Potential Sources of Error and Uncertainty in Radiocarbon Dates from North American Sites

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Abstract

Radiocarbon dating — the process of finding the age of a material by using the radioactive isotope carbon-14 — is an important tool in observing and inferring past ecological events and changes. However, it is not without its uncertainties. While contamination and poor treatment in the lab can lead to larger errors, so can mechanisms which convert the radiocarbon age produced by the dating process into a calendar age for scientists to use accordingly. There are more correlations between uncertainty and other factors — such as age and depth — which we will discuss in this paper.

In addition, we are using fossil pollen sediment core data from the Neotoma Paleoecology Database. Many of the fossil pollen sediment cores taken were from lakes all over North America. Not only did we use the sediment core radiocarbon data, but we also used the longitude and latitude of the sites to map the area of their respective lakes using Google Earth Pro. We then classified the lakes as being small, medium, or large, according to a framework used in this paper.

The dating process, along with the lake areas, gives us an idea of when an ecological event occurred using the radiocarbon date produced and whether the change was a local or a regional event using the area of the lake. By connecting these two parts, we gain a clearer sense of when and where an ecological occurrence happened.

Also, by knowing the sizes of lakes, we can evaluate the scale of ecological change through space and time. Therefore, ecological change can be better understood, which would ultimately lead to improved predictions of past changes in different ecosystems across North America

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Background Information

Radiometric dating is a process used to date different materials of varying ages (Andria Dawson, conversation with author, July 6, 2021). A type of radiometric dating, radiocarbon dating is a process used to find the dates of materials which are about 50 000 years old or younger using a radioactive carbon isotope (Andria Dawson, conversation with author, July 6, 2021). Radiocarbon dating must be performed on carbon-14 (^{14}C), the radioactive isotope of carbon, as opposed to carbon-13 (^{13}C) or carbon-12 (^{12}C), which are stable isotopes (Bronk Ramsey 2008, 250). Carbon-14 is primarily formed in the atmosphere through a series of reactions; these include thermal neutrons reacting with cosmic rays, and then reacting with nitrogen-14 atoms to form ^{14}C and a proton (Bronk Ramsey 2008, 250). Once formed in the atmosphere, ^{14}C is incorporated into the biosphere mainly by photosynthesis (Bronk Ramsey 2008, 253). As the ^{14}C atmospheric levels are relative to both the stable carbon atmospheric levels and the ^{14}C biospheric levels, it is not necessary to know the production rate for dating; one just needs the atmospheric concentration of ^{14}C (Bronk Ramsey 2008, 250).

Half-life is a key component of the dating process. It can be defined as the amount of time which half of the original amount of a radioactive isotope takes to decay (Dawson 2021a, 1). Today, the half life of ^{14}C is regarded to be about 5 730 years (Taylor 2000, 1). In one of the first radiocarbon dating methods proposed by Arnold and Libby in 1949, they realised that the following conditions must be satisfied: (1) the ratio of ^{14}C to stable carbon isotopes in the atmosphere must have remained constant, (2) the ratio of carbon in the dated materials must not have changed since the death of the organism — except by ^{14}C radioactive decay, (3) quick and thorough mixing of ^{14}C through the atmosphere, plants, and the rest of the biosphere must have taken place so that the ratios of radioactive to stable carbon in each reservoir stay constant, and (4) it is assumed that the half-life of ^{14}C is correct and that techniques used in the dating process can provide a date with applicable precision and accuracy (Taylor 2000, 1).

Once dated, the material returns a radiocarbon age, which must be converted to a calendar age (Andria Dawson, conversation with author, July 8, 2021). The radiocarbon calibration curve is the method used for this conversion; the curve fluctuates based on the different timescales of ^{14}C production (Bronk Ramsey 2008, 251). Therefore, short-term fluctuations in ^{14}C production rate throughout time also produce short-term fluctuations — or wiggles — on the radiocarbon calibration curve (Bronk Ramsey 2008, 251). Calibration, or comparing measurements of the ^{14}C age to the known age of its respective environment, is needed due to the varying ratio of ^{14}C to ^{12}C throughout history (Bronk Ramsey 2008, 260; Andria Dawson, comment to author, August 5, 2021). Such an example of the inconstant ratio of radioactive to stable carbon in the atmosphere is nuclear bomb tests — primarily those taking place in the 1960s — which nearly doubled the atmospheric concentration of ^{14}C (Bronk Ramsey 2008, 251).

