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Article

How Cultural Heritage Studies Based on Dendrochronology Can Be Improved through Two-Way Communication

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Abstract: A significant part of our cultural heritage consists of wood. Research on historical wooden structures and artefacts thereby provides knowledge of people's daily lives and the society in which they lived. Dendrochronology is a well-established dating method of wood that can also provide valuable knowledge about climate dynamics, environmental changes, silviculture, and cultural transformations. However, dendrochronology comes with some limitations that end users in cultural heritage sciences must be aware of, otherwise their surveys may not be ultimately performed. We have drawn attention to studies in which dendrochronological results have been misinterpreted, over-interpreted, or not fully utilized. On the other hand, a rigorous dendrochronological survey may not respond to the request of information in practice. To bridge this rigour-relevance gap, this article has considered and reviewed both the dendrochronology's science-perspective and the practitioner's and end user's call for context appropriate studies. The material for this study consists of (i) interviews with researchers in dendrochronology and end users represented by cultural heritage researchers with focus on building conservation and building history in Sweden, and (ii) a review of dendrochronological reports and the literature where results from the reports have been interpreted. From these sources we can conclude that a continuous two-way communication between the dendrochronologists and end users often would have resulted in improved cultural heritage studies. The communication can take place in several steps. Firstly, the design of a sampling plan, which according to the current standard for sampling of cultural materials often is required, is an excellent common starting point for communication. Secondly, the survey reports could be developed with a more extensive general outline of the method and guidance in how to interpret the results. Thirdly, the potential contribution from dendrochronology is often underused, foreseeing historical information on local climate, silviculture, and choice of quality of the wooden resource, as the focus most often is the chronological dating. Finally, the interpretation of the results should consider all the available sources where dendrochronology is one stake for a conciliant conclusion.

Keywords: tree-ring research; cultural heritage; historical buildings; archaeology; transdisciplinary; craft research

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1. Introduction

For thousands of years, wood has been used as a resource and has thus become a crucial part of our cultural heritage. Wood has, for example, been used as fuel for heating and cooking, to produce tools for hunting and fishing, and a source of constructional timber for buildings, bridges, and ships [1–4]. Moreover, wooden objects have been decorated, while sculptures, arts [2,5], and music instruments [6,7] have been made of wood. These facts not only show that trees have been accessible, and that wood is a material relatively easy to process, they also reflects the natural beauty of the wood, which is often enhanced in the artistry of craft works and constructions. An essential part of our history is simply made of wood, and the development of methods to analyse and date wooden objects is therefore crucial for documentation, research, and conservation of our cultural heritage.

The word dendrochronology as a term for tree-ring analyses was introduced in the early 1900s by the American astronomer Andrew Ellicot Douglass [8–10]. Following more recent improvements of the technique [11,12], dendrochronology has become a well-established method to date and analyse a wide range of wooden objects. Today results from dendrochronological analyses are important in several heritage science disciplines including cultural history [13–15], archaeology [16–20], fine arts [21–24], shipwrecks [25,26], timber trading [5,25,27] historical buildings and constructions [2,28–30], and silviculture [31,32]. Annual growth rings in trees are also archives of climate, environment, and cultural changes, allowing for age determination of ecological states and transformations [33,34], natural disturbances [35], and of course climatological changes [36,37], from which cultural responses can often be interpreted and derived [38,39]. In such contexts, dendrochronological data have been used to interpret societal transformations due to, for instance, land use and changes in silviculture [31,40], plague [38,41], or food crisis [42]. As the examples show, countless uses for tree-ring based studies have been applied and there is a great wealth of tree-ring-based research disciplines, such as dendroclimatology, dendroecology, dendroarchaeology, dendroprovenance, and dendrogeomorphology. However, in this article, for the sake of simplicity, we will use the basic term dendrochronology.

A common demand of dendrochronology in cultural heritage studies comes from the seemingly simple question: How old is this? However, despite many good examples showing that dendrochronology is an excellent tool for dating, provenance, and to generate information for silviculture studies, there are limitations with the method that practitioners and end users must be aware of. There are previous publications that aim to instruct dendrochronologists, the practitioners, in surveying, and end users of dendrochronological data about procedures of sampling and analysis [43,44], as well as to assess what information dendrochronology can provide regarding cultural heritage [3,45–48]. Despite this, dendrochronological surveys in the context of cultural heritage studies are ultimately rarely performed when taking both parts into consideration. The results are therefore often either misinterpreted or overinterpreted. This is, however, not a single-directed research-to-practice problem. Deficiencies in the practice of sampling and interpreting dendrochronological results are parts of a more complex reality. Cultural heritage practices must attend to conditions in context, such as economy, capability, and cultural significance. Furthermore, cultural heritage practices often use various sources of knowledge to draw conclusions from consilience. What may be perceived as a lack of rigor from one perspective may sometimes be considered a good enough base of evidence for the purpose of a cultural heritage project [49,50]. The scope of our study is to (i) review literature, reports, and interpretation of reports from surveys on construction timber from Swedish churches, and (ii) through interviews and dialogue between dendrochronologists and end users who use dendrochronological reports and data, formulate recommendations for how to improve surveys and interpretations of cultural heritage research based on dendrochronology.

2. Materials and Methods

This study differs from others that have been conducted because it has mainly emerged through dialogues during various dendrochronological surveys. We have noticed that regardless of the type of object under study, the same questions have arisen, and similar mistakes have been made. However, we do not want to point out researchers who have performed deficient studies; instead, we want to increase the understanding of dendrochronology to improve future studies. In addition to notes from these dialogues, we have been using parts of the data and reports that will be made available via the open access database *Old Wood in a New Light* that is under construction. This is a Strategic Environmental Archaeology Database (www.sead.se, accessed on 5 June 2021) in which, continuously, dendrochronological results and metadata from more than 40,000 samples will be uploaded during the period 2021 to 2024. Statistical calculations and percentages presented in this study are based on metadata from ca. 12,500 samples that have been published in the database so far. We will also review the literature, reports, and interpretation of reports from surveys on construction timber from Swedish churches, as well as summarize interviews and dialogues between dendrochronologists and end users who use dendrochronological reports and data for their work with cultural heritage issues concerning Swedish churches. For this purpose, reports with a focus on buildings being considered as part of the cultural heritage; foremost, churches and buildings included in archaeological studies have been reviewed. Among these writings, great emphasis has been placed on studies and articles about Swedish churches [51–65], as well as the literature about dendrochronological techniques used in cultural heritage studies with a focus on building conservation [3,4,46,56]. Moreover, we looked at dendrochronological reports in which we could find follow-up publications (both scientific and popular publications, such as museum catalogues) written by authors other than the report author. In this study, we mainly base our examples on pine and oak, the two most common dendrochronologically analysed species in Sweden.

