Methodologies for dating wooden artefacts

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Abstract. In recent years, constant progress has been made with regard to wood-dating techniques. In Italy, both the number and length of dendrochronological reference chronologies have increased so that by now the last 10,000 years are almost completely covered. This indispensable dating method has provided new ways for studying archaeological and prehistoric finds. New technologies have remarkably improved the sampling techniques, which today, in most cases, are very effective and non-evasive. Modern software now allows easy data management and statistical analyses. Apart from dendrochronology, the diffusion of isotope analysis has also had great impetus. With regard to radiocarbon dating, the calibration curve has been enriched by new data, and several peaks of cosmic emissions have been identified that, in future, can be instrumental in improving dating precision. Apart from radiocarbon, the isotope analyses of O, H and Sr, especially if linked with dendrochronology, allow to refine the information regarding dating and, in many cases, permits to determine the timber’s provenance and even to define precisely the environmental conditions for the growth of the tree, from which the wood has been obtained. Today, finally, we can assert that all wood can be dated. Only the precision of dating still varies but constant progress is being made in that regard, too.

1. Introduction
The concept of chronological dating is very broad and potentially ambiguous. According to the general definition, dating is assigning an object to a specified time period. The accuracy of dating depends on the object's characteristics, the method used and finally, the objectives of the dating process. For a paleontologist, dating a fossil with a 50,000-year uncertainty is more than acceptable, while in particle studies the precision below hundreds of second is often necessary. Therefore, the required accuracy depends on the purpose of the study, and each of the above mentioned dating results can be considered correct.

The most common wood dating techniques are dendrochronology and radiocarbon. Both of the methods have strongly evolved in the recent years, and this has opened new research opportunities enabling applications that are, however, still largely unknown to scientists from other fields.

This following review paper is mainly addressed to scholars in the field of cultural heritage. It aims to discuss the state-of-the-art and perspectives, including integrative and alternative methods, in wood dating techniques and to provide new insights on timber dating and on identification of its geographic origins.
2. The current state of dendrochronological analyses

Dendrochronology is a scientific discipline that relates the tree-rings growth with the calendar year in which they were formed. Dendrochronological dating allows to determine the age of wooden objects with a precision of a year or a year fraction. Standards and guidelines on producing and interpreting dendrochronological dates have been established in many countries. In Italy, the methodological rules of dendrochronology have been reported in the UNI Standard 11141, published in 2004 [1].

The width of each individual ring of temperate-zone trees depends on environmental growth conditions, in particular those related to climate. If these growth conditions are characteristic for a larger area, the growth rate will be synchronized among multiple trees [2], and in years with favorable climate most trees in the same stand or region will produce wider rings, while in unfavorable years will form narrower rings.

Dating of wooden objects is obtained by comparing the pattern of growth rings (dendrochronological series) of the investigated object of an unknown age with long and well-replicated reference series (also called “master” or “standard series”) of accurately dated rings. The selection of the correct reference chronology is crucial to the success of the dating process. Ideally, the sample should be matched against reference chronologies representative for the species being investigated and suited to the geographic area of the sample to ensure corresponding growth conditions. Given these requirements, the age of a wooden object can be determined, even if it must be noted that this may not necessarily correspond to the date of the manufacturing process.

Although dendrochronology has been in practice for a long time [3] and it has provided numerous applications in the field of cultural heritage [4], the recent advances in this method are still not very well-recognized. In Italy, until a few years ago, the lack of sufficiently long and well-replicated reference chronologies for many species and the use of chronologies geographically distant from the sampling site, resulted in largely uncertain dating results and loss of confidence in the technique itself. The longest available series, stretching back only slightly more than 1000 years, barely covered part of the Middle Ages period [5].

In recent times the situation has changed significantly. In case of conifer forests of the Alps, reliable chronologies based on analysis of thousands of plants, dating as far back as 11000 years, are now available [4]. The effectiveness of dating has been significantly increasing and now it extends even to prehistoric periods. Another limitation of the method that has recently been overcome was related to the scarce distribution of reference series in Italy, which did not allow for consistent dendroprovenancing analyses.

