A calendar chronology for Pleistocene mammoth and horse extinction in North America based on Bayesian radiocarbon calibration

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Abstract

Recent debate about the timing of late Pleistocene extinctions in North America has taken place on the radiocarbon timescale. Since the current internationally-agreed radiocarbon calibration curve (known as IntCal04) extends back well into the Pleistocene, however, it is possible to make inferences on the calendar scale. To do so requires some fairly sophisticated, tailored statistical tools, to allow for a) the presence of considerable uncertainty on individual radiocarbon ages and on the IntCal04 estimate, and b) the inevitable incompleteness of our access to the fossil record. In this paper we demonstrate Bayesian radiocarbon calibration software, known as BCal, which: implements models with both of these features, is tried and tested within the archaeology research community, but has not previously been used by those engaged in extinction research. We conclude that the extinction of horse (*equus ferus/caballus*) in Alaska and the Yukon is broadly contemporary with the arrival of humans in the area and took place at around 14,200 cal BP. We find that the extinction of mammoth (*mammuthus primigenius*) in the same region occurred around 900 calendar years later (c. 13,300 cal BP). We also establish, with high probability, that the start of the Bölling warm phase occurred before these events and that the start of the Younger Dryas cold period occurred after.

1 Introduction

Study of megafaunal extinctions during the Pleistocene-Holocene transition (PHT) is currently benefiting from a tremendous renewal of interest because it offers a benchmark for testing our ability to quantify the impact of global warming on entire ecosystems (Barnosky *et al.*, 2004). For North America, changes in the megafauna during the PHT are quite complex because this period also corresponds to the first colonisation by humans who heavily relied on hunting the megafauna. Surprisingly, two recent papers provide conflicting reconstructions of the timing of the extinction of mammoths (*mammuthus primigenius*) and horses (*equus ferus/caballus*), relative to the arrival of first humans in the critical zone of the Alaska and Yukon Territory. One concluded that, unlike mammoth, the disappearance of horse preceded the arrival of man and was mainly linked to vegetation changes related to the climatic improvement which accompanied the last deglaciation (Guthrie, 2006). The other, by contrast, concluded that it cannot be ruled out that horses did, in fact, survive human arrival (Solow *et al.*, 2006).

Here, we take a fresh look at the updated radiocarbon data set relating to these extinctions (Guthrie, 2006), significantly improving the approach by considering three issues overlooked in previous work. The first novelty is our use of radiocarbon calibration, in particular the most recent calibration curve (Reimer *et al.*, 2004). The second is our consideration of the fact that the time period of interest is characterised by two abrupt climatic changes, namely the start of the Bölling warm phase (SBWP) and the start of the Younger Dryas cold phase (SYDCP). The third is our adoption of a suite of Bayesian statistical tools aimed at quantifying probabilities for the absolute and relative timings of the different faunal and climatic events.

Calibration is vital in radiocarbon dating because the amount of radioactive carbon in the Earth's atmosphere is naturally varying and is known to be non-monotonic or "wiggly" (Figure 1). Although during much of the Pleistocene, the 2004 internationally-agreed estimate of the radiocarbon calibration curve is monotonic (i.e. not "wiggly"), this should not be taken to indicate that the relationship between radiocarbon and calendar age really was monotonic during this period. The current estimate is just that, an estimate, and is almost certainly only monotonic because of the lack of resolution and the relatively large uncertainties in the data used to estimate it. We fully expect future estimates of the Pleistocene portion of the calibration curve to look more like the Holocene portion shown in Figure 1 and so all statistical procedures that we devise should work equally well whether our current estimate of the curve is monotonic or not.

One important feature of the need to calibrate is that, at the PHT, radiocarbon ages are approximately 2,000 years younger than calendar ages.As noted by other authors including Solow *et al.* (2006), Strauss and Sadler (1989), Marshall (1990) and Solow (1996), it is also vital to take into account an unavoidable characteristic of extinction research which is often forgotten; namely, that we are extremely unlikely ever to find fossil evidence of the last member of a species in existence. So, we need to calibrate our radiocarbon dates and, at the same time, acknowledge that extinction will have taken place more recently than any of the samples that we have dated. Bayesian models for doing both of these things together have been used for some time in archaeology (Buck *et al.*, 1996; Zeidler *et al.*, 1998; Blackwell and Buck, 2003). Here we use them for the first time in extinction research.

[Figure 1 about here.]