To describe the situation and develop a standard procedure of practice when it comes to initiating dendrochronological investigation in churches, interviews have been performed with researchers and consultants in dendrochronology, as well as historians focusing on building conservation. During sampling of a Medieval roof layer in Strängnäs diocese, participants could observe potential sources of error in the process. From these observations, questions could be developed through situations that otherwise could not have been foreseen. The first three interviews were done in 2019 during the research projects at the Stora Hammar and Rängs churches, Lund diocese. The analysed samples were later included in the project Timmermanskonst (www.timmermanskonst.se, accessed on 5 June 2021) in Lund diocese. Thereafter, interviews on Ripsa church, Strängnäs diocese, with two building antiquarians at Sörmlands museum and a craftsman from construction and crafts in Karlskoga AB were done. The interviews were conducted with two construction craftsmen and carpenters, and two dendrochronologist, as well as a senior lecturer in cultural preservation. To get an objective view of the compilations from the interviews and conversations, the compilation texts were reviewed by (i) diocesan antiquaries and engineers from all 13 dioceses in Sweden, (ii) cultural environment officers from all 21 counties in Sweden, as well as (iii) representatives from the church office and the National Heritage Board. We have also participated in seminars at Heritage Science Sweden 2018 and the Building Maintenance Convention 2019. In total, five such seminars with heritage officers and professionals in built heritage conservation were conducted aiming to discuss what a good practice is and should be. In addition, we can add our various backgrounds in dendrochronology, cultural heritage studies, and craft research. The combined results from these processes have also been used to illustrate and underline the findings in this article.

3. Results

3.1. The Parties at Dendrochronological Analyses of Cultural Heritage

For obvious reasons, a dendrochronologist who is responsible for the scientific analysis of the annual rings in the wooden samples is required to perform a dendrochronological study. However, for studies of cultural–historical buildings, there are usually one or several clients of the assignment and end users that will interpret the results. The process for a dendrochronological survey may differ depending, not only on the properties of the object, but also on the purpose, organisation, and formal framework of the survey. Here, we find many different practitioners with various roles, stakes, and competences. In any case, there is a client demanding and paying for the survey, which is here referred to as the end user. The client may be a property owner, a researcher or expert in distinguished fields. In a larger context, the dendrochronological data may be used by many other stakeholders, such as property managers, researchers, curators, or educators. A genuine problem is that these secondary users seldom question a result or account for their interpretation. The first-hand client may be the one performing the survey and sampling, but commonly an expert surveyor or sampler is commissioned by the client. This expert may be a craft researcher, an archaeologist, a restoration architect, or a heritage officer. The dendrochronologist, on the other hand, is not necessarily an active agent in the process and participating in planning and sampling. Since we focus on studies of listed historic buildings and churches, authority or expert competence is usually required.

3.2. Research Questions from an End-User Perspective

Regardless of who the practitioners or end users of a dendrochronological study were, we could note one or several research questions they wanted the survey to answer. Common questions asked prior to a dendrochronological investigation are: (i) what is the age or construction year of an object, (ii) what is the geographic origin of the object or the wood used for the construction of the object, (iii) are there one or several construction phases of the object, (iv) what tree species and preferred wood quality have been used for the construction of the object, and (v) what can the timber used tell us about the silviculture and how timber was processed in the past?

During the planning of a dendrochronological survey, questions of a different nature may arise, for example, (i) is the study object listed or protected, and are permits from authorities and owners thereby required, (ii) how will the analysis affect the study object and can dendrochronological analysis be performed without destructive sampling, (iii) if not, what is the best sampling strategy, (iv) how many samples are required, and (v) what should a good sample look like?

During the study, or perhaps even more often after it was completed, follow-up questions or completely new questions may arise, for example, (i) how precise is tree-ring dating, (ii) why do different samples from a construction give different ages and accuracy of the dating, (iii) why does the wood material have several geographic origins and how precise can a provenance study be, (iv) why has the object been restored, repaired or rebuilt at some point in time, (v) what type of forest did the trees used for the construction of the object originate from, (vi) in which part of the tree may the wood be taken from, and (vii) are there any certain features of the analysed wood that make it especially good for the purpose it has been used? An experienced building archaeologist or craft researcher may, for example, already have discovered all the renovation and rebuilding phases even before the dendrochronological investigation begins and may, therefore, have other questions than a curious homeowner. A dendrochronological analysis can often answer some of these questions, but only in rare cases all of them. Usually, the questions may be partially answered and there is room for interpretation, both from the dendrochronologist and the end user. It is, therefore, of the utmost importance to clarify and distinguish what is scientific evidence and what are interpretations.

It is also common that another category of questions arises, such as (i) how will the analysed samples be stored, (ii) how will the samples and the dendrochronological report be accessible for future studies, and (iii) what is the precision and extension of the reference curves? Since these questions do not affect the analysis or interpretation of the results, we did not put them in the focus of this study.

3.3. Possible Interest Conflicts between Scientists, Practitioners, and End Users

End users often have a conflicting concern for, on the one hand, to preserve authentic material and, on the other hand, to acquire new knowledge of the object through analysis. In buildings, dendrochronological samples are commonly taken through radial drilling and obtaining a wooden core. The drilling leaves behind the holes that may destroy historical paint or carpentry marks, cause aesthetic detriment, or weaken the construction. Invasive sampling could be devastating for the authenticity and integrity of a smaller wooden artefact. The eventual hazard and negative effect on the cultural property by sampling, and the benefit of the possible answers provided by dendrochronological analysis must therefore be considered and weighed against each other. Regarding protected buildings, fine art, and music instruments, a non-invasive approach is often mandatory to allow for dendrochronological analysis. From the end-user perspective, the possibilities of using non-invasive methods instead of coring or surface preparation is of great interest. There are standards and guidelines in various fields of cultural heritage that exhort precaution in the collection of sampling materials and use non-invasive methods where applicable. The European standard (EN 16085) for sampling from materials of cultural property proscribe that, "sampling should be done so as to minimize any visible and/or disrupting/damaging effects and taken, when possible, from an as inconspicuous place as possible provided that it fulfils the aims of the sampling" (ibid., §4). Furthermore, "only a minimum though sufficient number of samples should be taken" and that the amount of sample material has to be relevant to "the type of cultural property, the nature of the material, and the kind of scientific investigation to be employed" (ibid., §7–8).

3.4. Steps in Dendrochronological Surveys That End Users in Cultural Heritage Studies Must Be Aware of

3.4.1. Tree Species Represented in the Study Material

From our review of dendrochronological reports, pine (*Pinus* sp.) was found to be the most common tree species (60.4%), followed by oak (*Quercus* sp., 33.2%), spruce (*Picea* sp., 4.6%), and beech (*Fagus* sp., 0.9%). All other tree species combined make up the remaining 0.9%. In Swedish forests, on the other hand, the most common tree species are Norway spruce (*Picea abies* L., ~41%), Scots pine (*Pinus sylvestris* L., ~39%) and birch (*Betula* sp., ~12%), whereas the remaining ~8% mainly consist of various broadleaved trees [66]. The differences between the composition of the forest and what tree species are ultimately analysed reflects the fact that most species have unique characteristics that make them suitable for specific purposes. Sometimes, this may be anatomical wood features that allow a certain species to be used. In other cases, species may be chosen because they are easy to access in a geographical region, which is a factor that may have changed overtime. The distribution among the tree species used for construction materials in buildings may therefore be different from the distribution in the forest. Another selection process takes place when samples for dendrochronologically dating are to be chosen, because suitable samples should preferably be from species (i) producing reliable and visible annual growth rings, (ii) grow under a wide ecological and geographical range, (iii) be durable to ensure preservation of the wood, and (iv) that have been used over a significant period. However, tree species that are not suitable for a dendrochronological dating may still be interesting to study for craft or silviculture researchers to determine tree species, wood quality, and growth rate of the trees used as a source of timber.