The theory behind using tree-ring research to determine the origin of dated wood derives directly from dendrochronology. The formation of growth rings in wood depends on numerous environmental factors, including the climate, which is the most important variable. In a fairly well-defined region, these factors are rather similar, and this explains the usually high level of cross-matching between trees of the same species from the same area. Indeed, when comparing a single dated time-series of unknown provenance with a sufficient number of reference chronologies, the correlation between the ring-widths will be the greater, the greater the similarity between the environmental factors between the object of unknown and the reference of known provenance. Therefore, the higher the correlation between dendrochronological series, the closer the distance between the growth locations of the investigated and reference plants. The large number of currently available reference chronologies spread over the entire Italian territory allows solid dendroprovenancing analyses, providing new and often surprising insights on the origin of the studied objects [6].

A similar logic applies to artworks attribution. The great abundance of dendrochronological studies currently available allows to easily assign work to a specific author or school. In this case, the theoretical basis of analysis is linked to the selection of wood by a craftsman who, after finding the wood suitable for his works, tended to continue to use wood of the same provenance, from the same stand or even from the same trunk. This assumption was confirmed by very strong correlations between tree ring series found in objects produced by the same craftsmen. Musical instruments are a good example. Many violins built by Stradivari, considered the greatest violin-maker of all time, can...
be easily recognized on the basis of their characteristic dendrochronological series obtained from their soundboards [7]. Thus, even if the violin has not been dated on the basis of a comparison with the reference chronology, it can still be dated and plainly attributed based on a comparison with ring series from artefacts from the same author.

To the innovations reported above one can add those related to the technological progress achieved in the recent years, which resulted in more efficient sampling (Fig. 1A and B) and data intercomparison. For instance, data management and analysis have been improved by developing numerous dedicated computer software that enable effective statistical and visual comparisons. Moreover, the state-of-the-art sampling methods based on innovative optical scanners and digital cameras allow for conducting dendrochronological analyses in a non-invasive manner (Fig. 1C). The photographic technique is gaining importance in case of items where tree-ring series are clearly visible to the naked eye, while in situations when tree rings are not directly visible, such as in case of painted sculptures, X-ray computed tomography can be used for non-destructive evaluations. Recently, a medieval wooden artwork, the Torchiara choir, was successfully dated only on the basis of images sent via WhatsApp [8]. Therefore, the current dendrochronology keeps abreast of progress in technology and offers great possibilities to study any wooden object of historical and cultural interest.

Figure 1. Examples of dendrochronological sampling activities. A-B, using the increment borer - a very versatile tool allowing to extract wooden cores in various conditions. C, digital sampling of the Amati cello from the Cherubini collection in Florence. Data were collected without removing the instrument from the glass case.

3. Radiocarbon and other isotopes

Radiocarbon dating is a radiometric dating method based on measuring the residual activity of carbon-14 ($^{14}$C) in the remains of organic material. $^{14}$C is an unstable radioactive isotope, and therefore subjected to decay, but its production and concentration in the atmosphere are fairly constant. Living organisms absorb $^{14}$C, but upon death, the absorption process stops and $^{14}$C starts to decay gradually reducing its concentration at a relatively fixed rate. Therefore, by measuring the amount of $^{14}$C in once-living organism, we can deduce the amount of time that has passed since its death [9]. However, when working with radiocarbon in organic samples, $^{14}$C data need to be corrected for isotopic fractionation using the $\delta^{13}$C values. The corrected radiocarbon age of the sample is expressed in years Before Present (BP), where "present" is defined as 1950 CE. Such ages can be calibrated to give calendar dates.

Also this dating technique has been given a strong boost recently and now is rapidly evolving. The first innovation of this method concerns technical aspects, such as sample size and analysis time. Nowadays, very small in size wood samples can be used for dating, which is particularly important when studying valuable works of art. Similarly, the duration of the analysis has been significantly reduced compared to several years ago.

A promising approach, which combines radiocarbon dating and dendrochronology, is the so called "wiggle matching". This method is based on Bayesian statistics using groups of samples with a defined chronological relationship. The known number of tree rings between different samples is, in fact, used as a statistical constraint in the calibration of a single radiocarbon data, which reduces the uncertainty of the final result.
The “wiggle-matching” technique is very suitable for analysing tree-ring series, and its use is constantly increasing in various fields [10], such as the dating of panel paintings (Fig. 2) or different construction phases of historical buildings [11]. This method is particularly useful when dendrochronological analysis is not possible, for instance due to the limited number of growth rings in the sample or the lack of reliable master chronologies [12].

Figure 2. Calibration results of 14C wiggle matching of a sequence from the panel painting attributed to Michelangelo Buonarroti [13]. The panel was dated to 1478.5 CE ± 24.5.

Indeed, one drawback of the traditional radiocarbon method is that its dating precision may be more than ±100 years [14]. Such results can be acceptable when dating prehistoric samples, but may be insufficient for medieval objects or attributions.

Today, research in the field of 14C dating is moving towards two direct ions. Laboratories around the world are trying to extend the calibration curves of 14C as far back as possible (beyond 50,000 years). At the same time, there are efforts to make the annual data more and more precise to improve the dating accuracy.

Concerning this last point, the worldwide measurements on individual wood rings dated with high certainty, have led to generation of new, more precise calibration curves. Currently, IntCal13 and SHCal13 radiocarbon age calibration curves are used in the Northern and Southern hemisphere, respectively [15, 16], while Marine13 serves as a baseline for marine data [15]. Further updates providing valuable improvements in terms of reliability and precision are expected to be released soon.

Furthermore, the identification of peaks in the concentration of 14C isotope, such as the nuclear Bomb Peak of the 1960s (Fig. 3) or the extreme events of the year 774 and 993 CE [17], functioning as chronological hinge points, can allow high-precision dating in the future [18].

Interesting perspectives apply also to dendrochronological series, which are not based on ring width, but on isotopic concentration of C, H and O. The stable isotope ratios of carbon (δ13C), hydrogen (D/H) and oxygen (δ18O) measured in tree ring cellulose are commonly used as indicators of eco-physiological processes and associated climatic conditions that regulate tree growth [19].

The isotope ratios of C, H and O allow for an effective reconstruction of the climatic conditions in which photosynthesis process and ring formation occurred. As a result, each wood element is characterized by a unique isotopic signature that reflects its climatic history. This suggests the use of these isotopic impressions also for dating studies, especially in cases where classical dendrochronology exhibits difficulties. For instance, in low-elevation sites it is usually difficult to obtain significant correlations between the ring-width series and, as a consequence, a lot of material remains undated. In these cases, stable isotopes in tree-ring time series could be very useful [20]. Furthermore, in some cases, isotopic analysis can also provide valuable information for dendroprovenancing studies [21].
Figure 3. The effects of nuclear tests, which resulted in large “spikes” in 14C levels in the 1960s (Source: Wikipedia, Public Domain).

A research topic that deserves further investigation concerns application of strontium (Sr) isotope analysis in dendroprovenance studies. The underlying background is that trees absorb chemical elements, such as Sr, from local soils and atmospheric dust, and incorporate them into wood [22]. Mountain ranges differ in chemical composition and geological history and the plants growing there retain these geochemical markers in wood. The comparison of the isotopic content of timber of unknown origin with that characteristic of the surrounding mountain ranges can give indications regarding its origin.