2 Methods

Like other authors who have taken a statistical approach to the use of radiocarbon data in extinction research (e.g. Strauss and Sadler, 1989, and Solow *et al.*, 2006), we start by acknowledging that, although it is extremely unlikely that we will ever find physical remains of the very first or very last animal of a particular species in a particular region, there was a moment at which a species arrived and another (later one) at which it became extinct. Unlike previous authors, since we are aiming to make inference on the **calendar** rather than the radiocarbon timescale, we represent the earliest **calendar** date of arrival of species n by α_n cal BP and the latest **calendar** date at which it was present by β_n cal BP. (Note here that other authors (in particular Solow *et al.* (2006) used similar notation, but worked on the radiocarbon timescale—the two should not be confused.) In a particular application, $n = 1, 2, \ldots, N$ where N represents the total number of species under investigation. For each species, α_n and β_n cannot be observed directly; the only evidence we have about them are radiocarbon dates for material deposited somewhere between them. [Note here that **cal BP** stands for calendar age before present (where, in radiocarbon dating, present is taken as 1950 A.D.) and that, because we are working on the cal BP timescale, α_n is always greater than β_n.]

In order to learn about α_n and β_n using the available radiocarbon ages, we need to make an *a priori* assumption about the rate of deposition of dateable material between α_n and β_n. The most commonly implemented deposition model within Bayesian radiocarbon calibration (Zeidler *et al.*, 1998) is based on the assumption that dateable material was deposited at a uniform rate between α_n and β_n. We adopt this uniform deposition model by using the freely available Bayesian radiocarbon calibration software known as BCal (Buck *et al.*, 1999): http://bcal.sheffield.ac.uk (similar models are also implemented in OxCal (Bronk Ramsey, 1995)). The validity of the assumption of uniform deposition is discussed below.

Since BCal and OxCal are so freely available, most readers will not need to implement Bayesian radiocarbon models for themselves. For readers who wish to experiment with their own implementations, however, details of the models and examples of the algorithms that can be used to estimate their parameters are given in several places (including Buck *et al.*, 1996: Chap. 9, Litton and Buck, 1996 and Zeidler *et al.*, 1998). Here, we apply the BCal implementation to the radiocarbon ages from Alaska and the Yukon that Guthrie made available in the Supplementary Material for his 2006 *Nature* paper (Guthrie, 2006). We focus here on results arising from the analysis of radiocarbon ages relating to two animal species, mammoth and horse, and to radiocarbon ages from material deposited as part of early human activity in this region. We are primarily interested in establishing the most likely **calendar** ages for: the extinction of mammoth and horse and the arrival of humans. Consequently, following the notation outlined earlier, we have $N = 3$ species (labelled 1=mammoth, 2=horse and 3=human) and are seeking to estimate and compare the calendar ages β_1, β_2 and α_3. Since much of the data Guthrie supplies relate to very old mammoth and horse material that does not provide any extra information about β_1 and β_2 over that provided by the more recent material, we work here only with the most recent fifty radiocarbon ages relating to these two species. Guthrie provides only forty-six radiocarbon ages for the early human use of this landscape and so we utilise all of these. These decisions about which data to use may seem somewhat arbitrary, but cutting out unhelpful data considerably speeds up computation of the estimates of the dates of events of greatest interest. In addition, experiments using both more and less of the mammoth and horse data established that (to the degree of accuracy reported here) all of the results were the same.

3 Results

Adopting the BCal Bayesian radiocarbon calibration software to implement the uniform deposition model outlined above, leads to estimates for the calendar dates of extinction of mammoth (β_1), the extinction of horse (β_2) and the arrival of humans (α_3) in Alaska and Yukon that are summarised in Figure 2. Rounding all results to the nearest five years, we find that the most likely dates for the extinction of mammoth and horse are 13,330 cal BP and 14,210 cal BP respectively (95% credible intervals 13,590 to 13,075 and 14,670 to 13,070 cal BP respectively). While the most likely date for the arrival of humans is 14,225 cal BP (95% credible interval 14,555 to 14,045 cal BP). Also, in Figure 2, we provide summaries of the most recent estimates of the dates of the SBWP and the SYDCP (Rasmussen *et al.*, 2006). For these latter plots, we assume that the uncertainty on the layer counted estimates of the dates of the climatic events have Gaussian distributions and that the errors reported by the original authors represent two standard deviations about the mean. In other words, the dates of the SBWP and SYDCP are assumed Normally distributed with mean 14642 cal BP and standard deviation 93 and mean 12846 cal BP and standard deviation 69 respectively.

[Figure 2 about here.]