The reports revealed that pine and oak represent more than 90% of the dendrochronologicaly analysed Swedish construction timber. Scots pine is a common evergreen conifer in large parts of Northern Europe. Due to distinct annual rings and its presence in a wide range of settings, Scots pine is also commonly used in dendrochronological studies [64,67]. Oak also has a wide distribution across Europe and has, since prehistoric times, been used as construction timber [3]. At present, there are more than twenty native species of the genus *Quercus* in Europe [68], of which *Quercus robur* L. (English Oak) is the most common in Sweden. Since oak has been used in many different contexts, it is a very common species in cultural–historical dendrochronological studies [3,5,12,24].

3.4.2. The Number of Annual Growth Rings

To succeed with a dendrochronological dating, the number of detectable annual growth rings in a sample is of utmost importance for the construction of long tree-ring series and reliable cross-dating statistics. The correlation values are more robust between longer tree-ring series than for series with few overlapping rings. There are studies suggesting a minimum of 50 overlapping rings to avoid accidental cross-matching [69] and many statistical tools and software for tree-ring analysis therefore exclude tree-ring series of 30-years or shorter as the statistical parameters are generally low and statistically insignificant, or high but erroneous. Despite this, there is no specified lower boundary expressing the required overlap. This means that the judgment and experience of the dendrochronologist can be of decisive importance when deciding whether a result from short tree-ring series are reliable or not. Even though 50 annual rings or fewer is considered as critical [69], the reports studied shows that more than 20% of the artefacts and construction timber analysed at Lund University contained 50 rings or fewer. Excluding such material from the analysis therefore causes a significant loss of fine detail. Moreover, for samples containing sequences where the growth rings are missing or not visible, the analysable sequence will be shortened, which hampers the possibility of dating the sample. It is therefore important to inspect the samples during the sampling procedure to ensure that there is a tree-ring sequence worth analysing. If short tree-ring series can be averaged into an extended joint tree-ring record, the dating can become reliable. However, from the end user side, this can cause greater costs and damage to the studied object.

3.4.3. The Number of Samples

As suggested in the previous section, increasing the number of samples improves the possibility of a successful dendrochronological analysis. However, again, there is no set limit. The reviewed reports show that sometimes a single sample can answer all the end-user's questions while other times it does not matter if all the accessible timber in a construction is analysed. In general, increased sample replication results in more representative tree-ring data, as the common signal will be strengthened and disturbances influencing individual trees will be attenuated. A tree-ring record developed from several overlapping samples thus generates a stronger regional signal and thereby improves the possibilities of a reliable dating. However, once again, increased sample depth will from the end-user´s perspective cause greater costs and damages on the studied object.

3.4.4. Tree-Ring Measurements and Cross-Dating

There are several methods used to analyse tree-ring sequences from historical buildings and archaeological artefacts. The most common tree-ring analysis is based on measurements directly on physical samples, such as cores or sections from the study object (Figure 1), but there are also micro-invasive image analyses of prepared wood surfaces [24], as well as non-invasive image analysis based on high resolution photos from unprepared surfaces taken with camera or USB-microscope [70,71], Figure 1, X-ray images [72], and CT scanning [73]. There are also alternative methods, such as isotope ratios in tree rings, that can be used instead of tree-ring width [74]. Regardless of the method, there are several common requirements that must be met for a successful dendrochronological dating analysis.

When tree-ring widths are measured, tree-ring series are developed (Figure 2). The tree-ring series can thereafter be statistically and visually compared to a reference chronology in a procedure referred to as cross-dating, which is standard in dendrochronology [75]. During the statistical comparison, two tree-ring series are shifted along each other at 1-year steps. For each position, correlation values are calculated and the most likely position for an undated tree-ring series on a dated master chronology is where the most significant statistically significant values are obtained. The *t*-value is the most used statistical parameter [75], but other statistical parameters, such as Gleichlaeufigkeit or coefficient of parallel run [76], should preferably be used as a complement to obtain a statistically reliable match. The statistical tests should also be justified with visual comparisons between the tree-ring series.

