Calibration of Radiocarbon Ages and the Interpretation of Paleoenvironmental Records

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Calibration of the radiocarbon timescale of paleoecological records is essential if they are to be explained correctly in terms of their governing ecological or climatological controls. The differences between calendar ages and radiocarbon ages that arise from variations in $^{14}$C production through time can distort the chronologies of individual records and the interpretations based on them. Misleading impressions of synchrony or diachrony of events among multiple records can result, and estimates of the apparent duration of episodes and rates of sedimentation and local population changes can be biased. Displays of the temporal patterns of migration or extinction may also be affected. Spurious correlations may arise between records with radiocarbon-controlled chronologies and time series of potential controls that are expressed on a calendar time scale. Support for particular explanations of features in a paleoecological record may vary depending on whether radiocarbon ages are calibrated or not. This situation is illustrated using the eastern Beringian Populus subzone as an example. When the radiocarbon ages that control the timing of the Populus subzone are calibrated, the contemporaneous decrease in ice volume and increase in summer insolation are implicated as the ultimate controls of the occurrence of the subzone. ©1995 University of Washington.

INTRODUCTION

The analysis and interpretation of paleoenvironmental records require accurate chronologies in order to determine rates of change and to understand the cause of temporal variations in the records. Radiocarbon chronologies are conventionally used for records that span the past 30,000 yr, but recent comparisons of radiocarbon ages with those determined by the U-Th method and by dendrochronology indicate that radiocarbon time deviates considerably from calendar time (Bard et al., 1990; Bard et al., 1993; Stuiver et al., 1986). Published calibration procedures (Stuiver and Reimer, 1993) now make it easy to calibrate radiocarbon ages over the past 18,400 $^{14}$C yr (i.e., to convert them to the equivalent calendar ages). Despite the longstanding availability of such procedures (e.g., Stuiver and Suess, 1966; Wendland and Donely, 1971; Klein et al., 1982; Stuiver and Reimer, 1986), calibration of radiocarbon ages has not been common practice. Although it might be argued that calibration is not essential if one is merely examining a selection of records with chronologies that are controlled by radiocarbon ages alone, this argument does not hold when comparisons are made among records with radiocarbon chronologies and those with chronologies determined by other means (e.g., varve-counting or dendrochronological methods), or when radiocarbon-controlled records are compared with time series with implicit calendar-age chronologies, such as insolation. Calendar-age/radiocarbon-age differentials may also have significant effects on the calculation of rates of change within a single record, the detection of time-transgressive features (such as migrations) or synchronous events (such as extinctions), and the resolution of the apparent synchrony or diachrony of an event seen in several records.

In this paper we use a feature of the paleoecological record of eastern Beringia—the Populus subzone—to illustrate the range of issues that must be considered in interpreting radiocarbon-dated paleoenvironmental data. In particular, the relative merits of several climatic and paleoecologic hypotheses that have been advanced to explain the Populus subzone turn out to be highly dependent on the time scale used. Before discussing this example, we illustrate some of the potential effects of the calendar-age/radiocarbon-age differential (which we refer to as the “age differential”) on the interpretation of individual records.

THE CONSEQUENCES OF THE AGE DIFFERENTIAL ILLUSTRATED

The relationship between radiocarbon years and calendar years has two prominent features. A first-order feature is the
general tendency for radiocarbon ages to be younger than calendar ages over most of the past 20,000 yr. This departure is related to secular variations in geomagnetic intensity that govern the production rate of $^{14}C$ (Stuiver et al., 1991). A second-order feature is the occurrence of steps and plateaus in the relationship caused by shorter term variations in the production of $^{14}C$ (thought to be related to solar variability and to variability in the ventilation rates of the ocean; Stuiver et al., 1991; Stuiver and Braziunas, 1993). These features also lead to indeterminacy of $^{14}C$ ages and, in turn, to the existence of multiple calibrated ages for $^{14}C$ ages over certain time periods (Stuiver et al., 1986).