Since the Bayesian approach is a probabilistic one, and we have assumed that the dates of interest are independent of one another, we can use the same results that we used to provide the (posterior) distributions in Figure 2 to establish the following. The probability that: the SBWP occurred before horse extinction is 0.97; the SBWP occurred before mammoth extinction is 1.00; the SYDCP followed the extinctions of both mammoth and horse is 1.00; horse became extinct before mammoth is 0.99; humans arrived before mammoth extinction is 1.00; and humans arrived before horse extinction is 0.59. This latter, probability suggests that these two events could have been contemporary i.e. that early humans in America could have contributed to the demise of the horse population. This is crucial for those wishing to make comparisons between our findings and outputs from models which simulate the response of ecosystems (Barnosky *et al.*, 2004). As a result, we also use our results to make probabilistic statements about the length of time elapsed between the main ecological and climatic events.

Figure 3 provides a numerical summary of the likely length of time elapsed between a selection of the events discussed above. The most debated one (Guthrie, 2006; Solow *et al.*, 2006) is the time elapsed between the arrival of humans and the extinction of horse. The most likely (modal) estimate of which falls in the interval 0 to 100 years. Some simple calculations confirm that the most likely 10 year period for the time elapsed is centred at 55 years. Looking in a little more detail, we find that the length of time elapsed between the arrival of humans and the extinction of horse is in the range -20 to +20 with probability 0.06, is in the range -200 to +200 years with probability 0.5 and is in the range -500 to +500 years with probability 0.9.

[Figure 3 about here.]

Since there are two crucial components to the statistical approach we have taken, it maybe helpful to readers to indicate the impact that each has had on the conclusions obtained. The two major features of our method are: the use of the α,β model (which acknowledges that, it is extremely unlikely that we will ever find physical remains of the very first or very last animal of a particular species in a particular region) and our adoption of radiocarbon calibration. In Table 1, we show the results of a set of experiments to investigate the impact of these features on our conclusion about relative timing of the arrival of humans and the extinction of horse. These results make it clear that, whether or not we calibrate, unless we adopt the α,β model we are not likely to reach clear conclusions about the relative order of the two events given currently available data. They also show, very clearly, the spurious improvement in precision that we can appear to obtain if we adopt the α,β model, but do not calibrate the radiocarbon determinations. It must always be borne in mind that, contained within the error envelope of the current estimate of the radiocarbon calibration curve (IntCal04), there are lots of plausible reconstructions; many of which exhibit inversions and flat portions of the sort known to exist in the Holocene (see Figure 1). For this reason, we must be very wary about making any chronological inferences (relative or absolute) without calibration, despite the fact that we may appear to get more conclusive results if we do.

[Table 1 about here].

4 Summary and suggestion for future work

From currently available radiocarbon evidence, interpreted within the Bayesian radiocarbon calibration framework, we find that in Alaska and the Yukon mammoth was extinct before horse with probability 0.99 and that humans arrived before mammoth was extinct with probability 1.00. The distributions for our current estimates of the calendar dates of these events are shown in Figure 2. We cannot unequivocally resolve the order of the arrival of humans and the extinction of horses. On the basis of current evidence, however, it is likely that the two events were either contemporary or that humans arrived shortly before horses became extinct.

Here, we have demonstrated the power of the Bayesian radiocarbon calibration framework (already well established in the archaeology community) to provide probabilistic answers to questions relating to chronology, contemporaneity and the sequence of events in extinction research. This is the first time that anyone has tried to apply Bayesian radiocarbon calibration methods to problems of this type, however, and none of the tools that we have used were developed specially for this purpose. As a result, there are at least three important areas that require more work.

The first is to continue to seek more radiocarbon determinations from late horse and early human occupation deposits in an attempt to reduce the uncertainty in the related calendar age estimates and hence get closer to an unequivocal statement about the order of these events. The second is for the radiocarbon community to continue to seek high quality calibration data for the late Pleistocene so that we can decrease the standard deviation on our estimate of the calibration curve. The standard deviation on IntCal04 is of the same order of magnitude as the standard errors on the best quality single radiocarbon determinations of about the same age (i.e. c. 100 years) and we ought to be able to improve quite considerably on this in the coming years.

