection is recommended after every growth release analysis, to estimate the validity of every detected release, as well as to include other, missing releases (Fraver and White, 2005).

3.3. Comprehensive evaluation of the three methods

Each method has specific benefits and drawbacks (Table 2). For instance, the low data storage requirement for Lintab was a benefit (best score), whereas the difficulty to double-check RW measurements was a clear drawback (lowest score). The digital workflow of Flatbed, but especially of XCT with its automatic ring detection procedure,

Table 2
Comprehensive evaluation of the three measurement methods: Lintab (L), Flatbed (F) and XCT (C). Several quantitative (Type = Q1) and qualitative (Type = Q2) criteria are scored from 1 (best) to 3 (lowest) for each method. Quantitative criteria were scored based on real values or orders of magnitude, and qualitative criteria were scored based on personal experience. "Arguments" explains the reasoning behind the scores. The white, light grey and dark grey shading reflects the best, medium and lowest scored method per criterion.



CRITERION	TYPE	LINTAB	FLATBED	XCT	ARGUMENTS
Time consumption (min)	Q1	44	56	34	Total average time required to measure one core, based on mean value of *Q. robur* and *F. sylvatica* (Table S1). This partially depends on the use of a manual (**L, F**) vs. an automatic ring demarcation procedure (**C**).
Cost (€)	Q1	13.100	5.500	500.000	Approximation of total (buying) cost to perform methods: **L:** 4900€ (Core-Microtome) + 8200€ (Lintab v6) **F:** 4900€ (Core-Microtome) + 600€ (A4 scanner) **C:** ca. 500.000€ (Nanowood scanner Woodlab)*
Data storage (KB)	Q1	2	4.000	24.000	Storage capacity (KBs) required to attain the RWs of one core: **L:** format Heidelberg file; **F:** scanned TIFF-file; **C:** multi-page TIFF-file
Core length (cm)	Q1	∞	29.7	32	Maximum core length that can be measured. **L:** no maximum; **F:** A4: max. 29.7 cm; **C:** 110µm: currently max. 60 cm**
Ring-width resolution (mm)	Q1	0.01	0.042 (*Q. rob.*) 0.028 (*F. sylv.*)	0.11	The precision with which ring widths can be measured: **L:** standard resolution = 1/100 mm = 0.01 mm **F:** optical resolution of 600 (*Q. robur*) & 900 dpi (*F. sylvatica*), i.e. spatial resolution of 0.042 and 0.028*** **C:** scanning resolution of 110 µm = 0.11 mm
Fibre structure correction	Q2	2	3	1	Potential to correct for fibre structure deviations: **L:** through manual rotation of sample **F:** not possible in current *measuRing* setting **C:** 3D correction, based on digital structure indications
Wood anatomy	Q2	1	3	2	Ease of recognizing ring boundaries of species: **L:** microscopic view = best potential **F**: less detail; based on 1 image**** **C:** 3D + density information = additional info to recognize rings
Availability of hardware	Q2	3	1	2	Hardware requirements to perform the methods: **L**: very specific hardware with narrow field of application **F & C:** Flatbed and XCT scanners (world-)wide available with broad field of application (with Flatbed scanners easier obtained than XCTs)
Availability of software	Q2	3	1	2	Software requirements to perform the methods: **L:** TSAP-Win = very specific and costly software with narrow field of application **F & C**: imageJ, R & *DHXCT*: free software with easy access

(*continued on next page*)

Table 2 (*continued*)

					(with imageJ already more easily obtained than *DHXCT* of Woodlab UGent)
Core destructiveness	Q2	2	2	1	Intactness of core after the method has been carried out, based on requirement of surface preparation steps or not: **L & F**: surface preparation needed: microtome (both species), sanding (only *F. sylvatica*) **C:** no surface preparation needed****
Core drying	Q2	1	1	2	Whether drying the samples before performing the measurements was necessary or not. **L & F:** No drying required **C:** Drying required to ensure correct density estimates (used in the tree-ring detection process).
Verifiability	Q2	3	2	1	Simplicity to post-edit, double-check or back-up measurements or core images. This depends strongly on whether the method allows a digital image and digital measurements or not. **L**: post-editing possible, but difficult: you always have to search the specific ring under the stereoscope again **F & C:** medium and good ability to review your measurements on the scanned images afterwards, this strongly facilitates post-editing process
Added value	Q2	2	1	1	Whether additional data is acquired through the method: **L:** no added value from measurements **F & C**: added value from scans, e.g. colour vs. density information from flatbed vs. XCT images as climate proxies respectively
User-friendliness	Q2	1	3	2	Expert knowledge required to perform measurements: **L:** low barrier for Lintab & TSAPWin, no programming **F:** scan is easy, but R knowledge required for *measuRing* **C:** learning curve to use XCT scanner & software, but no computer programming required

*XCT: Cost can be lower when building a dedicated tree-ring analysis scanner (Nanowood was built for different purposes).