Figure 1 shows the effect of the two features discussed above. The figure was constructed by generating “calendar” ages at 250-yr intervals between 0 and 23,000 yr B.P. Corresponding radiocarbon ages were then generated by linear interpolation within the table of equivalent radiocarbon and calendar ages contained in the file intcal93.14c that accompanies the CALIB program (Rev 3.0.3) of Stuiver and Reimer (1993). Line segments join corresponding ages. Radiocarbon years deviate increasingly from calibrated years as one goes back in time, so that by 20,000 cal yr B.P., radiocarbon ages are about 3000 yr too young. In the interval 0–11,390 cal yr B.P., (that part of the calibration controlled by the dendrochronological record), the influence of the short-term variations can also be seen as the convergence (or divergence) of adjacent lines. For example, the radiocarbon age range of 10,000–10,500 $^{14}C$ yr B.P. is equivalent to the longer interval of 11,250–12,250 cal yr B.P.

Some of the consequences of the features seen in Figure 1 can be demonstrated by simple simulations (Fig. 2). In these simulations, we neglect the further uncertainties in radiocarbon ages that may arise in both the field and laboratory in order to concentrate on the age-differential effects. For these simulations, random distributions of “calendar” ages were generated at selected times and converted to radiocarbon ages. The times and distributions of the simulated ages were selected to provide examples of the kinds of artifacts that can be induced by the age differential.

In each example in Figure 2, the range of “calendar” ages is older than the corresponding range of radiocarbon ages, illustrating the first-order effect. Superimposed on this pattern are several interesting features related to the shorter-term variations in $^{14}C$ production. Figure 2A (top) shows the histogram of 1000 random calendar ages generated from a uniform distribution between 9000 and 13,000 cal yr B.P. Such a distribution might arise from a set of ages from different sites for a diachronous or time-transgressive paleoecological change, such as the northward migration of tree taxa in eastern North America (Webb, 1988). The histogram of the corresponding radiocarbon ages is shown in Figure 2A (bottom). The 4000-yr-long calendar-age range is shifted and compressed to 11,000–8000 $^{14}C$ yr B.P., reflecting the first-order effect. The radiocarbon age distribution also has several distinct peaks, a consequence of the second-order effect (related to short-term plateaus in $^{14}C$ production); the most prominent of these is centered around 10,000 $^{14}C$ yr B.P. This pattern of “false peaks” demonstrates that a distinct cluster of radiocarbon ages, which might be interpreted as evidence for a synchronous event, could instead be an artifact and actually be consistent with an episode of diachronous change.

Figure 2B (top) shows the histogram of 1000 calendar ages generated using a normal distribution with a mean of 11,000 and a standard deviation of 500 yr. A distribution like this might arise in a collection of ages that apply to an event, where the variability in ages is attributed to local variations in the expression of the event. The distribution of the associated radiocarbon ages (Fig. 2B, bottom) has two notable features. First, the broad single peak in the calendar ages is split into two sharper peaks in the radiocarbon ages. Second, the overall variability of the associated radiocarbon ages is less than that of the calendar ages (the standard deviation falls to 325 yr). This example demonstrates that (i) multiple clusters of radiocarbon ages could be consistent with a single event, and (ii) an assemblage of radiocarbon ages may underestimate the uncertainty in the timing of the event. Both of these examples illustrate the tendency for some radiocarbon ages (e.g., 10,000 to 10,500 $^{14}C$ yr B.P.) to occur preferentially, which in turn may lead to overemphasis of those parts of the record.

At other times, short-term overproduction of $^{14}C$ leads to an expansion of radiocarbon time relative to calendar time. In such cases, a collection of radiocarbon ages may give an inflated estimate of the uncertainty of the timing of an event. For example, Figure 2C (top) shows the histogram of 1000 calendar ages generated using a normal distribution with a mean of 7500 and a standard deviation of 250 yr. The variability of the associated radiocarbon ages (Fig. 2C, bottom) is greater, in contrast to the previous examples, with a standard deviation of 2500 yr.

**FIG. 1.** Relationship between equivalent calendar (or calibrated) and radiocarbon years before present. The figure was constructed using the data contained in the file intcal93.14c that accompanies the CALIB program (Rev 3.0.3) of Stuiver and Reimer (1993).
300 yr. This example illustrates that at certain times, an assemblage of radiocarbon ages may suggest that a diachronous event covers a broader expanse of time than is actually the case; in some cases a heterogeneous set of ages could be consistent with a synchronous event.

