SYNCHRONICITY IN CLIMATE AND VEGETATION TRANSITIONS BETWEEN EUROPE AND NORTH AMERICA DURING THE HOLOCENE

K. GAJEWSKI[1], ANDRÉ E. VIAU[1], MICHAEL SAWADA[1], DAVID E. ATKINSON[1,2]
and PHILIPPE FINES[1,3]

[1]*Laboratory for Paleoclimatology and Climatology, Department of Geography, University of Ottawa, Ottawa, ON K1N 6N5 Canada*
E-mail: gajewski@uottawa.ca
[2]*International Arctic Research Center, University of Alaska, Fairbanks AK 99775-7320 USA*
[3]*Department of Mathematics and Statistics, University of Ottawa, Ottawa, ON K1N 6N5 Canada*

Abstract. Interpreting the postglacial climate history of the European continent using pollen data has proven difficult due in part to human modification of the landscape. Separating climate from human-caused changes in the vegetation requires a strategy for determining times of change across the entire region. We quantified transitions in the vegetation across Europe during the past 12,000 years using a mixture model approach on two datasets: radiocarbon dates from pollen diagrams and zone boundaries from selected reference sites. Major transitions in the vegetation, as recorded in pollen diagrams, appear synchronous across the continent. These transitions were also synchronous with those identified in North America pollen diagrams and major environmental changes recorded in North Atlantic marine records and Greenland ice cores. This synchronicity suggests that the major vegetation transitions in Europe during the Holocene and late glacial were primarily caused by large-scale atmospheric circulation change. These climate changes may have caused some of the cultural, political and migration changes in European societies during the Holocene.

1. Introduction

The European landscape shows indications of millennia of human use, resulting in a "cultural landscape" (Birks et al., 1988; Bell and Walker, 1992) that has influenced thinking about environmental change on the continent. Human activities such as agriculture or settlement have been an important influence on vegetation change (Turner, 1962; Behr, 1988; Birks et al., 1988; Berglund, 1991; Bell and Walker, 1992; Chambers, 1993; Parker et al., 2002; Berglund, 2003). Separating the relative impacts of human activity from those due to climate change has, however, proven ambiguous (Smith and Pilcher, 1973; Magny et al., 2002). On the one hand, it is felt that increasing technological ability and centuries of anthropogenic landscape modification may have progressively isolated societies from climate impacts (Bell and Walker, 1992; Messerli et al., 2000). Alternatively, evidence shows a continuous climate impact on society, as indicated in historical and proxy records (Rotberg and Rabb, 1981; Pfister and Brázdil, 1999; Berglund, 2003). The relative importance

Climatic Change (2006) 78: 341–361
DOI: 10.1007/s10584-006-9048-z

of landscape, climate and social factors is, however, not easy to disentangle (Bell and Walker, 1992; Roberts et al., 2001).

Archaeological evidence of local resource utilization suggests human impacts on the landscape, including the vegetation, for millennia (Vernet, 1997). Historical evidence of resource utilization includes increases in the pollen of weeds or changes in tree percentages in pollen diagrams, both of which indicate increased resource utilization (e.g. Turner, 1962). The appearance of charcoal or weed pollen in the sedimentary record has been used to infer the presence of slash-and-burn agriculture (Behr, 1986). Not surprisingly, such observations have had a significant impact on the interpretation of the vegetation history as recorded in pollen diagrams and other records (Birks, 1988; Bell and Walker, 1992; Jalut et al., 2000; Magny et al., 2002). The importance of human activity, including the establishment of agriculture has been emphasized, suggesting that creation of the cultural landscape is the dominant factor in European vegetation history.

Alternate explanations center on the idea that climate changes have primarily shaped vegetation changes (e.g. Huntley, 1990a,b), although it is recognized that human activities have significant local effects or interact with climate factors (e.g. Carrión et al., 2001). Disentangling climate change and human impacts is further complicated since climate change may act on the vegetation indirectly through the influence on human activity or movements (Roberts, 1998). This has implications for the analysis of human history as well (Willis and Bennett, 1994; Huntley, 2002).

European palynological studies have attempted to separate human- and climate-caused changes on the vegetation in several ways. One is the use of “anthropogenic indicators”, which are pollen taxa that indicate activities such as forest clearance and, assuming pollen are not transported too far, agricultural activity (Behr, 1988), although these taxa may also indicate natural disturbance (Huntley, 1992). In addition, human activity can be inferred from changes in forest pollen taxa (e.g. Aaby 1986), because forests have been managed for centuries (Rackham, 1988; Gulliver, 1995). Another method used to disentangle human and climate impacts is the comparison of transitions in pollen diagrams across a region (Turner, 1962; Parker et al., 2002) where time-transgressive changes may indicate human impact. Climate changes are expected to be regionally synchronous, whereas human impacts should vary more erratically in time. Even this has proven ambiguous, however, due to errors in dating and issues regarding the choice of transition that should be dated within a pollen diagram (e.g., the first appearance of the pollen grains of a taxon, the beginning of a continuous curve, or the beginning of the increase in pollen abundance; Smith and Pilcher, 1973). Resolving the question of human vs. climate impacts on vegetation is a pressing question (Huntley, 1988).