The third area that is worthy of further work is to consider tailoring the (*a priori*) statistical models used to represent deposition of dateable material. In this paper we have assumed uniform (*a priori*) rates of deposition of material from each species. For mammoth and horse this seems broadly sensible, but for human activity it may be less so. Since we are interested here in colonisation of a new landscape by fairly mobile people, it seems likely that there may have been an initial 'pioneer' phase in which the resources and landscape were reconnoitred prior to more settled habitation. If this is the case, a slightly more sophisticated (*a prior*) model of deposition may be needed (Blackwell and Buck, 2003). One model, which has been suggested as a potential way to represent human colonisation (Housley *et al.*, 1997), was recently evaluated as part of a PhD project and almost certainly deserves further consideration (Karlsberg, 2006). Intuitively, this model can be thought of as a trapezium-shaped distribution in which we see a gradual increase in deposition during the 'pioneer' phase followed by a period of constant deposition and then a gradual decrease in deposition rate to zero as the species declines. Such models tend to lead to earlier estimates of initial colonisation and so, if we have reason to think that they might be appropriate, they should certainly be explored further.

5 Acknowledgements

We are grateful to two anonymous referees and to the QSR editor, Edward Brook, for their constructive comments which have led to substantial improvements in this paper. Caitlin Buck is also grateful to the UK Department of Work and Pensions for their support via the Access to Work Scheme.

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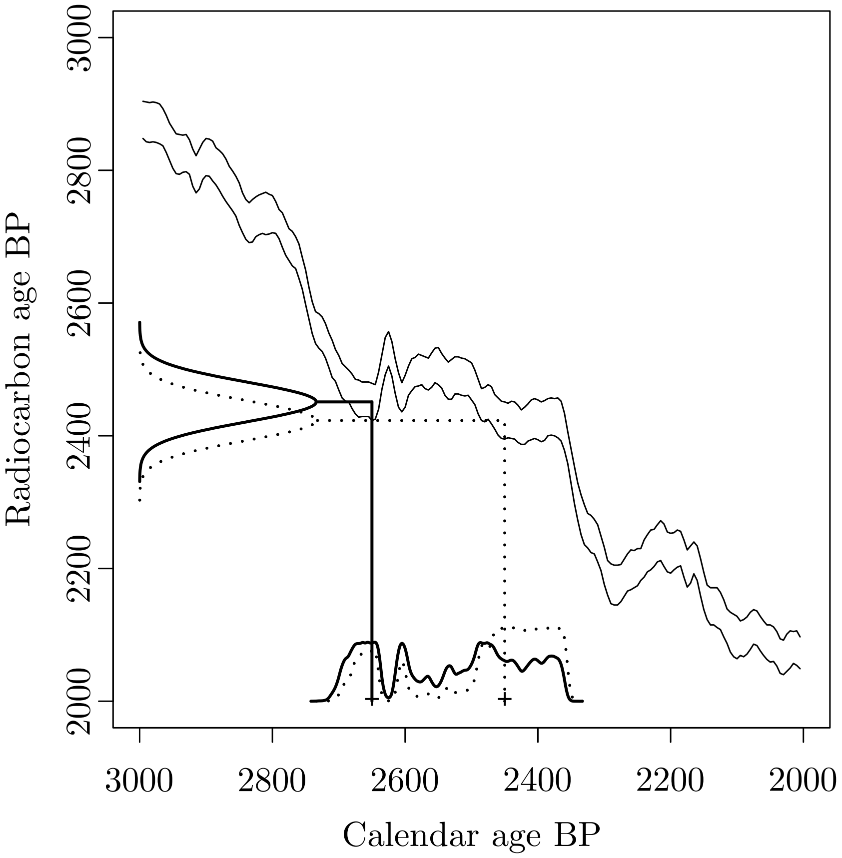
Figure captions

Figure 1: Two standard deviation envelope around the IntCal04 (Reimer *et al.*, 2004) estimate of a Holocene portion of the radiocarbon calibration curve (Reimer *et al.*, 2004) and an illustration of the fact that events with quite different calendar ages can appear contemporary on the basis of radiocarbon dating. Two crosses near the x-axis indicate the calendar ages of events that took place 200 years apart. Suppose that we obtain short-lived samples that ceased metabolising contemporaneously with these events and send them for radiocarbon dating. Given the fluctuations in the levels of radioactive carbon during this period, the radiocarbon laboratory returns age estimates very similar to one another (indeed indistinguishable given laboratory uncertainties). We illustrate this by plotting two likely radiocarbon age distributions against the y-axis. Calibrating, we obtain the multimodal probability distributions shown against the x-axis. Thus, two events that were not contemporary can appear to be contemporary on the basis of radiocarbon dating evidence simply because of the nature of the radiocarbon fluctuations in the atmosphere at the time and the analytical uncertainties associated with radiocarbon dating.