These examples imply that some of the chronological features of paleoenvironmental records that are used to interpret those records may be artifacts of the age differential. Such features include observations of contemporaneous changes in multiple records, systematic (e.g., time-transgressive) changes among several records, clusters of radiocarbon ages and episodes of faster or slower change within a single record, and coincidences between times of change in a record and events or extrema in its potential controls.

THE POPULUS SUBZONE IN EASTERN BERINGIA

To illustrate how the interpretation of paleoecological records may depend on the choice of whether to calibrate or not, we use an example from eastern Beringia (essentially the present northern Alaska and northwest Canada). Eastern Beringia was largely ice-free at lower elevations during the last glacial maximum and glacial-interglacial transition and is thus well situated to record changes in climate (as opposed to effects of local deglaciation) over the past 20,000 yr. The range of potential large-scale controls of the regional paleoclimate of eastern Beringia has been discussed by Bartlein et al. (1991) and Barnosky et al. (1987). These controls include, in particular, the size of the Laurentide Ice Sheet (and its attendant effects on atmospheric circulation and hemispheric-wide temperature) and seasonal variations of insolation.

The Populus subzone is a widespread, though not ubiquitous, feature in pollen records from eastern Beringia (northern Alaska and northwest Canada). At sites within and beyond the current continuous range of the genus, pollen records show an interval of relatively high percentages of Populus between ca. 11,000 and ca. 8000 14C yr B.P. The subzone is the first widespread feature in the postglacial record that indicates substantial tree cover on parts of the landscape and is a significant event in postglacial vegetation development (Anderson et al., 1988; Anderson and Brubaker, 1994).

Anderson and Brubaker (1994) suggest that Populus was present if any pollen at all occurs in the record, as it is a low pollen producer and its pollen is poorly dispersed (Anderson and Brubaker, 1986; Edwards and Dunwiddie, 1985). Using this interpretation, there were scattered and sporadic occurrences of Populus prior to 11,000 14C yr B.P. Low, discontinuous levels of Populus pollen throughout the Holocene and the current widespread, though patchy, occurrence of both species (P. balsamifera, P. tremuloides) on the modern landscape argue for a continuous presence in eastern Beringia from the late Wisconsin onward. However, only during the Populus subzone do relatively high values occur regularly, suggesting a particularly high abundance of Populus at that time.

The timing of the Populus subzone in 14C yr is shown in Figure 3A. We used eastern Beringian sites from the published literature that have radiocarbon dates bracketing, or nearly so, an interval of elevated (>2%) Populus pollen frequencies represented by several levels in the pollen diagram. The subzone covers approximately 3000 yr, but at most individual sites it is of shorter duration, there being some apparent asynchrony in timing between sites.

At least three explanations of the Populus subzone have been advanced. One is based on the observation that Populus
FIG. 3. Timing and potential controls of the Populus subzone in eastern Beringia. (A) Timing of the Populus subzone on a radiocarbon time scale. The bars indicate the duration of elevated values of Populus, the vertical tick marks indicate the controlling radiocarbon ages, and the horizontal tick marks extend to one standard deviation either side of the age. For those sites where the beginning or end of the Populus subzone is not directly controlled by a radiocarbon age, the time of the beginning or end was determined by linear interpolation between radiocarbon ages; uncertainties in the radiocarbon ages were ignored in this procedure. Tick marks that are labeled by ages fall outside the range of the horizontal axis. (B) Timing of the Populus subzone on a calibrated or calendar time scale. The multiple vertical tick marks are the calibrated radiocarbon ages and reflect the indeterminacy of the calibrated ages (i.e., at some times, more than one calibrated age is equivalent to a particular radiocarbon age). The horizontal tick marks extend to the minimum and maximum of the calibrated age ranges as reported by the CALIB program (Rev 3.0.3) of Stuiver and Reimer (1993). For those subzones not directly controlled by a radiocarbon age, and where the calibration yielded multiple potential ages, the time of the beginning or end of the subzone was determined by linear interpolation using the calibrated age with the highest associated probability value (see Stuiver and Reimer, 1993, CALIB Method B). (C) Time series of the July insolation anomaly (difference from present) at 65°N (dashed curve, Berger, 1978), and relative sea level (solid curve, Fairbanks, 1989). The relative sea-level curve is used here as a general index of the progress of the glacial/interglacial transition. Data sources: KP, Kettlehole Pond (Cwynar, 1988); ML, M Lake (Ritchie 1977); HR, Harding Lake (Ager, 1983); JL, Joe Lake (Anderson, 1988); NL, Niiq Lake (Anderson, 1988); ST, Sands of Time (Edwards and Barker, 1994); RL, Ruppert Lake (Brubaker et al., 1983); WL, Wien Lake (Hu et al., 1993); SY, Screaming Yellowlegs Pond (Edwards et al., 1985); TT, Twin Tamarack Lake (Ritchie, 1985); SL, Sihlyemenkat Lake (Anderson et al., 1990); HI, Hidden Lake (Ager, 1983); TH, Two Horseman Pond (Keenan and Cwynar, 1992); TL, Tinkdhu Lake (Anderson et al., 1988); MP, Monkshood Pond (Cwynar and Spear, 1991); and PP, Ped Pond (Edwards and Brubaker, 1986).
often acts as a pioneer taxon, capable of colonizing areas that have been recently disturbed. Its widespread appearance in North America (Lamb and Edwards, 1988; Webb, 1988) and in western Europe (Huntley, 1988) is therefore regarded as a step in the transition from Pleistocene to Holocene plant communities (Mott, 1978; Brubaker et al., 1983). As such, the *Populus* subzone does not require a specific local climatic explanation *per se*, apart from the general climatic change accompanying the glacial-to-interglacial transition. Although some regional synchrony in the occurrence of the peak is implied by this explanation, no specific climatic threshold for the spread of *Populus* is postulated.

A second explanation comes from Ritchie et al. (1983) who suggested that some vegetational changes that mark the early-Holocene transition from tundra to woodland in northwestern Canada (including the *Populus* subzone) were a direct response to the maximum in summer insolation about 10,000 cal yr B.P. (the “Milankovitch thermal maximum”). Chronologies established for individual records using uncalibrated radiocarbon ages place the *Populus* subzone squarely on the insolation peak (Fig. 3). Ritchie et al. (1983) suggested that the maximum in net radiation due to the greater-than-present insolation resulted in a major increase in temperature, which in turn was reflected by the vegetation. Synchrony in the occurrence of the *Populus* subzone among sites is implied by this explanation, as is the existence of a threshold of insolation (or net radiation) close to the maximum, which when exceeded resulted in sufficient warmth to support a characteristic vegetation assemblage. The focus on net radiation, a direct response to insolation, implies a regional climatic control.

A third explanation for the *Populus* subzone incorporates elements of both climate and landscape-scale controls. The absence of *Populus* at some sites, and the among-site variability in the timing of the *Populus* subzone led Anderson et al. (1988) to suggest that the expansion of *Populus* did not occur in response to a climatic change alone. Given the lack of a recognizable geographic pattern in the dates and the probability that *Populus* survived the full-glacial interval within refugia in eastern Beringia, they also concluded that the *Populus* subzone is unlikely to reflect the long-distance migration of *Populus* into the region following a climatic change. Rather, at individual sites the response of *Populus* to some regional environmental change was modified by local conditions, such as substrate, drainage, and existing vegetation. Additional variability in the apparent timing of the response could be due to the usual uncertainties in radiocarbon dates. Although ultimately invoking control by climate, this explanation, like the first, points to local factors that mediate the response of *Populus* to the larger-scale changes. The three explanations contain two common elements: (i) climate change, either the general glacial-to-interglacial change, or the specific climatic anomaly associated with the insolation peak, and (ii) local factors that introduce variability (asynchrony) in the timing of the occurrence of the subzone.