Numerous case studies have been performed analyzing the regional evolution of the landscape in relation to human activity (e.g., Behr, 1986, 1988; Robinson and Dickson, 1988; Butlin and Roberts, 1995; Berglund, 1991; Ramrath et al., 2000; Tolonen, 1981; among many others). Among the conclusions are that human impacts can show expansions followed by regressions (Berglund, 1988), but there has been an overall trend through time toward increasing human impacts. Grazing by animals can further complicate the interpretation (Vera, 2000). Although local impacts of human activity may be evident, the mechanisms by which these are scaled up to regional and continental vegetation changes are not clear. For example, the well-documented elm decline may be locally caused by the use of elm as fodder, but the extent of this decline, as measured in many pollen diagrams, is so large that it is difficult to imagine such extensive human activity (Parker et al., 2002). Human activity may be associated with the development of blanket bogs in the British Isles, although climate factors seem involved as well (e.g. Chambers, 1982).

Even if ultimate causes of vegetation change in pollen diagrams can be separated, local human impacts complicate the derivation of past climates from fossil pollen (Guiot, 1987). The effect of human activities will alter the relative percentages of the pollen taxa, making statistical comparisons of fossil and modern pollen assemblages difficult. Nevertheless, several continental-scale paleoclimate reconstructions have been attempted (e.g., Davis et al., 2003) and maps of pollen assemblages published by Huntley and Prentice (1993).

In this study, we test the hypothesis that *periods of major transition recorded in pollen profiles from Europe are largely synchronous across the continent and thus are likely driven by climate changes.* We further determine the extent to which these transitions are synchronous with transitions identified in North American pollen sequences that have presumably been less influenced by human activity, as well as ice core and marine records from the North Atlantic region. Accepting this hypothesis implies that, despite human impact, these climate changes influenced not only the European vegetation but were nearly hemispherical in nature. This hypothesis may be tested in several ways.

One method used in the literature is to take some particular event, such as the elm decline, and compare the date of this event in a spatial context (Smith and Pilcher, 1973; Parker et al., 2002). Similarly, one may zone the diagrams and compare the timing of zone boundaries for synchronicity (Bennett, 1988; Gajewski, 1998). Pollen profiles can be divided into zones, where the within-zone variation in pollen assemblages is less than that between zones, as a convenient way to simplify interpretation and comparison between diagrams. To use this method to test the hypothesis, the zones would need to be based only on changes in the pollen diagram, that is, they need to be pollen assemblages zones (Berglund, 1986; Birks, 1986). As an example, the northern-European Blytt-Sernander zonation has been applied across Europe, but this has caused problems in interpretation. Forcing any particular pollen sequence into the same cool-dry/warm-wet climate interpretation as occurred in southern Scandinavia has proven difficult due to regional climate changes that may be out of phase with northern Europe. Regional zones, defined solely by the pollen assemblages are more appropriate (Moore et al., 1991), where any climate interpretation and correlation with other regions is performed subsequent to the zonation and local interpretation. We use this method on pollen assemblage zones from Berglund et al. (1996).

Another approach is to search for times of more rapid transition in pollen sequences. Jacobsen et al. (1987) and Grimm and Jacobsen (1992) quantified "times-of-change" by computing dissimilarity between samples in several sediment sequences from North America and Huntley (1990c, 1992) applied the same method to data from Europe. Both of these studies identified more rapid change during the late glacial, but few changes during the Holocene, except in the past 1000 years. Both synchronous and time-transgressive changes were reported within the 2 regions and between them. Using a complementary, but more powerful approach, Wendland and Bryson (1974) and Viau et al. (2002) searched for modes in the distribution of transition dates from pollen diagrams using radiocarbon dates as a proxy for transitions in pollen diagrams. This method is based on the assumption that pollen analysts preferentially select transitions in pollen diagrams as locations for extracting sediment for radiocarbon dates, and thus the resultant date distributions represent times of major climatic change (Wendland and Bryson, 1974). Although any one pollen diagram may have few dates and thus document only some of the transitions, a population of diagrams will have many dates documenting the major transitions. Errors in radiocarbon dates or ambiguities in the position of the date in relation to changes in the pollen diagram can be interpreted as time-transgressive changes of the event in question, or lack of climate signal, but in this approach they are treated as normal deviations around target dates.

We are hypothesizing that millennial-scale climate changes are global, that they are impacting the vegetation of all of Europe in some way, although not necessarily in the same direction, and that these impacted the vegetation in spite of or above any human impact. In this paper, we will (a) show that this hypothesis is reasonable using a method to identifying climate transitions and (b) illustrate that the these transitions are synchronous with transitions in North America and the North Atlantic.