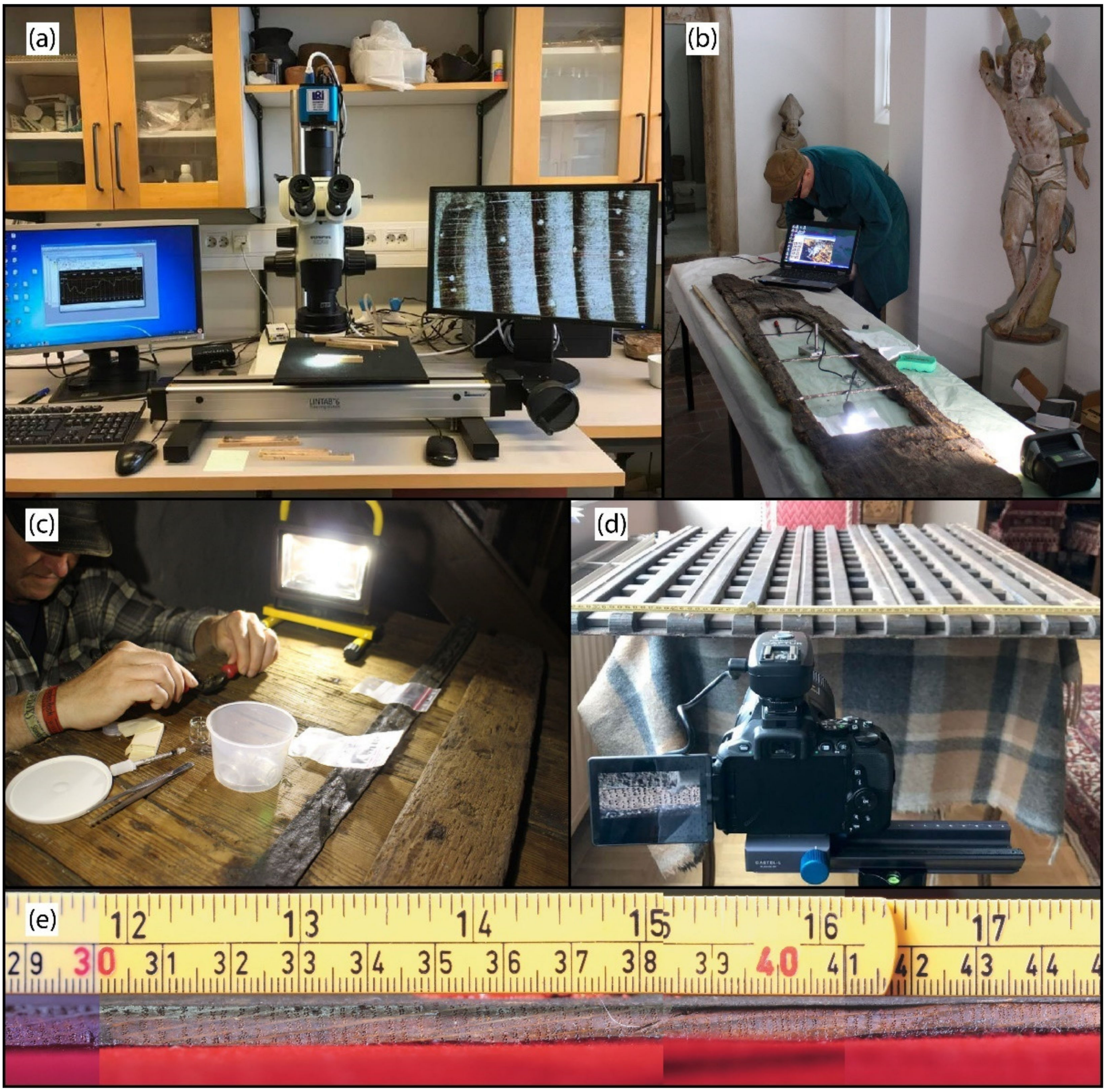

Figure 1. (**a**) Tree-ring measurements directly on a core from a pine tree. (**b**) Micro-invasive image analysis on a window frame from Ignaberga church based on high resolution images taken with USB-microscope. (**c**) Measurement on a horizontal door leaf. In parallel with the measurements small wood samples were taken to allow for radiocarbon dating if the dendrochronological analysis would not yield a reliable result. (**d**) Micro-invasive image analysis on an oak panel based on high resolution macro photos. Note the magnified annual rings on the camera screen. (**e**) Composite pictures of an oak plank from macro photos. The scale is helpful when the images are to be linked together and to calibrate the image before the annual rings are to be measured.

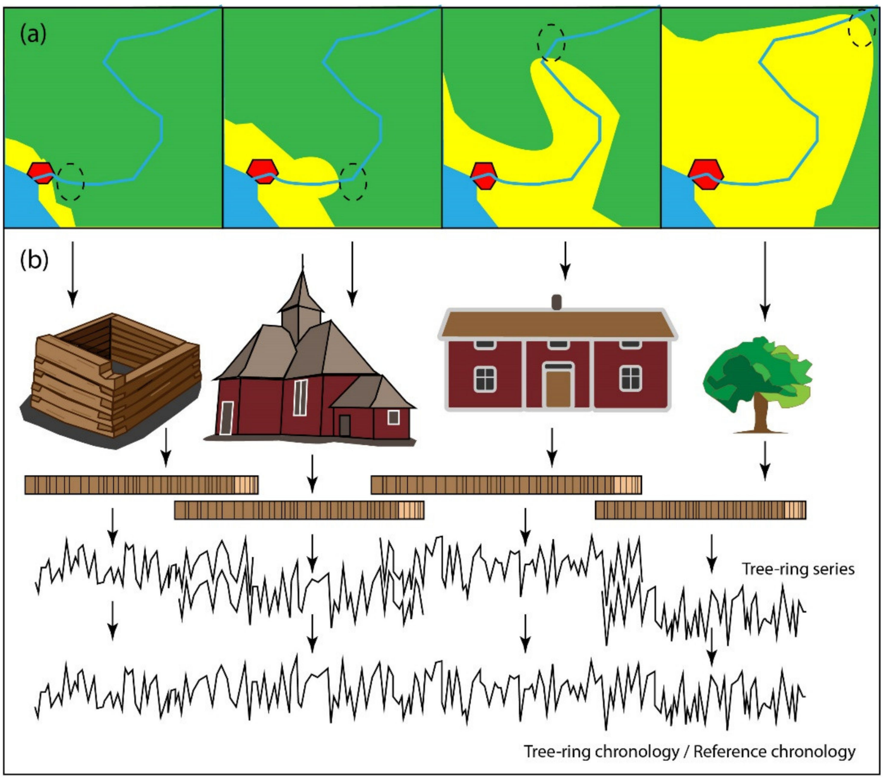

Figure 2. (**a**) The source area for the timber (dashed circle) is gradually moved away from the city (the red marking) when the forest (green area) is replaced by arable land (yellow area), which means that the provenance of the timber has changed as the surroundings were deforested. (**b**) A tree-ring chronology can be developed from tree-ring series from living trees and historical timber that are averaged into a tree-ring chronology.

3.4.5. Estimation of the Felling Year

Once a tree-ring series has been dated, the next question and possibility of interpretation is whether we have the felling year of the tree or not. Already, at this stage, our interviews and the literature studies show that it is often difficult for end users to separate results from interpretations. Moreover, end users often make incorrect interpretations of the results if the reports are unclear. Knowledge of common wood characteristics, such as annual growth rings, heartwood, sapwood, waney edge, bark, and pith (Figure 3), which are of importance for enabling and determining the precision of the tree-ring dating, is therefore desirable among everyone who is to interpret dendrochronological reports and results.

Annual growth rings are usually formed in trees growing in temperate regions, in which the trees have a growth and a dormant season each year [77]. These changes cause variations in radial growth resulting in the pattern we can observe as annual rings (Figures 3 and 4). Each annual ring normally consists of earlywood and latewood (Figures 3 and 4). In coniferous trees, such as pine, earlywood is characterized by large-diameter and thin-walled tracheids whereas latewood is developed when cell division activity declines in the cambial meristem and can be observed as narrow-diameter tracheids with thick cell walls [77] (Figure 3). Hardwood trees, such as oak, form large earlywood vessels prior to bud break, and thereafter the radial growth is completed from the development of the significantly denser late wood during the summer and autumn [3]. For both pine and oak, it is often possible to observe differences between the normally darker inner part of the stem, which is referred to as heartwood, and the brighter outer part of the stem which is called sapwood (Figures 3 and 4). Sapwood can be described as the outermost part of a woody stem containing living parenchyma cells, whereas the heartwood is the inner part with dead cells.

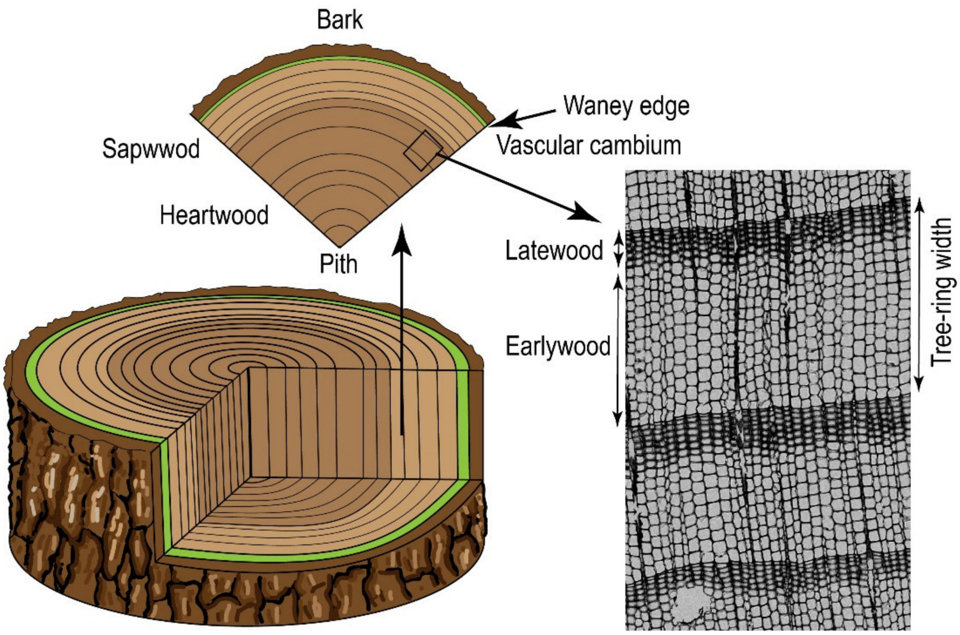

Figure 3. Schematic cross section of a tree with pith in the centre, thereafter heartwood, sapwood, waney edge, vascular cambium, and bark. The oldest rings are located closest to the pith, whereas the most recently formed ring is located just beneath the waney edge and the bark. To the right, annual rings from a pine tree showing earlywood, latewood, and total tree-ring width.