When the radiocarbon ages that control the apparent timing of the *Populus* subzone are calibrated using the program of Stuiver and Reimer (1993), aspects of the chronology of the *Populus* subzone change. The subzone is shifted back ca. 2000 yr, at any one site its duration is longer, and the asynchrony among sites of the beginning and end of the subzone is also slightly increased. These changes in the timing of the subzone alter the relative merits of the different elements of the above explanations. The shift backward in time eliminates the summer insolation maximum as a potential climatic control of the *Populus* subzone. The beginning of the subzone now occurs during the rise in insolation and follows the first step in hemispheric deglaciation about 14,000 cal yr B.P. (Mix and Rudimnan, 1985). Insolation likely had both an indirect effect on climate in eastern Beringia, through its control of regional atmospheric circulation patterns, and a direct effect, through its control of net radiation. Bartlein et al. (1991) proposed that the Laurentide Ice Sheet, when large, depresses temperatures in eastern Beringia from 2 to 4°C as part of its general effect on the temperatures of the Northern Hemisphere. The reduction of this ice-sheet influence at a time of increasing insolation, as during the interval from 14,000 to 12,000 cal yr B.P., might therefore have significantly increased summer temperatures in eastern Beringia. The beginning of the *Populus* subzone during this interval would be consistent with such a climatic change. The end of the *Populus* subzone at many sites occurs roughly at the time of the second step in hemispheric deglaciation (about 11,000 cal yr B.P.), when insolation was near its maximum. This vegetation change, and the subsequent onse resulting in the establishment of spruce (*Picea*) forest in eastern Beringia, are consistent with the further warming and increase in moisture that likely accompanied these changes in external controls (Edwards and Barker, 1994; Anderson and Brubaker, 1994).

Is the variability in the timing of the subzone due to dating errors, the radiocarbon/calendar age differential, or to truly diachronous, individualistic, site-based responses (i.e., ecological effects)? Comparisons between AMS dates of macrofossils and conventional bulk dates in Alaska show that considerable variability can occur among radiocarbon ages from the same stratigraphic level (Anderson et al., 1994), and it is possible that at least the outliers in the dataset may reflect dating errors. We have shown that a normal distribution of calendar ages for a single event becomes considerably altered in radiocarbon time (Fig. 2B). The simulations shown in Figure 2 suggest that for the period 11,000–9000 14C yr B.P. calibration would tend to increase the range of the dates, thus adding to the asynchrony rather than reducing it. This suggests that there is diachrony in the expression of the *Populus* subzone, lending support to the proposal that ecological effects were modifying any regional response, as proposed by Anderson et al. (1988).

Consequently, we propose that the *Populus* subzone reflects a regional-scale increase in temperature, related ultimately to increasing summer insolation and decreasing size of the Laurentide Ice Sheet, with variability in the presence or absence of the subzone at any particular site, and timing where it occurs,
introduced by landscape-scale controls. Calibration of the radiocarbon ages thus points to a different climatic mechanism than was suggested previously (i.e., to the rise in summer insolation as opposed to the occurrence of the maximum) and leaves open the role of local factors in contributing to variability in the expression of the *Populus* subzone.

Edwards and Barker (1994) examined the impact of calibration on the timing and interpretation of other features of the paleoecological records of eastern Beringia. As is the case for the *Populus* subzone, calibration indicates that the individual steps in the reorganization of the vegetation over the past 25,000 yr each occurred earlier than previously thought. As a result, the conventional interpretations in climatic terms of many of these changes must be reconsidered.

**OTHER IMPLICATIONS OF THE RADIOCARBON/CALENDAR AGE DIFFERENTIAL FOR PALEOECOLOGY**

Not all the features of the age differential that affect the interpretation of paleoecological records are illustrated by the *Populus* example. Radiocarbon-controlled estimates of pollen accumulation rates (PARs) will appear inflated over several critical periods during which radiocarbon time is “compressed.” Estimates of sedimentation rates, and hence PARs, during the Holocene will therefore be generally lower on a calibrated timescale (Webb and Webb, 1988). It is possible that in some pollen records, sharp increases in PARs at about 10,000 $^{14}$C yr B.P. are artifacts of overestimated sedimentation rates associated with the radiocarbon plateau (Fig. 1; the opposite would be true for the period 8000–7000 cal yr B.P.; Fig. 2C). Estimates of population doubling time based on PAR curves (e.g., Bennett, 1986; Tsukada, 1982; MacDonald and Cwynar, 1991) for intervals on the radiocarbon timescale at ca. 10,500–10,000, 8250–8000, and 4500 $^{14}$C yr B.P. could be misleading for the same reason.