**For both Flatbed and XCT, you could rotate the core or use another scanner (e.g. A3 flatbed) to increase maximum length.

***Spatial resolution, i.e. 25.4 [mm/inch]/optical resolution [dpi].

****Flatbed and XCT: This depends of course to a large extent on the scanning resolution, which can be increased.

Table 3
Summary table of the growth release results using Radial Growth Averaging for release detection. Values denote the number of moderate (Mod), major (Maj) and total (Tot = Mod + Maj) releases detected with the three methods in the tree-ring series of *Quercus robur* and *Fagus sylvatica* (Details Table S2).

Method	Mod	Maj	Tot	Mod	Maj	Tot
	Quercus robur			*Fagus sylvatica*		
Lintab	24	3	27	22	17	39
Flatbed	24	3	27	22	17	39
XCT	25	4	29	23	19	42

allowed large sets of cores to be measured in a short time span and the additional visual back-up was of high value in the post-editing process (good score for time consumption and verifiability). In terms of software requirements, Flatbed and XCT both scored well, because they use freely available computer programs. At the same time, however, the expert knowledge or "learning" time needed to use these programs was considered a drawback (low score for user-friendliness). The time required to measure the RWs of a core was less than half for XCT compared with Flatbed for *Q. robur* (25 vs. 58 min), but the difference was smaller for *F. sylvatica* (42 vs. 53 min) (Table S2). This was probably because of the more difficult ring recognition in *F. sylvatica,* more time was required for the measurements, independent of the method used.

The evaluation of our three methods (Table 2) provides a framework for method evaluation, but it remains a snapshot and should be reassessed in the context of other studies. That is, the criteria were scored according to the exact settings of this particular study, but these scores may change when a different measurement method (e.g. Atrics, Levanič, 2007) or semi-automatic image analysis program (e.g. CooRecorder, Cybis Elektronik, 2010) is involved, as well as if technological advances (e.g. better scanners) or simply other choices (e.g. higher scan resolution) are made. A number of other, proprietary programs

Table 4

Summary table of differences in detected releases in the RW series obtained with Lintab (L), Flatbed (F) and XCT (C) for *Quercus robur* (top) and *Fagus sylvatica* (bottom). The number of equal (Tot=) and different (Tot Δ, L ≠ F = C, F ≠ L = C, C ≠ L = F, L ≠ F ≠ C) release signals detected among the methods is expressed in absolute numbers and percentage of all detected release signals (i.e. Tot #). L ≠ F = C implies the different release signal was detected in the Lintab series, but the same signal was detected in the Flatbed and XCT series. Either the release signals differed in magnitude (Δ magnitude), in timing (Δ timing) or in both (Δ magnitude + Δ timing).

Tot #	Tot=	Tot Δ	L ≠ F = C	F ≠ L = C	C ≠ L = F	L ≠ F ≠ C
Quercus robur						
29	14 (48%)	15 (52%)	4 (14%)	3 (10%)	6 (21%)	2 (7%)
Δ magnitude:			2 (7%)	0 (0%)	3 (11%)	0 (0%)
Δ timing:			2 (7%)	3 (11%)	3 (11%)	2 (7%)
Fagus sylvatica						
44*	26 (59%)	18 (41%)	6 (14%)	2 (5%)	9 (20%)**	1 (2%)
Δ magnitude:			2 (5%)	0 (0%)	5 (11%)	0 (0%)
Δ timing:			4 (9%)	2 (5%)	2 (5%)	0 (0%)
Δ magnitude + Δ timing:			0 (0%)	0 (0%)	2 (5%)	1 (2%)

* = 42 (maximum no. releases detected was with XCT, see Table 3) + 2 (undetected releases with XCT, but detected with Lintab and Flatbed).

** Sum of the numbers below will be 21% due to rounding.

such as CooRecorder, which also use semi-automatic image analysis on Flatbed scanned images, do allow correcting for deviating rings. Yet, we decided to use *measuRing* because it is open-source (i.e. an R-package (R Development Core Team, 2016)), which is attractive for scientific studies. As another example, the HECTOR scanner (http://www.ugct.ugent.be/instruments.php) allows to scan longer cores (up to 1 m) than the NanoWood XCT scanner we used, but requires much longer scanning times (Masschaele et al., 2013). Finally, increasing the resolution of Flatbed or XCT scans might increase the ease of ring boundary recognition, but also implies higher costs, longer scanning times as well as larger data volumes.