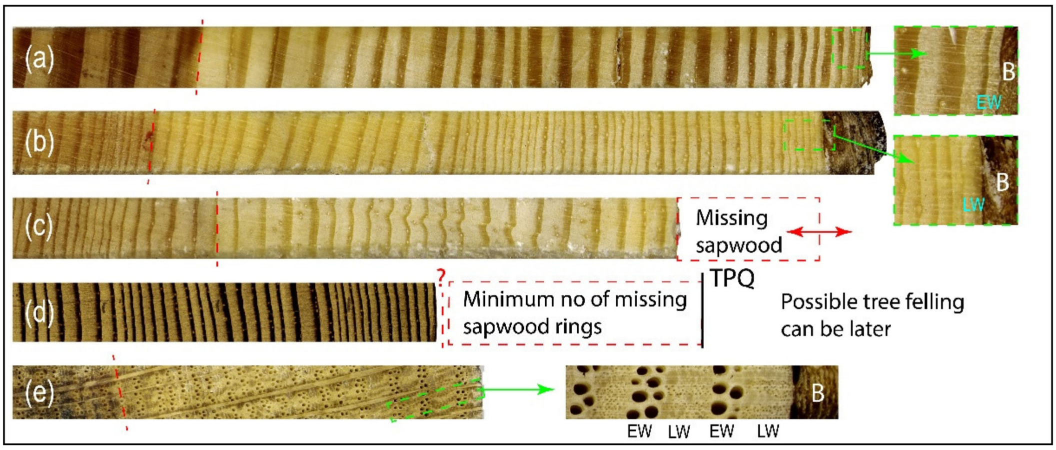

Figure 4. (**a**) Pine wood sampled 10 June 2019 in South Sweden. The 2019-year ring is not complete and the waney edge and some bark (B) is preserved. A dendrochronological dating of the sample would therefore be as precise as summer 2019. (**b**) Pine wood sampled in August 2019 in central Sweden. The 2019 growth ring contains both earlywood (EW) and latewood (LW) under the bark (B). A dendrochronological dating of the sample would therefore be the dormant (autumn/winter) season between autumn 2019 and spring 2020. (**c**) A pine sample with sapwood, but no bark or waney edge preserved. Missing sapwood rings must therefore be considered in dating, which means that the dating has a margin of error. (**d**) A pine sample without sapwood. A terminus post quem (TPQ) date is therefore the only correct option. In this case, the outermost ring is AD 1098. Based on the growth rate of the tree as well as number of sapwood rings from other matching samples from the same building, an estimated minimum of 55 sapwood rings were in this specific case added. The earliest possible tree felling can then be estimated to AD 1153. However, pine trees with more than 100 sapwood rings have been observed. Moreover, we do not have any information about the number of missing heartwood rings. The felling year can therefore be decades, perhaps even centuries after the terminus post quem dating. (**e**) Example showing heartwood and sapwood of an oak sample with close up on the outermost rings to show earlywood and latewood. The dashed red lines show the boundaries between heartwood and sapwood.

The preservation bark, waney edge, and sapwood are crucial for the estimation of the tree-felling date. If there is bark and/or the waney edge preserved, an exact year for the tree felling can be determined [78]. It can also be indicated whether the timber was felled during the growth (spring/summer) or dormant (autumn/winter) season (Figure 4). Here, however, it is important to emphasize that trees classified as felled during the summer have been felled during the growing season, while winter felled trees have been felled during the dormant season. The exact length of the growth and dormant season varies between different geographical region, tree species, and even from year to year. It is also worth noting that a tree felled in early spring, when the xylem sap detaches the bark from the sapwood, can be classified by the dendrochronologists as "winter felled" since the formation of new cells has not yet started. If the bark or waney edge is missing in an analysed wooden sample, an estimation of the number of lost growth rings is required to approximate the felling year of the tree.

If the sapwood is preserved, an approximate date for the tree felling can often be estimated. For tree species, such as oak, this estimate can be made with a small margin of error since the approximate number of sapwood rings usually is known [3] (Figure 5). However, the estimation must be done with caution as rare examples of oak trees with significantly more sapwood rings have been observed. Moreover, carpenters may have selected a certain quality of the trees for a construction which may mean that the analysed material does not correspond to the norm. If several trees from the same construction can be analysed, the dendrochronologist can create specific sapwood statistics for the analysed timber.

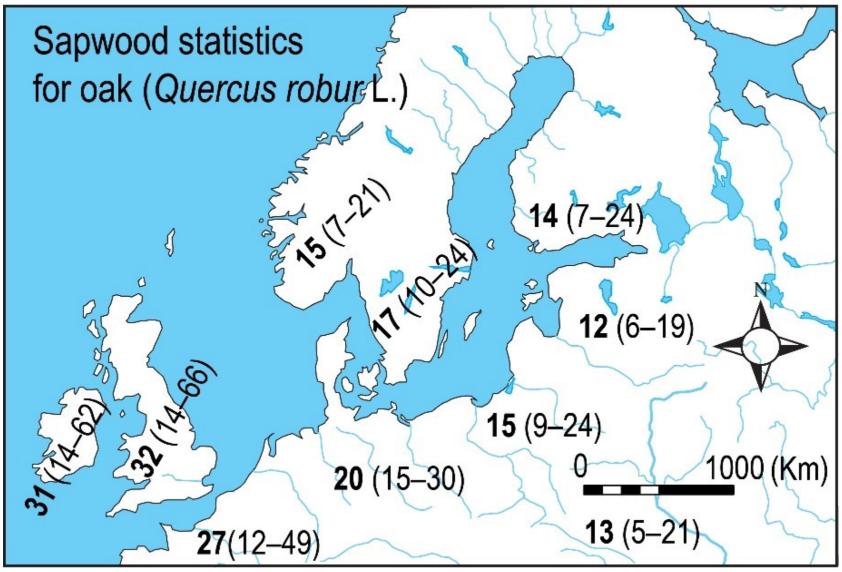

Figure 5. Map showing the geographical distribution of the estimated number of sapwood rings in oaks growing in Northern Europe: Sweden [79], Norway [80], Finland [3], Ireland [81], Northern France [82], Northern Germany [83], England [84], Northern Poland [85] Czech Republic [3], and Eastern Baltic [86]. In bold is the average number of sapwood rings for 100–200 years old oak trees in the geographic region and in brackets the range (min–max) of sapwood rings.