Through the dating process, one obtains a radiocarbon age, but through calibration, one gains the uncertainty associated with the age produced (Bronk Ramsey 2008, 261). A straight line on the calibration curve would result in high precision of the date because it shows quick and well-defined changes in atmospheric levels of ^{14}C (Bronk Ramsey 2008, 264). If the curve were to fluctuate or wiggle, the effect would be the opposite: more uncertainty would be present due to a lower precision (Bronk Ramsey 2008, 251).

Not only is taking into account the calibration curve important, but also the age-depth relationship. Age-depth models are those made from existing radiocarbon dates which can serve as a source of interpolation and extrapolation of the dates (Andria Dawson, conversation with author, July 12, 2021). Allowing for predicting the time at which an ecological event took place, the age-depth relationship is important because it is useful in determining events throughout time, but it is not without its uncertainties (Parnell et al. 2008, 1872). There are large difficulties encountered when studying the age-depth relationship such as determining a depth associated with an ecological event and modelling the age associated with the depth (Parnell et al. 2008, 1872). Although many uncertainties exist in the age-depth modelling process, it is nonetheless useful in predicting and determining the relationship between the depth of a material and the radiocarbon age associated with it (Parnell et al. 2008, 1872). One will have to know the age of a sample — for example, a fossil pollen sample — to learn about the timing of change of an ecosystem in the past (Andria Dawson, comment to author, August 5, 2021).

Introduction

This paper assesses correlations between potential uncertainty-impacting factors and uncertainty or error itself. Potential factors which could impact uncertainty in radiocarbon dates include those such as depth, dating method, age, and accuracy rank (Andria Dawson, comment to author, August 5, 2021). We will use the programming language R to view datasets with variables such as the radiocarbon age of the dated material, the depth of the dated material, and so on. R is a coding language that we have used for statistical computations and analysis of radiocarbon date uncertainties. Also, we will use the accuracy rankings of radiocarbon-dated materials put forth by Blois et al. to utilize in our analysis of the data (2011, 1928). Using data from North American sites of the Neotoma Paleoecology Database, we intend to find potential factors which impact uncertainty in radiocarbon dates from different sites and different materials while keeping in mind that accounting for uncertainty allows our predictions to be reflective of our understanding (Dawson 2021b, 6).

A sediment core is defined as a core of rock, dirt, and other material taken from the ground which helps to show a geological record on the land (Andria Dawson, conversation with author, July 8, 2021). The data with which we are working comes from a specific type of sediment core: a fossil pollen sediment core; although there are many different types of datasets which use radiocarbon dating, fossil pollen is abundant, especially in the sediment of lakes

(Andria Dawson, comment to author, August 5, 2021).

In addition to analyzing the error of radiocarbon dates, we will also be observing whether the sizes of lakes from which sediment cores were taken represent a local or regional ecosystem. If the lake from which data was collected has a large surface area, there is also a large potential that materials — such as pollen, leaves, and many other biospheric materials — could land in the lake, eventually becoming part of the lake's sediment (Andria Dawson, conversation with author, July 23, 2021). The sediment cores of large lakes represent the vegetational change of regional ecosystems, allowing scientists to infer that changes in the sediment cores correlate to changes in a large area around the lakes (Andria Dawson, conversation with author, July 23, 2021). Oppositely, the sediment cores of small lakes tend to represent the changes in their respective ecosystems (Andria Dawson, conversation with author, July 23, 2021). Due to the small surface area of the lake, less materials are likely to become part of its sediment, meaning that it represents the local ecosystem which it is a part of (Andria Dawson, conversation with author, July 23, 2021).

Motivation

It is no question that uncertainty and error are factors which affect the accuracy of a scientific result such as a radiocarbon age. However, what are factors that influence uncertainty and error themselves? Many labs have studied the meaning of a radiocarbon date, and have included the error, but it is very rare to see a report which outlines sources of error in radiocarbon dates (Andria Dawson, conversation with author, July 8, 2021). To date a type of material effectively, one must use pre-treatment techniques including cleaning, inspection, and chemical pre-treatment to reduce the amount of potential contaminants present on or in the sample; therefore, the uncertainty of the age produced is reduced (Bronk Ramsey 2008, 256). This is one method of decreasing contamination in the lab, but if there were more studies being done on the sources of uncertainty in radiocarbon dates, new techniques may be developed to reduce the potential error in the dates, giving scientists a clearer image of when the material originated (Andria Dawson, conversation with author, July 8, 2021). This is a motivational reason for reporting on the factors that correlate with uncertainty.