The geochemistry of Sr isotopes is currently known and the Strontium-87/Strontium-86 ratios ($^{87}$Sr/$^{86}$Sr) have been routinely used as environmental tracers in geology, hydrology, ecology and archeology [23]. Strontium is an alkaline earth metal and is present in all rocks. The $^{87}$Sr/$^{86}$Sr ratio of the rock substrate is a function of the initial $^{87}$Rb (Rubidium)/$^{86}$Sr ratio and the rock age. $^{87}$Sr is formed by the radioactive decay of rubidium-87 ($^{87}$Rb, $t_{1/2} = 48.8$ Ga). Older rocks and rocks with higher initial concentrations of $^{87}$Rb, such as granites, are characterized by higher $^{87}$Sr/$^{86}$Sr ratios than younger volcanic rocks derived from the Earth’s mantle, while sedimentary rocks generally exhibit intermediate values. By comparing the $^{87}$Sr/$^{86}$Sr isotope ratios of wood of unknown origin with ratios of trees growing in the surrounding mountains, it is possible to identify the area of origin of the timber [19]. Successful case studies have allowed identification of supply sites of timber used for construction of prehistoric buildings by the pre-Columbian Anasazi civilization in New Mexico [22] and identification of the provenance of timber used for the construction of various ancient watercrafts [24]. The identification and quantification of micro-elements, including isotopes and metabolite profiles, may also help in differentiating tree species and wood provenancing [25].

4. Other methods
Another dating technique worth further studies is the method that takes into account the chemical changes that occur in wood over time as a consequence of variations in ambient temperature and humidity [26]. In fact, over the years, some elements of the wood cell wall, in particular hemicelluloses, change [27, 28] and the degree of these modifications can be estimated using FT-IR spectroscopic analysis [29, 30, 26].

Although the relationship between wood degradation and time has been demonstrated [26], the degree of changes is strongly influenced by subjective factors, primarily by the peculiar history of
each individual artefact that makes each sample unique. In fact, each ancient wood is subjected to variable and specific storage conditions that cause different effects on different samples, with the result that time effects can only be partially distinguished.

Moreover, it is still unclear whether hemicelluloses are evenly distributed in the samples, since both the age of the plant and the environment in which the plant is growing affect their formation and distribution [31]. The large number of variables that affect the presence and degradation of hemicellulose over time makes the dating results obtained to date practically unusable in the field of cultural heritage studies. However, it is likely that more useful information from this type of analysis will be obtained in the future.

A promising perspective is the combined use of different dating techniques. In fact, if dendrochronological and isotope analyses (including the $^{87}\text{Sr}/^{86}\text{Sr}$ indicator), could be performed on a wooden artifact simultaneously, the determination of its microelements and metabolites, precise age and geographical origin, and thus its specific historical/cultural context would be very likely. In addition, this would eventually lead to the creation of a database with linked data, making the results more reliable and precise. This certainly requires effort in terms of time and resources but refining analysis techniques and shifting to a more open approach in wood research can offer a great potential in the field of cultural heritage studies.

5. Conclusion

Scientific dating methods provide the so-called terminus post quem, which indicates the calendar date before which the artefact could not be made. Dating refers to the age of the wood rather than to the age of the artefact itself, because the latter could have been manufactured even long time after the wood was formed. As an example one could bring the use of very old timber by art restorers and violin makers of today, who consider it to be of better quality, but also by counterfeiters who, by using old wood, try to make forged artworks look more genuine. Nevertheless, the age determined by scientific dating methods constitutes data of crucial importance for historical studies in the field of cultural heritage, because it is able to provide a chronological hinge, which serves as a basis for any subsequent historical analysis.

Especially for this reason, dating should be performed according to strict methodological standards. As Steele [32] writes about astronomical chronology, which is a scientific method of dating events or artefacts based on astronomical phenomena described in ancient sources: “Astronomical dating can be a powerful tool for establishing absolute chronologies, but it is also a tool that must be used conservatively for it can easily produce precise and impressive looking results based upon invalid assumptions - results so precise and impressive they may not be questioned by scholars in other fields”. I believe that these words also apply in the field of wood dating, where, at least in the case of dendrochronology and radiocarbon dating, there are well-established internationally available standards that must be respected for the results to be considered reliable.

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