If the sapwood is completely missing, the only option strictly speaking is to give the wooden sample an earliest possible felling date, sometimes referred to as a terminus post quem (Figure 4). It is therefore of the utmost importance that the person who does the sampling do their utmost to include any possible sapwood rings to improve the accuracy of the dating. A minimum number of missing rings can be calculated from sapwood statistics by taking the date of the outermost annual ring of the sample and adding the lower limit of sapwood rings in the confidence interval from regional sapwood estimates (Figures 4 and 5). Numerous empirical studies have been undertaken to produce sapwood statistics for oak trees [3,79–88]. The studies show geographic variations in the average number of oak sapwood rings (Figure 5). Moreover, slow-growing trees tend to contain more sapwood rings than fast-growing trees. The estimates of the amount of missing sapwood rings in oak trees should therefore be based on which geographical region the tree is believed to originate from and the age of the tree when it was felled [3]. For pine trees, the variation in sapwood rings between young and old trees, as well as trees growing under different environmental conditions are larger than for oak trees. Despite this, regional studies about sapwood statistics for pine are sparse if existing at all. For pine trees 100–200 years or older, there are often 50 to 85 sapwood rings [89], but extremes in the range from 30 to 120 sapwood rings have been noted in our review of the reports. An alternative method to estimate missing sapwood rings is to assume that the thickness of the sapwood appears constant for trees growing under similar ecological conditions, or for trees of similar ages and growth rates [90]. Based on the growth rate of a tree, it is possible to approximate the number of sapwood rings by comparison with similar trees showing complete sapwood.

3.4.6. Dendrochronology for Provenance Studies

Climate and environmental factors influence the radial growth of trees [10]. Trees growing in separate geographic regions, or under influence of different growth limiting factors (e.g., temperature or precipitation) show deviating tree-ring patterns. If strong statistical matches are obtained using reference chronologies from a specified region covered by the reference material (Figure 6), this indicates the provenance of the analysed timber [91,92].

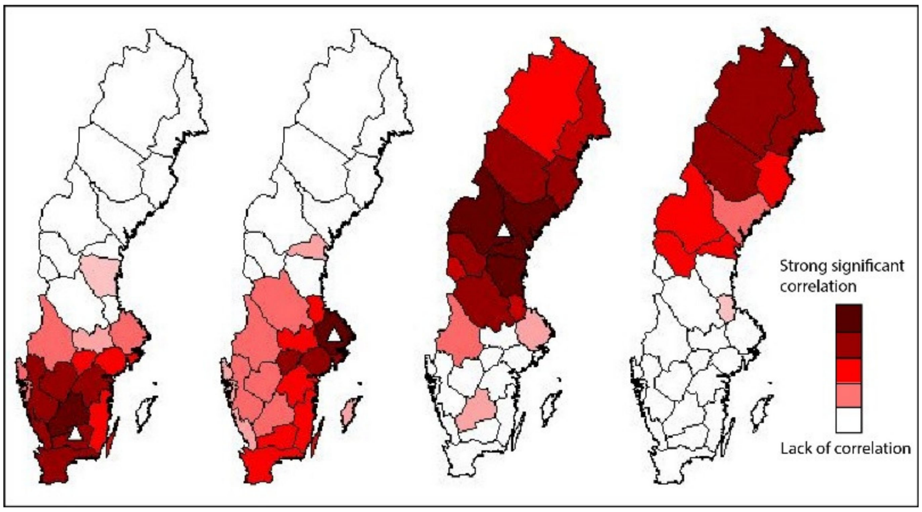

Figure 6. Examples that show how the determination of provenance works. The white triangles show areas where analysed spruce wood originates from. The darker the colour the stronger the correlation between samples and reference chronologies developed from each region.

Provenance studies are often used for wood from archaeological or historical contexts [91,92]. Timber provenance is of particular importance in regions or contexts where export or import of timber is common. Although dendroprovenancing is a key to investigating the origin of timber, there are shortcomings that may limit the accuracy of the method. Centuries of extensive timber trade may, for example, have resulted in wood of different origins being combined during the compilation of tree-ring chronologies from historical timber [91], or that the sources of timber gradually shifted over time (Figure 2). Another example are the Baltic oak chronologies [93], which have been developed from oak trees that were exported to Western Europe from non-specified geographic areas in the Baltic region. It can therefore sometimes be difficult to pinpoint precisely where specific trees grew.

To improve the dendroprovenancing, especially for difficult regions or tree species, various approaches can be employed. Stable isotopic ratios of carbon, oxygen, and sulphur [94,95], as well as strontium stable isotopes [96] preserved in the tree rings, have been successfully used for provenance studies. However, these methods may also have sources of error as the isotopic composition of wood may be influenced by biological and physico-chemical processes instead of geographical and climatic factors [97]. For archaeological wood, processes linked to diagenesis in soils can also modify isotopic composition in the wood [97]. Apart from tree-ring width, wood anatomical properties, such as vessel size in early wood in oak trees, have been used to differentiate oak populations from different geographic regions [98]. Moreover, DNA in historical wood has also proven to be an opportunity to trace the origin of the timber [99].

3.4.7. Additional Information from Dendrochronological Studies

Not all dendrochronological surveys can generate a more precise dating than what is already known to craft researchers or historians. However, in our experience, literature reviews and interviews reveal that additional information from dendrochronological surveys can still be of utter importance. The choice of tree species and wood quality, as well as information about land-use changes and the time of the year of tree felling can sometimes be more interesting for the end user than precise dating. By way of example, studies from France show that, as early as the 12th century, forests were cultivated and harvested at a young age [31,32]. Such changes can be visible as a sudden increase in the radial growth or an upturn in the number of new shoots. Such trees may be of little interest for the construction of a robust chronology, provenance studies, or climate data, but of relevance to understand how the landscape and the forest were used. Both silvicultural and historical studies may thereby gain highly relevant information from analyses of such trees. An example from our reviewed reports is a study in which an alder from a well that was constructed during the Bronze Age could not be dated by means of dendrochronology. The analysis could, however, reveal that the tree was felled around June and that the forest probably was thinned a couple of years before the tree was felled [18,100]. Moreover, several studies on prehistoric wagons in Nordic countries have been performed on samples with little to no potential for dendrochronological dating [18], but could confirm which tree species were preferred according to their functionality. Such investigations also revealed valuable information about prehistoric silviculture [16].

3.4.8. Alternatives When Results Are Questionable or Unreliable

For many reasons, a dendrochronological survey can end up with an unreliable dating. As already mentioned, historians, craft researchers, and archaeologists experience and knowledge about various building techniques can often give a narrow range for a construction. Thus, sometimes alternatives that are considered unreasonable can be excluded. However, there is a risk that this type of exclusion method provides circular evidence, which does not advance science. In such cases, radiocarbon dating [101] or wiggle matching [102] of tree rings in combination with dendrochronological analysis can help to exclude incorrect suggestions and suggest the best and most probable result. However, since the margins of error for radiocarbon dating from historical timber are sometimes large, we recommend a dialog between the end user, dendrochronologist, and an expert in radiocarbon dating before a decision is made. Stratigraphic records or historical sources can also be useful during the interpretation of results. If, for example, a church is from after medieval times, the suggested results can often be crosschecked by the church accounts. In Sweden, church accounts are preserved for a majority of churches from the early 17th century and forward.

4. Discussion

4.1. Suggestion for Improved Communication between Dendrochronologists and Cultural Heritage Researchers

Dendrochronology holds a great potential to explicate cultural heritage studies and sustain cultural heritage practice with evidence, but to get the best out of the method, both potentials and limitations must be clarified. Although we use examples from historical buildings in Sweden, we note that the same issues and problems arise regardless of geographical area and research discipline, since we discussed these same issues when we worked with church timber in Sweden as when we worked with fine art in Puerto Rico. The main conclusion of this research is the need for improved communication between dendrochronologists and end users of tree-ring analyses for all types of cultural heritage studies. The research has pointed out some of the main aspects that have to be attended to in the communication.