Another motivation was the curiosity about whether the lake sites from which data was collected represented local or regional past ecosystems. As previously stated, lakes with a larger surface area represent more regional ecosystems, as a variety of materials could become part of their sediment (Andria Dawson, conversation with author, July 23, 2021) Whereas larger lakes represent regional ecosystems, smaller lakes represent local ecosystems because their small surface area only allows for specific materials — mainly those within the lake's ecosystem — to become a part of its sediment. The motivation for viewing lake sizes was to have the ability to infer whether the change in the environment that can be accounted for is local or regional; this will give a better understanding of changes in North American ecosystems throughout history.

Lastly, the two seemingly-unrelated subjects we are studying are, in fact, related; by finding the size of a lake and determining its source area — or the vegetation area which the lake represents — we are in effect able to observe the ecosystem which the lake represents (Andria Dawson, conversation with author, August 9, 2021). With this information as well as the radiocarbon dates and their uncertainties, we are able to infer when ecological changes took place and which areas were affected by said changes or events (Andria Dawson, conversation with author, August 9, 2021).

Methods and Data

The data being used for this paper has been curated from a variety of sites in North America, and there are multiple types of materials being dated. These materials came from sediment cores which were taken at each site. In addition, the data used is from the Neotoma Paleoecology Database. It is a public database with multiple sites from which sediment cores have been collected for the purposes of dating various types of materials (Andria Dawson, conversation with author, July 14, 2021).

The data within this dataset was collected into a dataframe, and read into R.

The data included columns such as the radiocarbon age of the material, the dating type, the material type, the depth of the material, and more. To find the error of each row of data, we took the difference between the older limit of the data — the oldest possible age of the given material — and the radiocarbon age produced when dated.

In addition, using the accuracy rankings from Blois et al., we inferred the accuracy rankings of materials which were missing accuracy values (2011, 1928). The finalized dataset was used to create plots in R, demonstrating the relationship between error and age, depth and age, and others which are demonstrated in figures below.

Certain rows of data were eliminated from the dataset due to being problematic or outliers. We removed all negative depths from the dataset because, if the depth were negative, the material would have, in effect, been found above ground; due to the fact that our intention was to view data from sediment cores underground, negative depths demonstrate an issue, as they were found above the zero mark, which was the ground itself (Andria Dawson, conversation with author, July 23, 2021). In addition, negative errors were removed due to the impossibility of the situation. Error is the difference between the older limit and the radiocarbon age; if the radiocarbon age was larger than the older limit, it would not make logical sense, and therefore these negative errors were ruled as mistakes in the data. Also, we removed rows with errors in the data; such errors included listing the age of the material as the depth instead. Lastly, we removed errors over 2 000 years. Once the error reaches this point, the uncertainty is simply too great to know the age of the sample (Andria Dawson, conversation with author, July 23, 2021). For example, if an uncertainty was 4 000, the age of the sample would be the radiocarbon age plus or minus 4 000, giving a range of 8 000 separate values, and therefore making the error too large to have any certainty about the true age of the material (Andria Dawson, conversation with author, July 23, 2021).

In the given dataset, there are many sites at lakes, but many of the lakes did not have given areas. To solve this problem, we worked in Google Earth Pro to find the missing areas of certain lakes. To do this, we put a placemark on the coordinates of the lake given, and then carefully traced the area around the perimeter of the lake using the polygon function; the output was a lake area in hectares.

In defining lake sizes — in other words, whether they are considered small, medium, or large — we used an example size from Sugita, who considered a very small lake to be 0.13ha in area (2007a, 248). In addition, a paper by Trondman et al. defined a small lake as one which was between the areas of 0.0025ha and 9ha inclusive (2015, 136). For the purposes of this investigation, we used this information to help us define a "small lake" as one which has an area less than 10 ha and a vegetation area within 700m of the lake itself (Andria Dawson, email to author, August 8, 2021). In addition, large lakes were defined in the literature differently; there is no rule for what is considered small or large, meaning that we must use expert opinions (Andria Dawson, conversation with author, August 9, 2021). We found "large lakes" defined as both being larger than 100ha in area and greater than 50ha in area (Sugita 2007b, 243; Trondman et al. 2015, 136). In this paper, a "large lake" is therefore defined as one which has an area greater than or equal to 50ha and represents vegetation within at least 100km of the lake itself (Andria Dawson, email to author, August 8, 2021). The values between the large and small lakes are defined as "medium lakes" which, in this paper, are defined as having a source area — the vegetation area represented by the lake — of about 10km and an actual area of between 10 and 50ha (Andria Dawson, email to author, August 8, 2021).

Results and Discussion

In Figure 1, one can view a map of North America with visible points which represent the locations at which sediment core samples were taken.

