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## The "forest" of Notre-Dame de Paris: A possible path into medieval climate and time

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## ABSTRACT

Notre-Dame de Paris, the so famous Catholic cathedral standing on Ile de la Cité in Paris, was partially destroyed by fire on April 15 of 2019. This unfortunate destruction miraculously spared a part of the frame and made these woods accessible to the scientific community. As scientists particularly interested in the isotopic composition of wood as memory of past climate and as a clock to the past, we will take advantage of this tragedy and give new life to the Notre Dame woods. In the context of a programmatic action, the  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  chronologies will open a window on the climate of the Middle Ages. They will allow rekindling the debate on the geographical extension of the MWP and, therefore, on its origin. The  $^{14}\text{C}$  record, at a yearly resolution, is expected to be implemented in the next  $^{14}\text{C}$  calibration curve and to be used to document past changes in  $^{14}\text{C}$  production resulting either from changes in solar activity or supernovae.

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## Introduction

Notre-Dame de Paris, the so famous Catholic cathedral standing on Ile-de la Cité in Paris, was built in 1163, largely completed by 1260, then frequently modified in the following centuries until a major restoration between 1844 and 1864. All these steps of construction and modifications involved the frame, so-called "la forêt" (the forest). So, the woods used throughout the cathedral's history are samples and memories of the forests of oaks grown since the Middle Ages, in the Paris Basin as stated by the analysis of historical diplomatic and administrative documentation. The unfortunate destruction of the cathedral on 15th April of 2019, which miraculously spared a part of the frame, made these woods accessible to the scientific community. Some scientists are particularly interested in the isotopic composition of wood as memory of past climate and as a clock to the past.

On one part, the oxygen and carbon isotopes ( $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ ) of tree-ring cellulose will bring light to past climate. Indeed,  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of this component are determined by the conditions surrounding the trees during their growth. The variations of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  with time, recorded in the successive rings built by the trees year after year, allow reconstructing the evolution of some environmental or climatic parameters such as temperature or humidity. Isotope dendroclimatology, a rapidly expanding field of investigation, is applied to old living trees, sub-fossil woods from buildings or even fossil material to reconstruct past climate. This methodological approach will be applied to the cathedral's oak timbers that have escaped severe charring and to contemporaneous unburned woods from other buildings.

On the other part, measuring ring by ring the residual content of  $^{14}\text{C}$  isotope in cellulose will make it possible to refine the  $^{14}\text{C}$  clock. This will be achieved by providing new portions of the global calibration curve for the continental Western Europe from the 12th to the 18th century, from uncharred "forest" of Notre-Dame.

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## Rationale

The incorporations of carbon and oxygen in trees do not follow the same path from the source (atmospheric CO<sub>2</sub> and precipitation, respectively) to tree rings. As a result, the isotopic compositions of carbon and oxygen from tree-rings can provide different environmental information.

Water is often a limiting environmental factor for plants which regulate their rate of transpiration by modulating the opening of the stomata of their leaves. While stomatal aperture controls water loss, it also impacts CO<sub>2</sub> incorporation as this gas also passes through the stomata in its way from the atmosphere to the stomatal cavity in the leaf. The rate of exchanges of CO<sub>2</sub> between the atmosphere and the plant impacts the <sup>13</sup>C/<sup>12</sup>C ratio of the photosynthetic products. The more water-stressed the plant, the more closed the stomata, the lower the CO<sub>2</sub> concentration in the stomatal cavity and the isotopic discrimination against atmospheric CO<sub>2</sub>, the higher the δ<sup>13</sup>C of the sugar produced. The activity of the Rubisco enzyme, which gives the pace to carbon fixation, is light-dependent. When insolation increases, the activity of the enzyme increases, inducing a decrease of carbon isotopes discrimination and an increase of sugar δ<sup>13</sup>C. Therefore, the δ<sup>13</sup>C of the cellulose, a component of the wood that derives from sugars, witnesses the external conditions of humidity and insolation during the growing season. The δ<sup>18</sup>O in plants mimics the isotopic signal of its source water (precipitation, whose isotopic composition is mainly temperature dependent under temperate climate, infiltrated in the soil) modulo an isotopic fractionation which takes place during transpiration at the leaf level. The higher the water stress, the larger the fractionation and thus the higher leaf water and sugars δ<sup>18</sup>O. During the polymerization of sugars to cellulose in the trunk, about 40% of δ<sup>18</sup>O is exchanged between the organic compounds and the ascending sap. The resulting oxygen isotope ratios of cellulose bear the source water's signature, modified by the evaporative fractionation. It provides insights into the climatic conditions (temperature and humidity) prevailing during tree growth. The analysis of δ<sup>13</sup>C and δ<sup>18</sup>O of the cellulose in the successive rings of trees are invaluable tools for reconstructing the variation of some key parameters of past climate at a yearly resolution.

<sup>14</sup>C geochronology is based on the measurement of residual <sup>14</sup>C content (or activity as <sup>14</sup>C is a radioactive isotope) in a sample that is subsequently translated into calendar years. The conversion of the measured <sup>14</sup>C activity into years cannot be done thanks to the classical radioactive decay equation (Eq. (1)):

$$N = N_0 e^{-\lambda t} \quad (1)$$

where  $\lambda = \ln(2)/T$ , with T the radioactive decay of <sup>14</sup>C, N the residual <sup>14</sup>C activity (or content), N<sub>0</sub> the original <sup>14</sup>C activity (or content).

Indeed, many unknown parameters persist around this equation. The decay period of <sup>14</sup>C (T) is still not known with precision (e.g. [1]) and the initial <sup>14</sup>C content of the sample (N<sub>0</sub>) is not directly accessible. Even if we consider N<sub>0</sub> to be equal to the atmospheric content when the sample was still alive, N<sub>0</sub> cannot be modelled because processes of production and incorporation in carbonaceous reservoirs are much too numerous and complex. Therefore, to convert the measured <sup>14</sup>C activities in calendar years, the <sup>14</sup>C community has developed an empirically constructed curve, the calibration curve, that links residual <sup>14</sup>C activity (N) to calendar years [2]. It is constructed by combining residual <sup>14</sup>C activity measurements on samples whose absolute ages are independently obtained (dendrochronology, U/Th dating, varve counting or wiggle matching on well-dated paleoclimatic records). This curve is constantly being improved, and the latest one, IntCal20 [3], is considered a jump forward in the level of knowledge. Before IntCal20, historical time periods were documented by 5 to

10-year resolved <sup>14</sup>C records, obtained from tree rings. IntCal20 has begun to replace these with annually resolved and wood derived records. Thanks to the increase of the resolution, a new variability has appeared highlighting abrupt events and geographical offsets previously masked by the 5–10-year smoothing. Supernovae and fluctuations in solar activity have been invoked to explain such rapid events ([4] and citing articles) and local climate and geographical features acting on carbon cycle have been mentioned as an explanation for spatial variability [5]. For historical times, the radioactive decay has not yet smoothed the short-term variations evidenced thanks to the high-resolution <sup>14</sup>C records. At this scale, regional calibration curves are needed. <sup>14</sup>C measurements on wood cellulose are thus expected to complete the next calibration exercise (IntCal24), expected to take into account regional offsets.

## The added value of the wood of Notre-Dame de Paris

The climate of the Middle Ages, between the 11th and the early 14th centuries, is supposed to be relatively clement. The meteorological mildness gave its name to this period, called the Medieval Warm Period (MWP). It was a period of demographic and economic growth that led to the development of cities, including Paris [6]. Northern Hemisphere temperature reconstructions support the idea of the MWP being comparable to the mid-20th century Northern Hemisphere warm time interval [7]. However, reconstructions of the MWP remain rare in France, and are restricted to the Alps [8]. These reconstructions are not directly relevant to the lowlands, where most people live and Paris is settled. This makes the analyses of the impacts of climate variations on human activities speculative. In addition, the climate reconstructions are mainly based on tree-ring widths with the uncertainties that this implies [9] and a possible loss of information on climate variations at multi-decadal time scales.

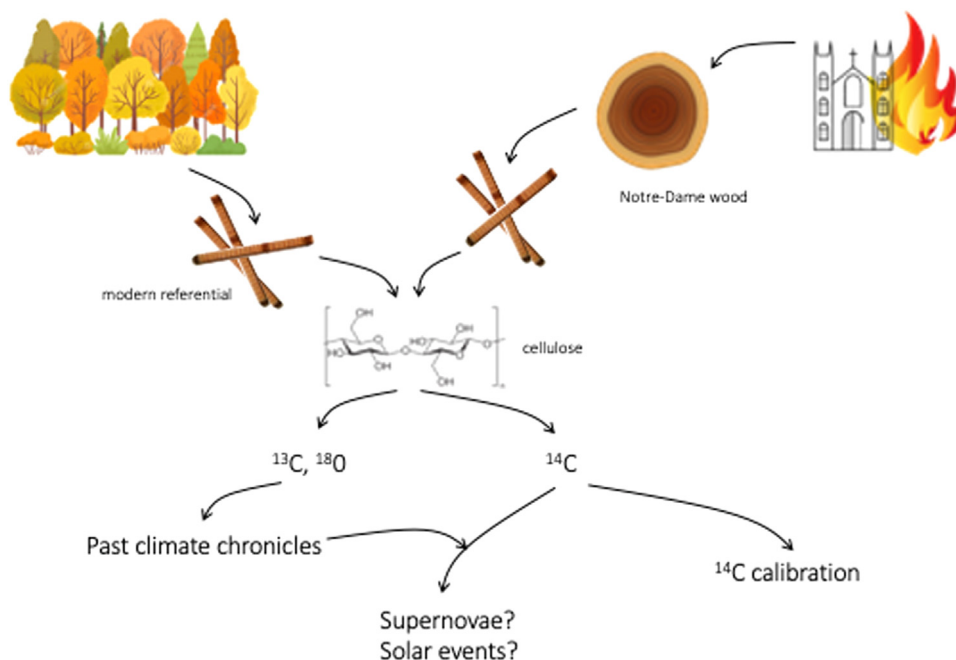
Absolutely-dated proxy records such as δ<sup>18</sup>O and δ<sup>13</sup>C isotopic chronologies from Notre-Dame's forest would fill a gap in the spatial coverage of climate reconstructions, and allow the characteristics of a warm period in a pre-industrial context to be described more precisely, and *in fine* shed light on the links between environment and human activities.