Firstly, standards for sampling from materials of cultural buildings (in Sweden the SS-EN 16085:2012) also provide a framework for dendrochronological sampling. After an initial building investigation and complementary archival studies, research questions should be formulated. Moreover, the development of a sampling plan is a possible common starting point for communication between dendrochronologists and end users. Here, the aims and questions for the sampling and the context of sources and previous investigations are presented. If the dendrochronologist is presented with a sampling plan, expert opinions on the potentials and limitations can be stated before the actual recording. Problems with the sampling plan can be corrected at an early stage which may save time, money, and avoid unnecessary sampling in objects worthy of protection.

Secondly, awareness of the common misinterpretation of dendrochronological results, survey reports could be developed with a more extensive general outline of the method and guidance in how to interpret the results. It is, for instance, important that the end user be fully aware that a dating result can indicate the time of the tree felling and not when a building or an artefact were made, or if the material were reused.

Thirdly, the potential contribution from dendrochronology is often underused, and, here, improved communication could lead to more effective uses of the results. Not all end users know that it is possible to also get historical information on, for instance, the age of the trees, the structure of a forest stand, or local climate conditions. The dendrochronologist could therefore enlighten end users regarding what information can be possibly extracted. A continuing dialogue between the dendrochronologist and the end user during the interpretation of the results is therefore highly recommended.

Finally, the interpretation of the results should consider all the available sources where dendrochronology is one stake of a conciliant conclusion. The results should preferably be discussed and jointly interpreted before publication. A strong hypothesis from historical or archaeological sources, craft research or heritage officers could be valuable to assess annual ring series and statistical parameters in dendrochronology and vice versa.

In a European context, the call for better communication and bridges between research and practice has been emphasised, both in committees for standardisation in cultural heritage conservation and in the new European Research Infrastructure for Heritage Science (E-RIHS). The baseline motive for these commendable initiatives and extensive investments are to improve the quality of cultural heritage practice, and to succeed we also need to address communication. The communication problem is not one-way from dendrochronologists and practitioners, it applies to both directions. Cultural heritage practice contributes data that accumulate in repositories and hence amplify potentials for cultural heritage research and the statistical support of heritage science.

4.2. Sampling Strategies—A Good First Step to In-Depth Discussion

Well-executed sampling campaigns based on thoughtful strategies are required for successful dendrochronological surveys. From our studies we can conclude that the planning of the sampling campaign are often special parts in cultural heritage surveys since these steps may be the only times when dendrochronologists, practitioners, end users, and authorities are involved. It is therefore an excellent opportunity for in-depth dialogue.

To compile a sampling strategy, we recommend an initial building inventory to identify if it is relevant to carry out a dendrochronological survey. If the inventory proves that important research questions might be answered through dendrochronological analysis, a discussion should be conducted in cooperation with all parties and provide a basis for decision-making on the following issues: (i) will a dendrochronological survey contribute to additional information and knowledge that is not already known through other sources, (ii) will such knowledge be of importance in a larger context, and (iii) how can an investigation be carried out with minimal impact on the study object? If the conclusion is that further studies are relevant archive and literature studies, as well as a review of care and maintenance plans for the study object should be undertaken. It is important to keep in mind that for listed buildings and churches, permissions are required from authorities before a sampling can be carried out. During the inventory, identification of recycled wood and building components, surface treatment techniques, and attachments that may contribute to the analysis should be noted. Furthermore, surfaces identified as possible sampling areas should be examined with raking lights to detect markings, carvings, or historical graffiti to ensure that the sampling can be made without damage to such traces. After the inventory, the research questions the survey intends to answer should be stated. Moreover, the sampling plan and method should be justified and compiled in accordance with the local sampling standard. The plan should also include a description of how surfaces that eventually have been affected should be treated or restored if needed.

Regardless of who performs the sampling, there should be a written protocol that clearly states which parts of the object have been sampled. Furthermore, information on how the sampling was carried out and peculiarities for each sampled element should be noted. Such information can be of utmost importance later in the process when interpretations of the results are to be made. It is, for example, not always possible to determine from a core if is waney edge or bark on the sampled timber. The person making the notes should therefore clearly state in the protocol if it is sure that there is bark or waney edge preserved or if it is an assumption.

Good foresight can minimize damage and generate good results. An excellent opportunity to minimize the impact from a dendrochronological sampling is to take advantage of restoration works during which historic timber is to be repaired or replaced. We can also recommend that offcuts from timber that are exchanged or restored be preserved. Such an approach may result in a stock of valuable material for dendrochronological analysis and minimizing the need for further invasive procedures. The approach can therefore be considered as non-invasive if the analysis can be performed on offcuts.

4.3. Rigour and Relevance

From the viewpoint of the end users in cultural heritage, dendrochronology may be a case of balancing rigour and relevance. From a dendrochronologist's perspective many samples taken in a construction within an assumed period support a statistically rigorous result. The end user may on the contrary want to restrict the number of samples to preserve the authenticity and integrity of the property [43,103]. If a building is not protected, there may be no fixed rules for precaution in sampling. Despite this, a professional sampler should perform the sampling procedure with the least possible impact and preferably follow procedures, such as those that the Principles for the Preservation of Historic Timber Structures (ICOMOS) have agreed on [104,105]. The ICOMOS aims to establish international standards for the preservation, restoration, and management of the cultural environment, and it should be in every owner or guardian of cultural heritage building to follow such procedures. However, we have noted examples, such as the Swedish medieval corner timber church of Tångeråsa, in which more than 70 drill holes from dendrochronological surveys can be observed. This may seem excessive and not proportional to the rigour of the building analysis, and most likely a result from several examinations performed without different dendrochronologists having access to each other's samples or data series. Rigour and relevance, and the precaution for the integrity and authenticity of the cultural property, must be articulated and balanced in a sampling plan. Resampling of already investigated objects might therefore become more difficult in the future as more buildings are classified as worthy of protection.

4.4. Triangulation and Consilience

In cultural historical studies dendrochronology is usually one of many methods to acquire a dating. Dendrochronology should preferably not be the first step in an investigation, rather a subsequent procedure after inspection of the object and examination of historic documents. The European standard for sampling states that a sampling plan should be established on the basis on a preliminary survey (EN 16085, ibid., §5). The sampling plan shall gear towards the research questions that are to be addressed, and furthermore, that all main roles in the process are consulted. From the end-user perspective, an indication of a dating from a short series of samples may be sufficient considering the information from other available sources. A conclusion may derive from triangulation of for instance interpretation of craftsmanship or artistic performance, attributes of construction and architecture, inscriptions, images, or information from archival material [29–31]. Dendrochronology may converge on strong conclusions with evidence from other independent sources [24,106,107].

4.5. Assessment and Access of Samples and Data

The end user who orders an investigation that includes dendrochronological analyses usually decides if the metadata, i.e., basic information about what was analysed and what the result was, is kept public or private. If and how measurement data is made available, however, varies greatly between individual actors and laboratories. If the end user aims to publish the results from a study, it might be important that the tree-ring series are accessible to other researchers to be controlled and re-used. One way to credit dendrochronologist who share such data may be if the end user credit the dendrochronologist co-authorship in publications as data used for scientific purposes should follow the scientific society's basic values where researchers receive credit through publication and merit through the peer-review system.