Estimated rates of migration will also be affected by calibration. For example, if the dates used to plot the migration of *Picea glauca* in northern North America (Ritchie and MacDonald, 1986) are calibrated, estimates of the rate of migration of spruce decrease from 2 km/yr to 1 km/yr.

Histograms of collections of radiocarbon ages that refer to extinctions (e.g., Melzer and Mead, 1983) will be altered by calibration as well. For example, the peak of extinction ages in North America between 11,000 and 11,500 $^{14}$C yr B.P. will be shifted backward in time, but may also change in shape, potentially influencing observations about the relative abruptness or progressiveness of the extinction. Similarly, the possibility exists that features in the histograms of large assemblages of radiocarbon ages that are interpreted as discontinuities between distinct climatic episodes (Wendland and Bryson, 1974) could be artifacts of the shorter term variations in $^{14}$C production.

Finally, rates of change estimated from time series might produce inaccurate values if radiocarbon dates are not calibrated. Jacobsen et al. (1987) and Overpeck et al. (1991) calculated rates of change in pollen records for networks of sites in eastern North America. Figure 1 shows how a continuous distribution of calendar dates can become compressed in radiocarbon time in relation to the various $^{14}$C production plateaus. This implies that, using uncalibrated records, spuriously high rates of change would be estimated at certain times (e.g., the interval 10,500–10,000 $^{14}$C yr B.P.). Conversely, spuriously low rates of change would be estimated for times when the $^{14}$C timescale is stretched, such as 6000–5500 $^{14}$C yr B.P.

The extent of agreement or lack thereof between paleoclimatic simulations and syntheses of observations may also be influenced by the age differential (Kutzbach et al., 1993; Tushingham and Peltier, 1993). This situation arises when boundary conditions of simulations (e.g., insolation) are determined on a calendric time scale, while the data syntheses are organized using uncalibrated radiocarbon chronologies. The implications of such a mismatch will be quite severe at the last glacial maximum (ca. 18,000 $^{14}$C yr B.P. or 21,000 cal yr B.P.), a frequent target for paleoclimatic simulation.

**CONCLUSION**

The radiocarbon/calendar age differential has widespread implications for interpretations of late-Quaternary paleoecological and paleoclimatic data, inasmuch as it may influence or even change those interpretations. Calibration programs are now readily available, and it should become a routine procedure to calibrate radiocarbon ages and to make interpretations based on the calibrated timescale. To enhance the utility and interpretability of published information, we recommend the following:

- When reporting ages, the distinction among radiocarbon ages, calibrated ages, and true calendar ages should be explicitly made. This is the policy of Quaternary Research, and should be adopted generally. Ambiguous expressions (e.g., 10,000 B.P.) should be avoided.
- Because a vast amount of data has been published with a radiocarbon timescale only, and because the specific calibrations will likely change in the future, the reporting of “raw” radiocarbon ages and their uncertainties should continue for consistency.
- Whenever feasible, diagrams and tabular information should be supplied with both a radiocarbon and a calendar timescale (e.g., Whitlock et al., 1993, Fig. 8; Bartlein and Whitlock, 1993, Fig. 10).
- Enough chronological information (i.e., ages and depths of radiocarbon-dated samples) should be provided (either in publications or in archival data bases) to enable subsequent investigators to develop new age models using as yet undeveloped calibration routines.

In addition to requiring a change in practice in reporting research results, the implications of the age differential are potentially significant enough to require changes in some of the conceptual models that underlie our understanding of Quaternary environmental change.
CALIBRATION OF BERINGIAN 14C AGES

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REFERENCES


Sruver, M., and Braziunas, T. F. (1993). Sun, ocean, climate and atmospheric
\(^{14}\text{CO}_2\): an evaluation of causal and spectral relationships. *The Holocene* 3, 289–305.