2. Methods

A sedimentary sequence undergoing palynological analysis typically has radiocarbon dates obtained at the base and at significant discontinuities (Wendland and Bryson, 1974; Viau et al., 2002). This is known from general practice as well as inspection of many pollen diagrams. Spatially widespread synchronous discontinuities should therefore correspond to major climate changes. These would be identified as modes, with normally distributed variation, within the multimodal frequency distribution of all radiocarbon dates. The variation around the modal value encompasses various errors and inter-laboratory difference in methods. In this study, we use a non-linear mixture modeling approach (Viau et al., 2002) to identify modes within the multimodal frequency distribution of transition dates in pollen diagrams from across Europe.

2.1. DATA

We apply our methodology to two independent datasets. The first contains 2493 radiocarbon (^{14}C) age determinations, used to date 492 pollen diagrams prepared from lakes and bogs (Figure 1a) and contained in the European Pollen database (EPD) (Contributors of the EPD, 2000). This analysis is comparable to our previous analysis of the North American pollen transitions (Viau et al., 2002). Basal dates,

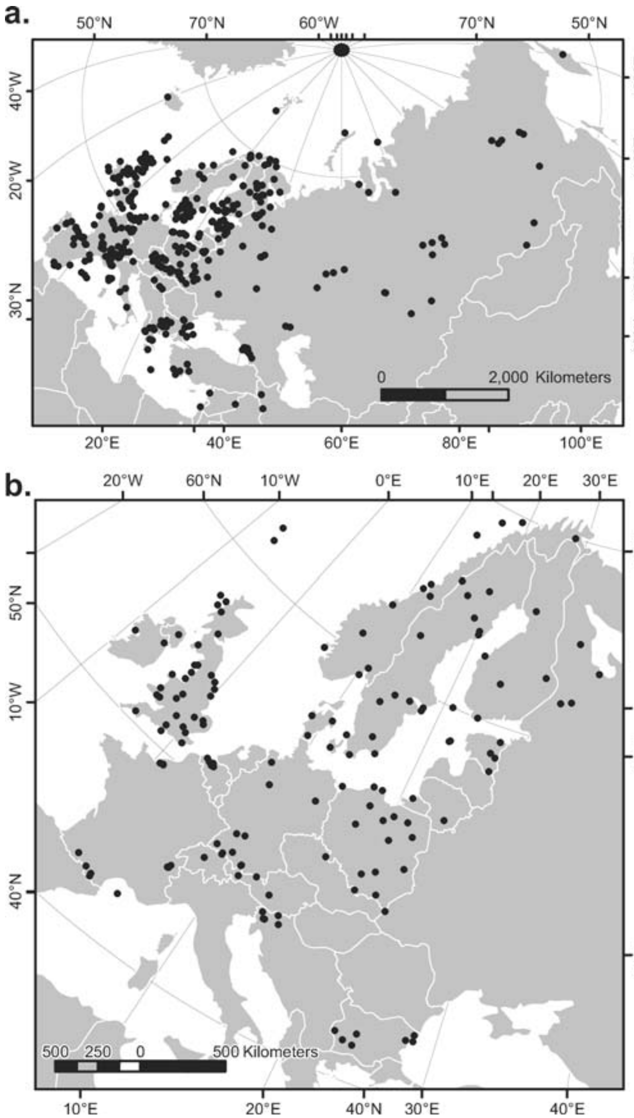

Figure 1. Distribution of available pollen diagrams used in analysis of (a) radiocarbon dates and (b) pollen assemblage zones (PAZ).

those <150 yr B.P. and dates older than 12000 ^{14}C yr B.P. were excluded leaving 2351 ^{14}C dates. We did not otherwise select or triage data. We analyzed only ^{14}C dates from pollen diagrams because these are transitions in a proxy with similar lag times to climate changes. Note that small violations of the basic assumptions should only affect the scatter around the modal values identified by the procedure, but still properly identify the transitions.

The second dataset represents boundaries of local or regional *pollen assemblage zones* (PAZ) interpreted from carefully selected reference sites from temperate Europe (Berglund et al., 1996) (Figure 1b). Temperate Europe was divided into type-regions, and experts from each country chose one or several pollen diagrams that best document the postglacial vegetation sequence of that region. Each pollen diagram was zoned, based on the pollen assemblages. By definition, *pollen assemblage zones are determined only by changes in pollen assemblages*, irrespective of sedimentological information or any underlying model of climate or vegetation variation. Berglund (1986) and Birks (1986) discuss this project and Birks and Berglund (1979) provide an example indicating the importance of independently defining zones for each pollen diagram. Transitions were dated by radiocarbon determinations, by interpolation between radiocarbon dates, or through correlation with another pollen diagram from the region. A total of 169 tables (sites) defining zone boundaries were available, containing 1118 transitions.

2.2. MIXTURE MODEL

In two independent analyses, clustering of both ^{14}C dates (EPD) and dated pollen assemblage zones (PAZ) from the sequences was solved using a nonlinear mixture modeling approach (Titterington et al., 1985). Normal curves were successively fitted to the multimodal distribution of all ^{14}C dates and dated pollen assemblage zones using the expectation-maximization (Newton-Raphson) algorithm implemented in SAS (Statistical Analysis Software) (Atkinson et al., subm). The expected value μ_i, standard deviation σ_i, and posterior probability of the distribution p_i, (for $i = 1 \ldots n$, where p_i must sum to unity) are each obtained for all n distributions. To avoid extremely spread distributions, a standard deviation constraint was applied, but was optimized to ensure that upper bounds were not too tight, as this would lead to non-optimal solutions. Determination of the optimal standard deviational constraint was done through repeated model runs for both datasets with the upper bound of the standard deviations varying from 500 to 1500 years. A 1,000-year standard deviation constraint was optimal for both sets of data (Figure 2a, b). The optimal number of components or modes is determined when the log-likelihood (NLL) ratio curve flattens out (Figure 2c, d). Once the modes were identified, the modal radiocarbon estimated dates were calibrated using INTCAL98 software methods a and b (Stuiver et al., 1998).

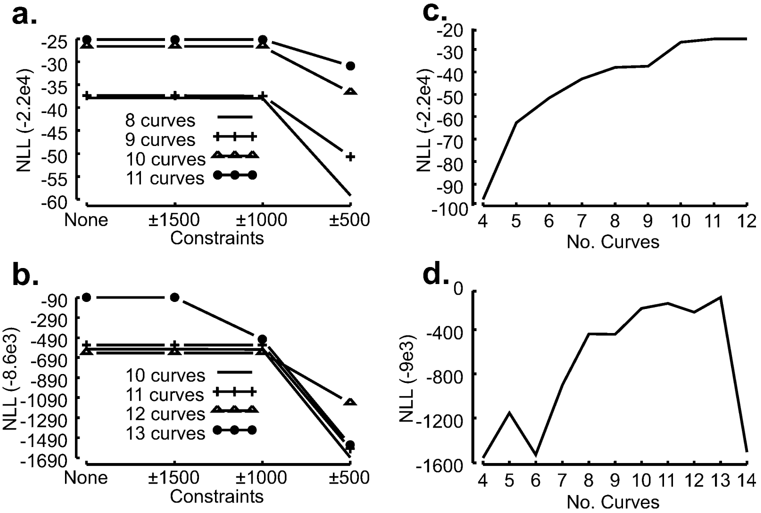

Figure 2. (a) Log-likelihood ratio illustrating optimal standard-deviation constraint for EPD dataset. (b) Same but for PAZ dataset. (c) Log-likelihood ratio curve illustrating optimal number of modes for the radiocarbon EPD dataset. d) Same but for PAZ dataset.

2.3. SPATIAL ANALYSIS

Subsequently, the locations of all sites associated with a mode were mapped to determine if they are widespread within the study region. If the sites exhibiting a vegetation transition are widely distributed, large-scale climate forcing is the expected cause. Key to this approach is that transition dates are used with no interpretation of the direction or nature of vegetation or climate change. As such, change itself is the focus and the methodology works in spite of regional differences in climate (e.g. cooling in one and warming in another) and irrespective of the particular taxa that have changed in abundance (Gajewski, 1987; Bennett, 1988).

The spatial distribution of sites that are associated with a modal event can be local, regional or widely distributed across the study region. Specifying the degree of clustering can aid in distinguishing local/regional vegetation changes from those due to a broader climatic origin. Simple tests comparing sites associated with a given modal event to those produced by a completely spatially random process are problematic in this study due to the existing clustered distribution of pollen assemblage zone (PAZ) and radiocarbon-dates from the European Pollen Database (EPD) sites from which each mode is a spatial subset. This existing distribution of PAZ or EPD sites therefore represents background populations within which sites associated with a mode could be distributed randomly, regularly or be clustered. If the pattern of sites associated with a given modal event cannot be excluded to be the result of a random process then we suggest climate as the cause of the subset distribution at our scale of study. Clustering due to regional changes may

TABLE I

Calibration of identified modal radiocarbon dates for the EPD and PAZ datasets for Europe and North America (Viau et al., 2002) using Stuiver et al. (1998) methods a and b

Europe[a]				Europe[b]				N. America[c]			
	Calibrated dates				Calibrated dates				Calibrated dates		
Modes ^{14}C	Start	Mean	End	Modes ^{14}C	Start	Mean	End	Modes ^{14}C	Start	Mean	End
				301	311	380	420				
408	472	500	506					647	562	600	653
1097	968	1020	1052	980	916	930	931				
1726	1571	1660	1692					1763	1615	1650	1709
2251	2182	2250	2332	1963	1876	1910	1925				
				2794	2853	2900	2945	2757	2786	2850	2914
3981	4416	4420	4502	3835	4154	4240	4273	3705	3987	4030	4087
				5124	5757	5910	5907				
6269	7103	7220	7248	6000	6747	6810	6867	5908	6671	6700	6780
				6834	7673	7660	7784	7259	7982	8100	8150
7965	8722	8900	8985	8000	8719	8880	8983				
				9081	10241	10220	10465	9003	10164	10190	10213
9754	11169	11180	11196	10000	11261	11440	11553				
11225	13005	13160	13439	11000	12677	13000	13159	10749	12629	12900	12976
11849	13625	13830	14061	11910	13605	13940	14051	11771	13499	13800	14009

"Start" and "end" dates are the calibrated age of the transition in the modal value using method b (2 sigma at 95.4%). The calibrated mean value, here and in Table II and Figures 3, 4 and 5, is derived using method a.

[a] This study, ^{14}C dates (EPD).

[b] This study, (PAZ).

[c] Viau et al. (2002).

be represented by a larger than expected number of sites in one region with fewer than expected (under a random process of selection) outside of this region.

The difference in K functions (K_{1-2}) (Ripley, 1976; Rowlingson and Diggle, 1993; Bailey and Gatrell, 1995) was used to test the null hypothesis that the horizontal spatial distribution of pollen diagrams associated with each modal date (i.e. ^{14}C dates) (Table I) was equivalent to an arrangement created by a random process of selection from all candidate sites that could potentially have exhibited the transition. For each modal event identified, we computed K_1 (test set) from all n_1 points defined by a mode within an interval of ±200 yrs and K_2 (control set) from all n_2 sites with dates older than the lower age bound of the mode considered. In order to ensure that results were not biased by our choice of ±200 yr interval around each mode, we varied this interval from ±100 to ±300 yrs by increments of ±50 yrs -undertaking five tests for each modal event. The 5th and 95th quantiles of nearest neighbour distances for the combined $n_1 + n_2$ points for both data sets ranged between 208–340 km for the ^{14}C and PAZ. In each case, we then determined the difference in K functions ($K_{1-2} = K_1 - K_2$) to 1000 km. Monte Carlo upper and lower simulation envelopes of K_{1-2} were estimated in 999 repeated simulations using the fixed $n_1 + n_2$ locations but randomly labelling n_1 of these locations as modal events at each iteration. Observed K_{1-2} was graphically compared to the minimum, 5th percentile, 95th percentile, and maximum observed K_{1-2} at each distance class from the simulations. Within the simulations, the landmass was represented by a simple convex polygon as no corrections for edge-effects were necessary since boundary effects were constant for all simulations. If the observed K_{1-2} for the spatial arrangement of sites comprising a modal event breached the 5th or 95th percentiles and remained within the minimum and maximum simulated K_{1-2} then this suggests weak departures from randomness at a given distance. If an observed K_{1-2} breached the minimum or maximum simulation envelope then we consider the distribution of sites comprising this modal event to be a significant departure from a spatially random subset at the distances in question.

3. Results

3.1. TRANSITION TIMES

Ten modes were identified using the distribution of radiocarbon dates from the EPD dataset while thirteen modes are optimal in the distribution of the pollen assemblage zone (PAZ) dataset (Figure 3a, b). To more easily and efficiently compare these transition times to previous studies, we use the mean calibrated calendar year (Stuiver et al., 1998, methods a and b) as a summary of transitions found between the EPD, PAZ and North American analyses in this section. Table I shows calibration of the modal ^{14}C estimates using both methods a and b to provide the ranges of calendar ages for a particular radiocarbon date identified by the mixture model (Stuiver et al., 1998). Given the errors associated with radiocarbon dating, and the spread of the distributions around the modal points we consider as synchronous peaks that differ by a few 100 years. Note that the standard deviations of the modes cannot be used to quantify the uncertainty in the modal values nor to derive confidence intervals due to constraints of the mixture model.

In the late-glacial, modes in the distribution of both radiocarbon ages (EPD) and PAZ boundaries are identified at approximately 13900, 13100 and 11300 cal yr BP (Table I), where these ages are the approximate and rounded central values of modes found in the 2 datasets from Europe. In the early and mid-Holocene, modes are identified at 8890, 7000 and 4300 cal yr. BP. In addition, the analysis on the pollen assemblage zones finds another peak between these each of these modes. In the past 3000 years, 4 modal values are found in each analysis with some variations among them while modes at around 2100 and 950 cal yr BP are identified in both datasets (Table I).

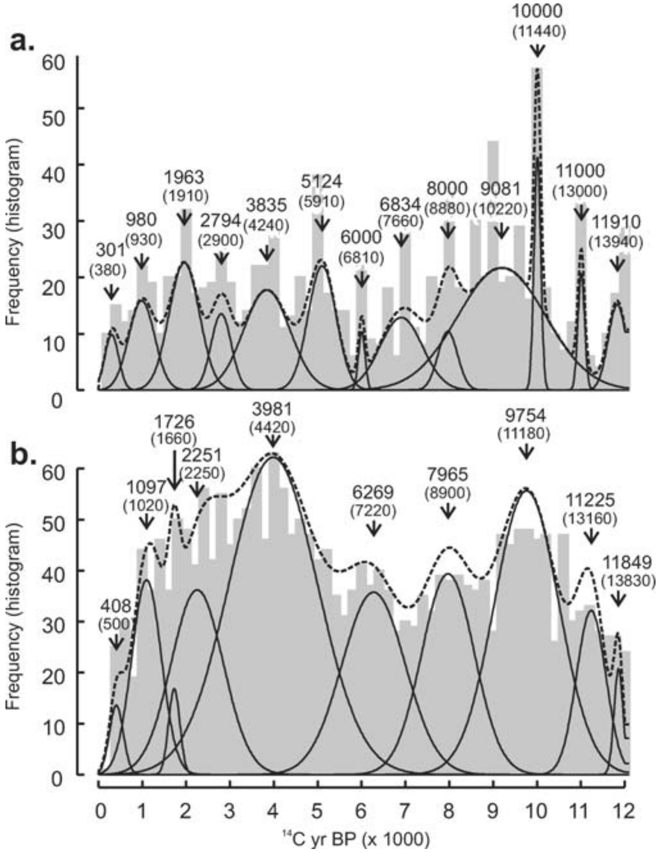

Figure 3. Frequency histogram of ^{14}C dates overlaid by optimum solution of nonlinear mixture model identifying the locations of modes for (a) pollen assemblage zones (PAZ) and for (b) radiocarbon dates (EPD). Dotted curves represent the respective kernel-density estimate for the optimal solution. Annotations indicate ^{14}C modal values from the mixture model with the mean calendar year equivalents in parentheses (Stuiver et al., 1998; method a as in Table I).

3.2. SPATIAL ANALYSIS

Sites associated with these modal values are widely distributed across the continent and generally show no strong clustering within any one region (Figures 4 and 5). Within the analysis of the radiocarbon dates from the EPD, only modes 1097 ^{14}C yr BP (1020 cal yr BP) and 1726 ^{14}C yr BP (1160 cal yr BP) showed significant departures from randomness and only at distances less than 100 km. At all greater distances there were only weak departures from random labelling (Figure 4). Small-scale clustering is evident but in addition there is second-order clustering, where small clusters are widely dispersed. For example, at 1097 ^{14}C yr BP (1020 cal yr BP) there are secondary peaks in K_{1-2} at approximately 300 and 500 km suggesting

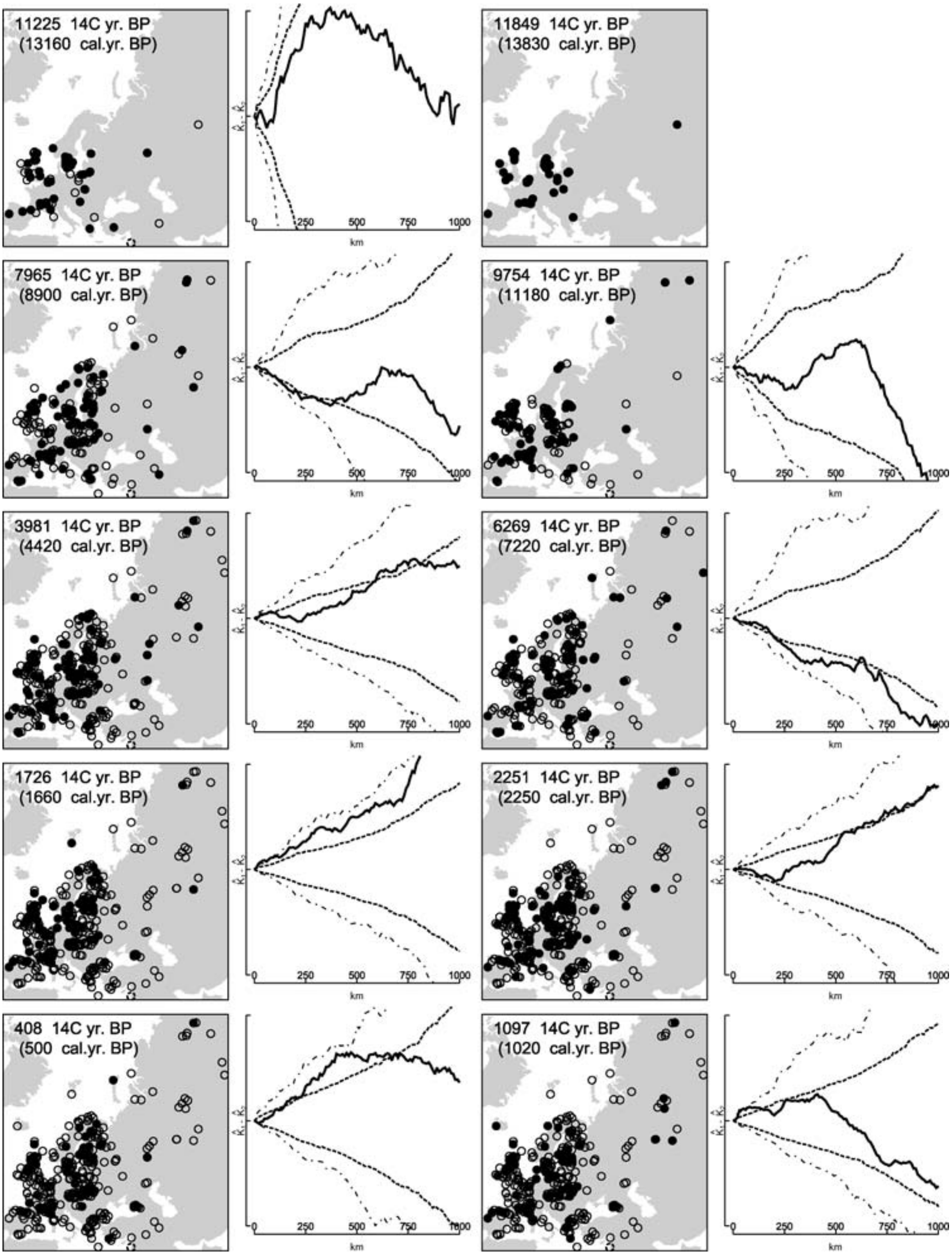

Figure 4. Maps showing sites that recorded a radiocarbon date (EPD) at the transition listed and difference in K functions (K_{1-2}) in 999 repeated simulations under the random labelling hypothesis. Dash-dotted lines represent the minimum and maximum simulated K_{1-2} and fine dotted lines are the 5th and 95th quantiles of the 999 simulated distributions. Open circles represent the population of sites that have records equal to or exceeding the modal date minus 200 years. Black closed circles represent the sites associated with a given modal value ± 200 years. Calendar equivalents as in Figure 3.

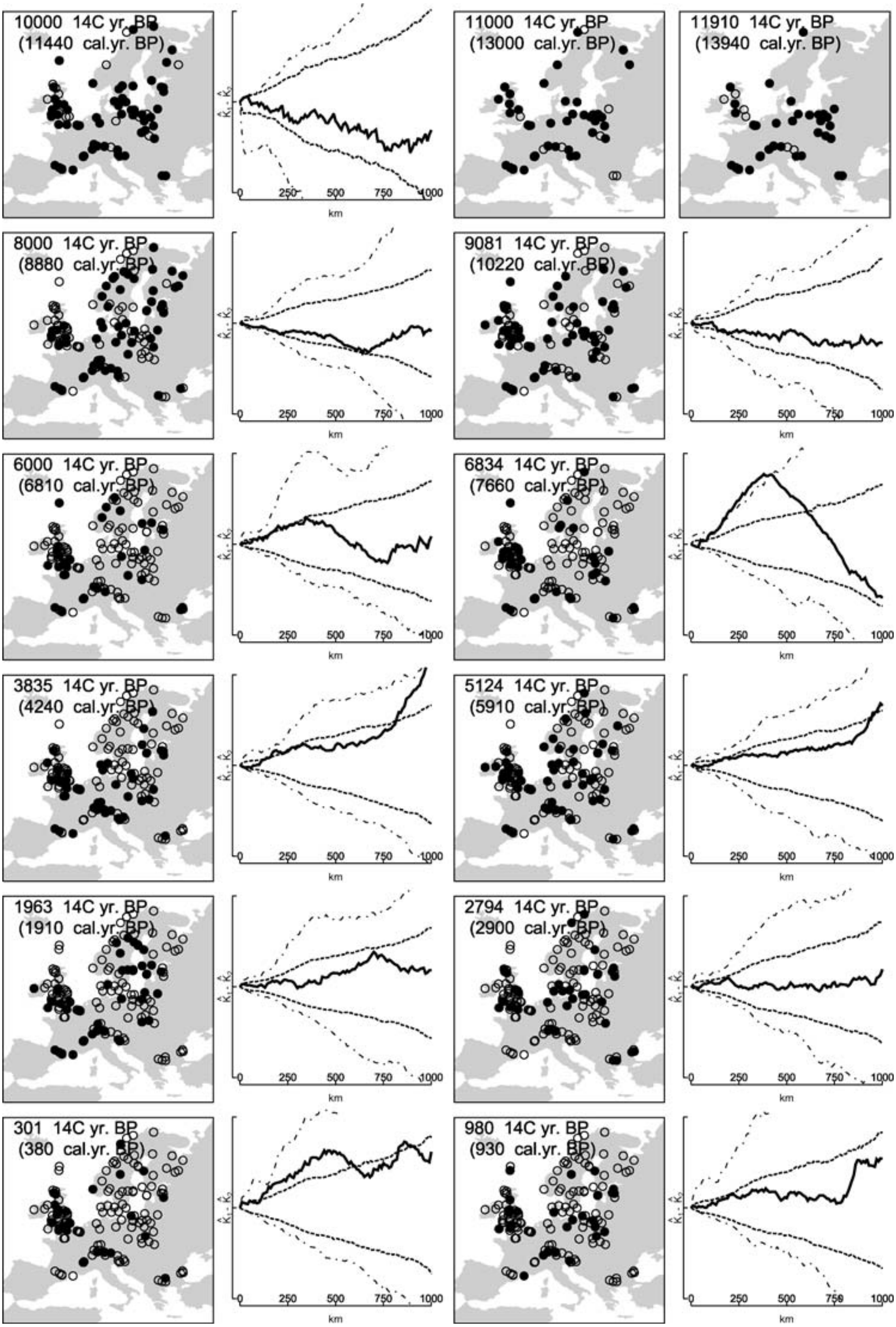

Figure 5. Maps showing sites that recorded a pollen assemblage zone (PAZ) transition at the time listed and K statistic compared to a random simulation of the same data. Symbology as in Figure 4.