4.6. Interpretation of the Reports and Biased Interests

We have seen examples where end users have interpreted dendrochronological reports without considering parameters, such as missing sapwood rings, eventual transportation, storage, and processing of the timber. A dendrochronological dating can provide the death or felling year of a tree, which rarely is the same as the production year of a wooden construction. There is also proof that during the medieval period, dead and dried pine trees were used as construction timber in the Swedish region of Jämtland [59], thus adding another source of misinterpretation. In such cases, analysis of craftsmanship and properties of the timber may indicate if the trees were seasoned before usage or not. Other factors that complicate the interpretation of correctly dated wooden objects is the reuse of material or material used in a secondary context. Contrary relationship can also occur when timber in a building have been replaced or due to extensions.

There may exist a biased interest to accredit historic artefacts as "the oldest", and hence the terminus post quem dating (Figure 4) may be presented as an actual dating. The oldest standing wooden building in Sweden is sometimes said to be the corner timbered church of Granhult that is dated to AD 1217 terminus post quem. Even though it is a "younger than" date, the building is frequently referred to without this reservation [108,109]. Another example of the importance to be precautions with this type of dating is the piece Gotlandic Eke stave church displayed at the Swedish History Museum. A decorated piece of the wall is said to be dated by dendrochronology to AD 900s while other sources indicate that the first Gotlandic stave churches were built in early 1000. The dendrochronology of the single piece of wood is set to after 920 [110] or to after 990 [111]. What is important here is, first, to acknowledge the fact that the date is terminus post quem, and second, how this individual sample relate to the series in the finding from the Eke stave church. This particularly early dated sample can be interconnected with other samples from the same finding where the youngest year ring dates after 1028 [111]. The History Museum displays one of the dendrochronologist results of one sample with an exceptional early dating. This has unfortunately been used as evidence by researchers in scholarly debate on the origin and time of Christianisation of Gotlandic society, and even as a geopolitical argument that Gotland ought to be seen as cultural heritage of Russia [112]. However, what is often ignored is the fact, disclosed through dendrochronology, that there are two building periods of the Eke stave church indicating that an old church was reused.

4.7. Information and Interpretation to Include or Exclude from the Reports

The information included in dendrochronological reports differs significantly between dendrochronologists. In parallel, the amount of information requested by end users varies depending on the aim of the study and what research questions the survey is supposed to answer. Preferably, the report is designed to answer research questions requested by the end user, which was already preferably discussed and decided when the study was designed before the sampling.

It can be discussed to what point a dendrochronological report should guide the end users. The dendrochronologist can of course mention which time span is considered most likely for a tree felling, but, if so, it is an approximation. However, the dendrochronologist should not do interpretations outside his area of expertise or make interpretations that the end users want.

The interviews revealed that some end users want a value for how reliable dating is. Therefore, *t*-values [75] are sometimes presented in the reports. However, the *t*-value alone must be used with caution because (i) different programs can calculate the value in different ways, (ii) the value is influenced by the length of the overlapping data series, and (iii) extreme changes in the growth patterns of trees can produce unreasonably high *t*-values. Reports presenting *t*-values must therefore clarify how the value has been calculated and how large the overlap is based on if the end user should be able to compare the *t*-values presented in different reports. Moreover, the dendrochronologist has other statistical parameters, opportunities for visual comparisons between annual tree-ring series, the possibility to eliminate the influence of extremes in the data series, as well as experience in being able to evaluate whether a cross-dating is reliable or not. With the aggregate information, a dendrochronologist can sometimes choose to rely on a cross-date with a certain *t*-value but dismiss another with a larger *t*-value. In such cases, this must be explained in the reports.

5. Conclusions

Historical timber occurs in a wide range of different contexts. It can therefore be a great challenge for both the end users and the dendrochronologist to optimise a survey to obtain all conceivable results. The quality and time required for the survey thus vary in terms of methods and complexity, as can the amount of useful information that can be obtained from a survey. However, continuous communication between end user and dendrochronologists can significantly improve the quality of a study. If the end user initially informs the dendrochronologist about the purpose of the analysis and what questions need to be answered, the survey can be designed to obtain best possible results. If this is not discussed before the sampling or analysis, some research questions might remain unsolved. From our experience, interviews, and literature studies we suggest a procedure as follows:

1. Prior to an investigation the end user should:
    a. Define overall research questions for the survey.
    b. Do an inventory and study of the object, preferably together with building archaeologists, craft researchers or historians. If the outcome of the inventory

shows that valuable results can be obtained from a dendrochronological survey, the status of the study object must be considered. For example, what permissions are required and have any surveys been implemented in the past?

2. Prior to sampling, the end user and the dendrochronologist should:
    a. Define and discuss the research questions in relation to the sampling.
    b. Identify all building and restoration phases and make sure the sampling is made on wood from the correct phase. A random sampling is likely to be both invasive and fruitless.
    c. Investigate if samples from previous surveys or renovations exist and can be used to answer the research questions.
    d. Discuss what sampling strategies that are allowed and possible (invasive, micro-invasive or non-invasive). Thereafter a decision of preferred strategy can be done. However, the decision may need to be re-evaluated when the sampling starts if the quality of the samples does not meet expectations.
3. During the sampling, the end user, practitioner and dendrochronologist should:
    a. Collaborate or at least having a good dialog. If the correct timber is sampled, fewer samples are needed to answer the research questions.
    b. Extract samples containing waney edge or as much sapwood as possible. If there is sapwood or bark on the timber, but not visible on the sample, make notes as it can improve the interpretation significantly.
    c. Write a protocol that clearly states which parts of the study object have been sampled and how the sampling was made.
    d. Document peculiarities for each sampled tree trunk, e.g., if there is sapwood or bark preserved, and if there are traces of damage on the timber.
4. During the tree-ring analysis, the dendrochronologist should:
    a. Follow a protocol to make sure that the end-user questions are being answered.
    b. Make a careful documentation to ensure that the analysis process can be recreated, results can be verified, or additions implemented.
5. Information stated in the report:
    a. The research questions the end user and the dendrochronologist have agreed on to study should be listed. The dendrochronologist should thereafter answer in the report if these questions could be answered or not.
    b. Results and interpretations must be clearly separated.
    c. The report should give information based on the dendrochronological analysis and avoid interpretations based on information from the end user. Such interpretations can be biased.
    d. The reports should inform the end users what calculations and assumptions are based on. By way of example, if the number of missing sapwood rings is an estimation or a statistically supported value or which assumptions support a terminus post quem dating.

Today, heritage science has emerged as a recognised field in many prominent universities worldwide. The European Research Infrastructure for Heritage Science E-RIHS is now an established platform for transdisciplinary and cross-national collaboration aiming to develop the potentials of science in cultural heritage for the benefit of economic efficiency and excellent research, and also for improved quality in practice. Our hope is that in the future this collaboration can take care of questions of how dendrochronological data, results, samples, and reports can be coherently assessed and made accessible for future studies. For science to deliver integrated access to expertise, data, and technologies, according to E-RIHS needs, will also require understanding and capability of the recipients. We would prefer to perceive the need, not as a one-direction dissemination, but more of a dialogue and exchange. The research presented in this article is a building block to an important bridge between research and practice, rigour and relevance.

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