Figure 2: Estimates of the calendar date (before 1950 AD), in Alaska and Yukon, of the five events discussed in the text.

Figure 3: Estimates of the length of time elapsed between a) the arrival of humans and the extinction of horse, b) the arrival of man and the extinction of mammoth, c) the extinction of horse and the SYDCP, d) the SBWP and the extinction of mammoth, and e) SBWP and the extinction of horse in Alaska and Yukon.

Table 1: The posterior probability that the arrival of humans predates the extinction of horse in Alaska and Yukon Territory when the two main components of our statistical method are considered separately.



Radiocarbon age BP
3000
2800
2600
2400
2200
2000
3000
2800
2600
2400
2200
2000
Calendar age BP

Figure 1:

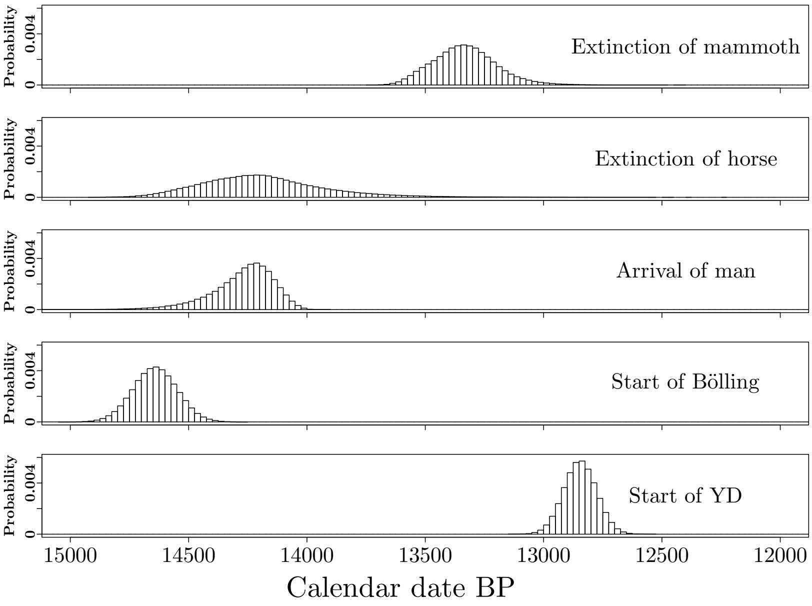

Probability
0.004
0
Extinction of mammoth
Extinction of horse
Arrival of man
Start of Bölling
Start of YD
15000
14500
14000
13500
13000
12500
12000
Calendar date BP

Figure 2:

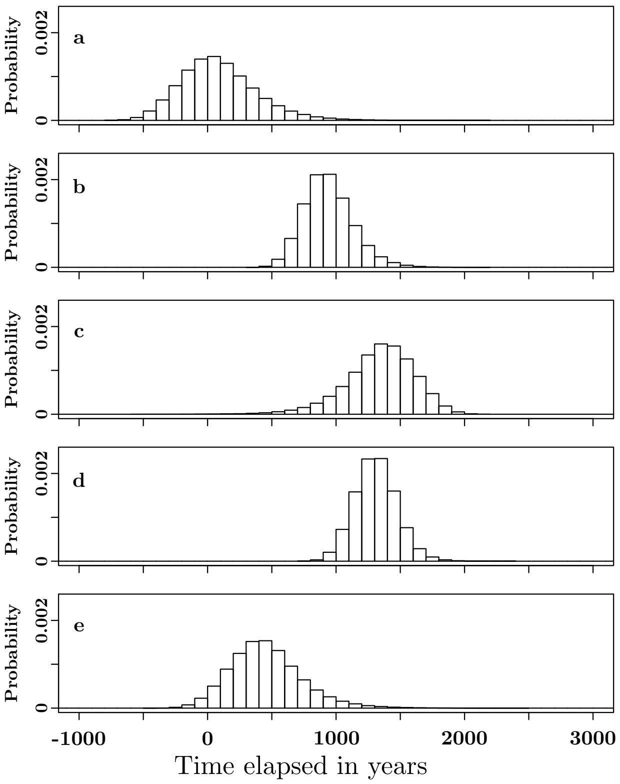

Probability
0.002
0
a
b
c
d
e
-1000
0
1000
2000
3000
Time elapsed in years

Figure 3:

Using α,β model?	Using calibration?	Posterior probability
Yes	Yes	0.59
Yes	No	0.81
No	Yes	0.43
No	No	0.48

Table 1: