Dendrochronology

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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. But dendrochronological surveys in the context of cultural heritage studies are rarely ultimately performed. In this study, we discuss how continuous communication between end users and dendrochronologists can significantly improve the quality of heritage studies based on dendrochronological results.

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

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. Moreover, wooden objects have been decorated, while sculptures, arts, and music instruments 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. Following more recent improvements of the technique, 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, archaeology, fine arts, shipwrecks, timber trading historical buildings and constructions, and silviculture. Annual growth rings in trees are also archives of climate, environment, and cultural changes, allowing for age determination of ecological states and transformations, natural disturbances, and of course climatological changes, from which cultural responses can often be interpreted and derived. In such contexts, dendrochronological data have been used to interpret societal transformations due to, for instance, land use and changes in silviculture, plague, or food crisis. 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, as well as to assess what information dendrochronology can provide regarding cultural heritage. 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.

2. 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. 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.

4. 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).

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

5.1. 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. 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. Oak also has a wide distribution across Europe and has, since prehistoric times, been used as construction timber. At present, there are more than twenty native species of the genus *Quercus* in Europe, 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.

5.2. 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 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, 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.

5.3. 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.

5.4. 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, as well as non-invasive image analysis based on high resolution photos from unprepared surfaces taken with camera or USB-microscope, **Figure 1**, X-ray images, and CT scanning. There are also alternative methods, such as isotope ratios in tree rings, that can be used instead of tree-ring width. Regardless of the method, there are several common requirements that must be met for a successful dendrochronological dating analysis.

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.

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. 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, but other statistical parameters, such as Gleichlaeufigkeit or coefficient of parallel run, 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.

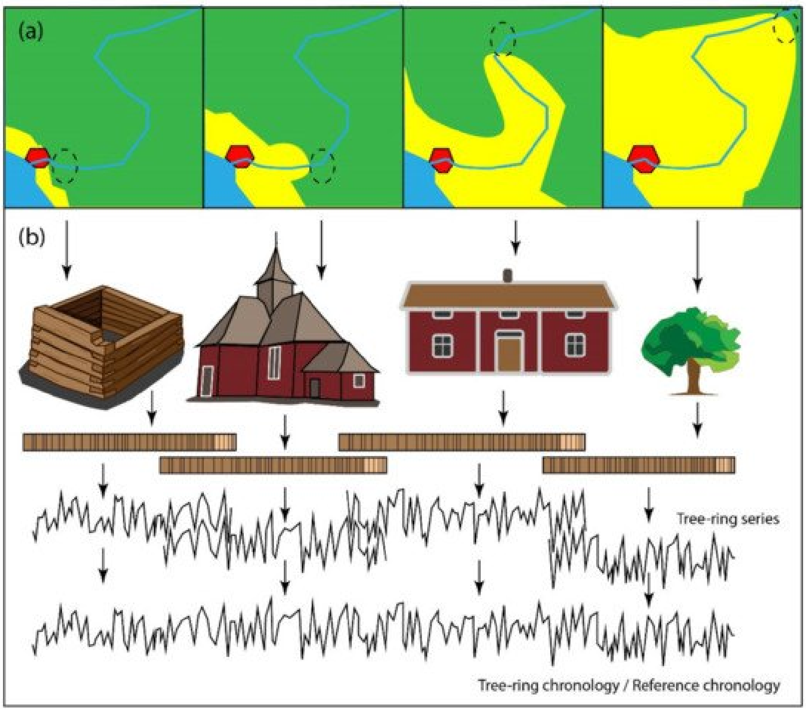

Figure 2. (**a**) The source area for the timber (dashed circle) is gradually moved away from the city (the red marking) when the forest (green area) is replaced by arable land (yellow area), which means that the provenance of the timber has changed as the surroundings were deforested. (**b**) A tree-ring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

5.5. 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.

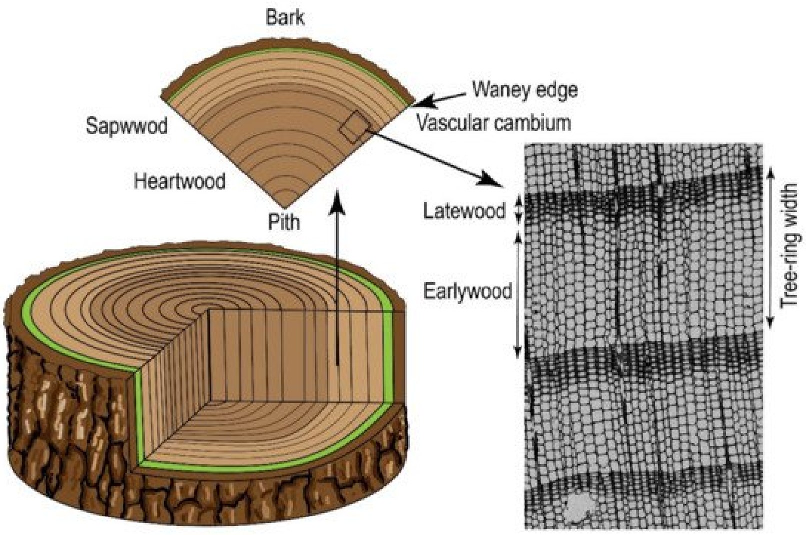

Figure 3. Schematic cross section of a tree with pith in the centre, thereafter heartwood, sapwood, waney edge, vascular cambium, and bark. The oldest rings are located closest to the pith, whereas the most recently formed ring is located just beneath the waney edge and the bark. To the right, annual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

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. These changes cause variations in radial growth resulting in the pattern we can observe as annual rings (**Figure 3** and **Figure 4**). Each annual ring normally consists of earlywood and latewood (**Figure 3** and **Figure 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 (**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. 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 (**Figure 3** and **Figure 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.

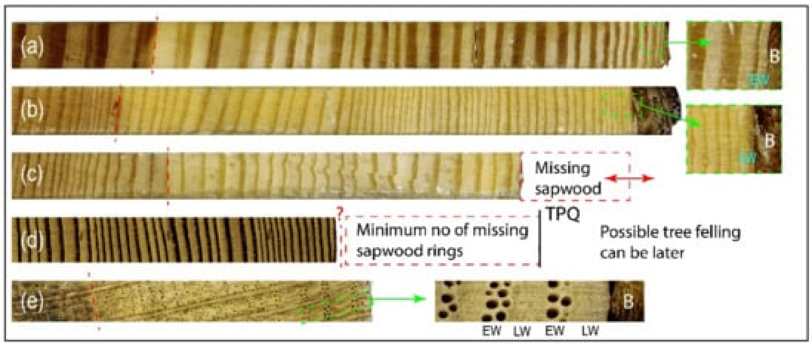

Figure 4. (**a**) Pine wood sampled 10 June 2019 in South Sweden. The 2019-year ring is not complete and the waney edge and some bark (B) is preserved. A dendrochronological dating of the sample would therefore be as precise as summer 2019. (**b**) Pine wood sampled in August 2019 in central Sweden. 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.

5.6. Methods to improve cultural heritage studies

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, microinvasive 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.