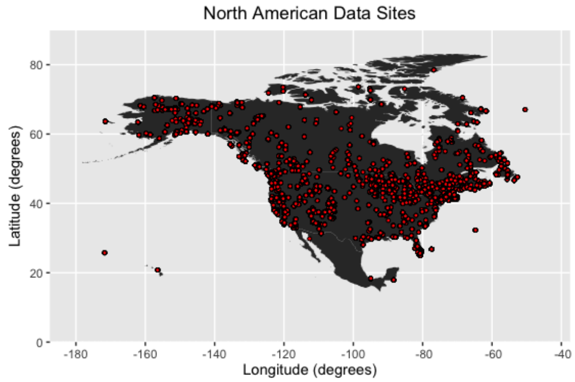

Figure 1: map of North America with points where sediment cores were taken

Through viewing the data in R, we had the ability to create plots demonstrating the trends in the data relating to error. As demonstrated in Figure 2.1, error is seen to increase with age no matter what the dating method is. The radiocarbon age is measured in years before present (YBP). However, the slope of the error-age curve does vary by type of dating method. As seen in Figure 2.1, each individual curve has its own unique slope which increases with age. In this figure, we have removed specific data for the reason that the dating methods were "unspecified." This means that the dating method used for each sample could have been one or a combination of the other methods listed (Andria Dawson, conversation with author, August 3, 2021). Therefore, the data for "unspecified" dating methods is not shown due to the assumed variability of true dating methods used.

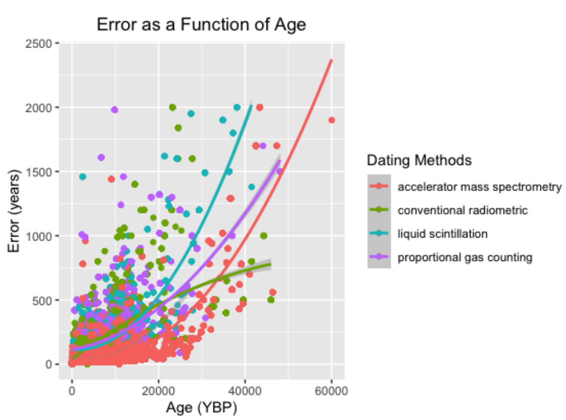

Figure 2.1: scatterplot of error as a function of age according to dating method

As seen in Figure 2.2, when viewing all of the data together — without specifying the dating method — there is a clear correlation between age and error. Although most of the data is concentrated in the bottom left-hand corner — where both error and age are small — there is still a recognizable pattern, one of an upward trajectory. As the curve veers upward, the uncertainty of the curve — as represented by the grey area around it — increases slightly as to demonstrate the increasing uncertainty when interpolating the data. Due to the fact that there are less data points as error and age increase, the graph will show less certainty in its trend.

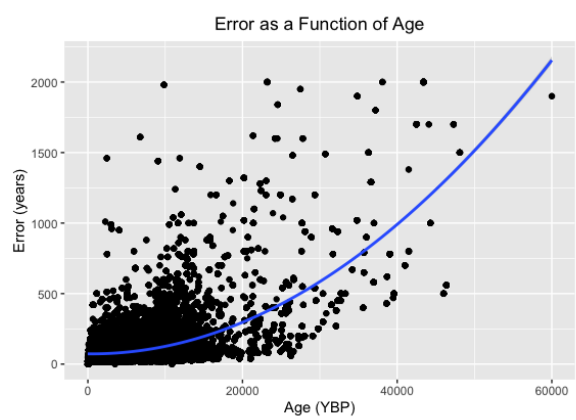

Figure 2.2: scatterplot of error as a function of age

Table 1 demonstrates the frequency of the dating method used. From this data, we can view — in a way the plot did not allow — which methods were used more prominently. By the data shown, it is clear that accelerator mass spectrometry (AMS) was utilized the most within this dataset. AMS was used in the dating process more than all of the other methods combined. This is likely due to the fact that AMS produces more precise ages than its conventional radiometric dating counterpart (Blois et al. 2011, 1927). As seen in Figure 2.1, the number of data points which have higher errors and use AMS is much less than the amount which have lower errors.

Table 1: Number of Samples per Radiocarbon Dating Method

AMS	Conventional Radiometric	Liquid Scintillatio n	Proportional Gas Counting	Unspecified
43 518	6 862	5 973	10 434	142

Figure 2.3 presents similar data to Figure 2.1, except, instead of presenting data by dating method, Figure 2.3 presents data by accuracy rank. Through this figure, we can assume that, although there is a difference in the slopes of the curves for each accuracy rank, there is not necessarily a direct correlation between error and accuracy (Andria Dawson, conversation with author, August 3, 2021). This is due to the fact that there are different amounts of data for each accuracy rank and the number of materials with each accuracy ranking from Blois et al. are different (2011, 1928), so there is a need to instead view the proportions of each of the plots. The accuracy rank 5 has the most data, so the number of outliers is substantial. The assertion that accuracy rank does not determine error is logical because, although a date may be accurate — meaning that there is little offset between the radiocarbon age and the true age (Blois et al. 2011, 1927) — that same date may still have a large error because of factors relating to precision or treatment methods used (Andria Dawson, conversation with author, August 3, 2021).

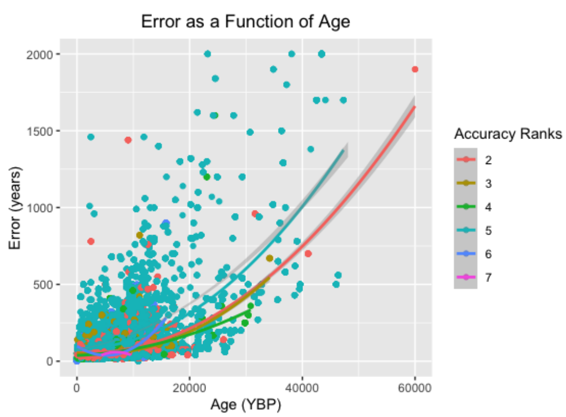

Figure 2.3: scatterplot of error as a function of age according to accuracy rank

Table 2 demonstrates the frequency of each accuracy rank within Figure 2.3. For this scale of rankings, 1 would be the best ranking, or the most accurate, and 8 would be the worst possible rank. Due to the fact that none of the materials dated received accuracy rankings of 1 or 8, the table shows results for accuracy rankings between 2 and 7 inclusive.

Table 2: Number of Samples per Accuracy Rank

2	3	4	5	6	7
9 753	4 735	4 310	41 601	2 280	78

Also, as demonstrated in Figure 3, the radiocarbon age increases when depth increases. The ages at larger depths, although more scarce, are larger than their smaller-depth counterparts. It is assumed that the deeper into the sediment core a material is, the older the material will be (Andria Dawson, conversation with author, August 3, 2021). Through this, we can also infer that error also increases with depth; both error and age, and depth and age, are directly related. Thus, error and depth are also directly related, meaning that error will increase with depth.

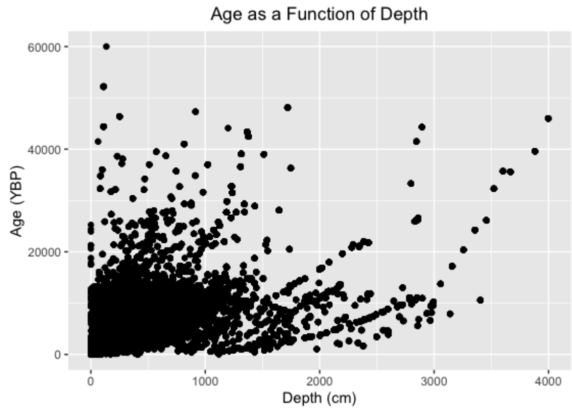

Figure 3: scatterplot of age as a function of depth

In viewing Table 3, we see the frequency of lake size categories used in this dataset. The table presented shows that a large sum of the lakes represent local ecosystems due to their small size. For the purposes of this paper, a small lake is considered one of an area less than 10ha, and a large lake is considered one of an area more than 50ha (Andria Dawson, email to author, August 8, 2021). Through this information, we can see that over a third of the lakes in the dataset are considered small, meaning that they represent a local ecosystem. The sizes of the lakes help to determine the radius and area around the lake from which we can track ecological change (Andria Dawson, conversation with author, August 9, 2021).

Table 3: Number of Lakes per Lake Size Category

Small	Medium	Large
382	207	226

Conclusion

Through the analysis of potential uncertainty-impacting factors of radiocarbon dates, we have viewed various plots which demonstrate the relationships between error and factors such as age and depth. In addition, the figures and results show that error and age, as well as error and depth, are directly related. As one variable increases, the other increases as well. Although there are differences in the slope of error-age graphs of different radiocarbon dating methods and different accuracy rankings, all still follow the same pattern of error increasing with age.

In addition, we have viewed that a large portion of the radiocarbon data collected comes from small lakes, and therefore represents local ecosystems. The results from this analysis show that there are many factors that impact the error associated with radiocarbon dates. There will likely always be some uncertainty when it comes to this process, as we will never truly know for certain when specific ecological events occurred. However, there is the possibility of decreasing error and uncertainty in radiocarbon dates with new research, new methods, and new ideas.

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