Spanning several periods from the central Middle Ages to the 19th century, the ring-to-ring analysis of Notre-Dame wood sections will provide portions of the <sup>14</sup>C calibration curve over 8 centuries for Western Continental Europe.

## Modus operandi and expected pitfalls

The modus operandi we will follow is presented in Fig. 1. <sup>13</sup>C, <sup>18</sup>O, <sup>14</sup>C data must be obtained on cellulose. Cellulose remains unchanged and immobile over long periods while lignin and hemicellulose are considered likely to change over time and cross "the edges" of the rings after their formation [10]. So that cellulose is considered the most suitable component for isotopic studies [11,12]. This raises the question of the cellulose preservation during fire and the classical protocol adaptation in this specific context. Cellulose decomposition is observed from 280 °C up to the complete destruction at 400 °C [13–15]. What will be the state of cellulose in the cathedral's woods when temperatures higher than 500 °C, or even 1300 °C were reached during the fire [16], even if a temperature gradient has to be expected in wood?

Paleoclimatic reconstructions based on dendro-isotopy require regional transfer functions established from modern reference frames. Thus, before determining the isotopic ratios in Notre Dame wood, we will sample live oaks from the Paris basin (from the area where the Notre Dame oaks come from). We will measure



**Fig. 1.** *Modus Operandi* we will follow to reconstruct past climate and past atmospheric  $^{14}\text{C}$  records at annual scale.  $^{14}\text{C}$  record is expected to complete the next  $^{14}\text{C}$  calibration curve and perhaps to highlight past solar events.

their  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  and use them to establish the regional transfer function. This will be done by regressing the isotopic variables on standardized meteorological temperature and humidity data. A dendroisotopic study conducted on oaks from Fontainebleau forest (50 km South of Paris) has shown that cohorts of 10 trees are needed to obtain reliable isotopic mean values [17]. Therefore, we will select sets of wood portions of unburnt beams from Notre Dame's framework to include the rings of 10 oak trees in each annual sample. If the cathedral framework does not provide sufficient material, we may add woods from other buildings of the same age and same geographic origin than those from Notre-Dame's forest to the collection. The selected pieces of wood will be cut ring-by-ring. The rings will be ground and their cellulose extracted following the chemical procedure described in [18].  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  of the cellulose will then be obtained simultaneously by pyrolysis in a high-temperature conversion elemental analyzer (TC-EA, Thermo Scientific) coupled to a mass spectrometer (IRMS, IsoPrime).

To provide robust sets of  $^{14}\text{C}$  data to be implemented in the next calibration curve (IntCal24), strict guidelines must be met. One of the prescriptions is to replicate a large part of measurements. This implies the analysis of very large sets of samples. To achieve this objective, three  $^{14}\text{C}$  sample preparation laboratories, the dendroclimatology group and two instruments join forces. This includes the groups under the responsibility of the authors of this article and the instruments ARTEMIS [19,20] and ECHOMICADAS [21]. Evaluating the protocols used in the different laboratories and the measurement modalities is the first step. The samples assignment to the three preparation laboratories, their chemical treatment and their measurement will constitute the next steps. The sample selection will be performed according to the dendrochronology results. Well-dated portions of wood will be selected to cover the longest possible period along the eight centuries of the cathedral's construction and restoration. Less or even not burnt wood will be preferred. Unlike in the isotopic dendroclimatology study, a single wood portion is sufficient to characterize the  $^{14}\text{C}$  signal of a given period. There is no need to combine several isotopic signals from several individuals to get the regional  $^{14}\text{C}$  signal, as it is required for climate reconstruction.

## Conclusion

The  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  chronologies of the Notre Dame woods that we are going to carry out, possibly supplemented by those of other monuments of the same age, will open a window on the climate of the Middle Ages. They will allow rekindling the debate on the geographical extension of the MWP and, therefore, on its origin. This issue is very important as the MWP is the second warmest period of the millennium after the current period of climate change. Understanding its origin and course can help clarifying the possible contribution of natural processes to a warmer climate.

The  $^{14}\text{C}$  records we will produce will be implemented in IntCal24. Their yearly resolution will make them suitable to document past solar activity more precisely than was possible with previous  $^{14}\text{C}$  calibration curves. They will also allow searching for small variations in  $^{14}\text{C}$  production attributable to cosmic events such as supernovae, undetectable in the previous multi-year resolution smoothed curves. The detection of  $^{14}\text{C}$  excess will be an independent way to set constraints on the flux emitted by and the rate of occurrence of supernovae.

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