3.4. General discussion

In our study, probably a combination of methodological factors – i.e. different sample preparation (drying), different potential to correct for non-parallel rings and different resolutions used – gave rise to the variation in RW measurements with the three methods, as hypothesized. These results highlight a number of important technical aspects regarding the accuracy of RW measurements, which should be taken into account during (preliminary) method evaluation. For instance, the shrinkage effect from drying is usually not taken into consideration during tree-ring studies, which mainly focus on the year-to-year growth variability (Latte et al., 2015). However, this caused strong methodological differences in RW measurements in our study as well as in a similar study by Vannoppen et al. (2017). Tree-ring scientists should thus consider this issue in the future. Our results also demonstrated that methodological choices should be assessed per study species, i.e. a measurement method with a higher resolution might be required for *F. sylvatica* compared to for *Q. robur*, in order to minimize the potentially larger errors that were found.

Next, comparing the growth release results among methods demonstrated that measurement method in itself did not affect the ultimate release results. This suggests that these methods are robust in terms of growth release detection, despite their obvious methodological differences. However, the initially perceived differences in growth releases did emphasize the need for a critical interpretation of release results when using a certain method, for instance by a sensitivity analysis of the parameter values defining a release. Also our findings should not be interpreted as an advocacy to use lower-resolution methods for growth release analysis. Instead, we put forward the idea that although the use of a certain method may entail a lower resolution and thus lower RW precision, this does not necessarily imply a bad choice in the case of release analysis.

From this apparent robustness, we suggest that the three methods could substitute each other in the case of growth release studies, if one carefully considers the potential measurement biases. This idea might open up new perspectives in the domain of dendroecology. For instance, tree RW datasets that were measured with various methods could be used within the same growth release analysis if one accepts the idea of measurement substitutability. This could offer opportunities to perform larger-scale data analyses on databases such as the International Tree Ring Data Bank. However, two important points should be considered. First, we add that – whenever possible – a combination of methods may be even more useful than a substitution, and at the same time increase reliability of the measurements. It was clearly shown that every method visualizes cores, hence growth rings in another way, offering specific benefits and limitations which could be optimized by combining rather than substituting methods (see Table 2). For instance, measuring a large batch of cores with *DHXCT*, but using Lintab to measure very narrow ring sections could optimize workflow by combining the higher time efficiency of *DHXCT* with the higher resolution of Lintab. Second, the idea that measurement methods could substitute each other is proposed here in the case of growth release analysis and should not be generalized for other applications of tree-ring series.

Besides these technical “accuracy” aspects, there are more facets to consider during the evaluation of a measurement method, which is why we performed an overall comparison of the three methods. In Table 2, we brought forward a method evaluation framework that might be useful for future tree-ring studies to determine which method might be more suitable in order to achieve ones’ study objective. This is relevant since the barriers to perform tree-ring studies are strongly diminishing because of (i) decreasing cost prices of data storage and material, (ii) increasing availability and accessibility of newer, often digitally advanced methods, as well as (iii) increased importance of tree-ring records in scientific studies.

Which method to choose in a particular study will strongly depend on the study context though. For instance, if low cost is crucial, Lintab or Flatbed might be a better option than XCT although the salaries needed to perform measurements also require consideration. Besides more practical criteria such as cost, time consumption, or hardware availability, the versatility of a method can also be important. XCT scanning of increment cores provides wood density information in addition to the RW measurements performed on the 3D volumes (Van den Bulcke et al., 2014), which might be used in paleoclimatic (e.g. Fritts, 1976) or physiological studies (e.g. Koga and Zhang, 2004). From a multi-value perspective, Lintab will generally be the lesser choice, as the Lintab measuring stage and TSAP-Win software was designed only for measuring RWs. Overall, we recommend that the complete set of method characteristics is important in deciding upon a method and different trade-offs will have to be made in each study design.

3.5. Conclusion

To conclude, our results demonstrated that measurement method in itself did not affect the ultimate release results, suggesting that these methods are robust in terms of growth release detection, despite their obvious methodological differences. Furthermore, the differences in RW measurements among methods were larger for *F. sylvatica* than for *Q. robur*, indicating that methodological choices should be assessed per species. For methodological choices in future tree-ring studies, we recommend that the complete set of method characteristics be considered, including both accuracy as well as more practical aspects such as time consumption or sample preparation steps.

Finally, more methodological evaluations taking into account the final goal of RW measurements would be useful in future studies. Especially since measurements from an increasing number of available methods are being used for a variety of analyses without a thorough understanding of how the method, in all its aspects may have influenced the RWs and thus the ultimate tree-ring analysis. Furthermore, as this study focused on release differences caused by differences in the RW measurements and not by differences in dating, future studies should evaluate the effect of measurement method on the temporal precision as well.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.dendro.2017.10.005.

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