small clusters at that scale when compared to a random labelling hypothesis. All modes except for 9754 ^{14}C yr BP (11180 cal yr BP) and 11225 ^{14}C yr BP (13160 cal yr BP) exhibit weak departures from randomness at some scales. Departures at 6269 ^{14}C yr BP (7220 cal yr BP) and 7965 ^{14}C yr BP (8900 cal yr BP) are towards more dispersed distributions when compared to the control population. There were no pollen assemblages dating older than 11849 ^{14}C yr BP – 200 ^{14}C yr BP (13840 cal yr BP), therefore no population could be defined, and we assume that this modal event is recorded at all sites.

Within the analysis on the PAZ boundaries, only mode 6834 ^{14}C yr BP (7660 cal yr BP) exhibited significant departures from a random selection hypothesis (Figure 5). At 6834 ^{14}C yr BP (7660 cal yr BP) there is strong clustering in Western Europe, particularly in the southern UK – northern France region. Modes 301 ^{14}C yr BP (308 cal yr BP), 3835 ^{14}C yr BP (4240 cal yr BP) and 6000 ^{14}C yr BP (6810 cal yr BP) exhibit some weak departures at large distances. Modes 8000 ^{14}C yr BP (8880 cal yr BP), 9081 ^{14}C yr BP (10220 cal yr BP) and 10000 ^{14}C yr BP (11440 cal yr BP) exhibit a tendency towards patterns more dispersed than a spatially random subset. Modes beyond 10000 ^{14}C yr BP (11440 cal yr BP) could not be tested due to an inadequate number of controls available.

Site distributions breaching the 95th percentile may be indicative of a tendency towards local influences if there is no evidence of 2nd order clustering at larger scales. The direction of departure is also important in this study since site distributions that can be accounted for by a random process of selection and those that exhibit greater dispersion than a random selection process are both indicative of a widespread events. Only PAZ 6834 ^{14}C yr BP (7660 cal yr BP) in this study shows significant small-scale clustering. All others may have some small-scale clustering but such clusters tend to be widely dispersed throughout the population of sites.

We conclude that the majority of modes identified in both the PAZ and EPD analyses are widely distributed within the population of sites. Although some transitions have regional characteristics (e.g., PAZ 6834 ^{14}C BP or 7660 cal yr BP), others that exhibit weak clustering do so at large scales ($>$ 400-500 km) and scrutiny of the mapped patterns supports these conclusions.

4. Discussion and Conclusions

The modes correspond in most instances to those found in pollen diagrams from North America (Table I; Viau et al., 2002) and also to those found in North Atlantic marine records (Bond et al., 1997, 2001) and Greenland ice cores (O'Brien et al., 1995) (Table II). Some of these transitions, such as the Ållerød (transition 1) and Younger Dryas (transition 2) are well known for their impact on the vegetation (Wright, 1989). Not all transitions found in North America are identified in Europe. For example transition 3 is evident in both the PAZ and EPD analysis, but absent in North America (Table II). However, it appears in the North Atlantic and GISP2 ice

TABLE II
Correlation of transition times between several studies

Transitions	Europe[a]	Europe[b]	North America[c]	North Atlantic IRD[d]	Greenland (GISP2)[e]	Summary
		380		300		
12	500		600		600	550
	1020	930				
11	1660		1650	1400	1500	1550
	2250	1910				
10		2900	2850	2800	2750	2850
9	4420	4240	4030	4200		4200
8		5910		5900	5550	5800
7	7220	6810	6700		6300	6750
6		7660	8100	8100	8100	8000
5	8900	8880		9400	9300	9100
4		10220	10190	10300	10600	10350
3	11180	11440		11100	11300	11250
2	13160	13000	12900	12600		12900
1	13830	13940	13800			13850

All dates expressed in calendar years (Stuiver et al., 1998) using method a as in Table I.
[a] This study (EPD).
[b] This study (PAZ).
[c] Viau et al. (2002).
[d] Bond et al. (2001).
[e] O'Brien et al. (1995).

core records. Similarly, transition 5 is not identified in North America but is identified in all other records. Transition 6, corresponding to the 8.2 ka event (Alley et al., 1997) is not clearly identified in continental Europe, but evident in North America, the North Atlantic and Greenland records. However, high-resolution analyses in Europe have subsequently identified vegetation changes at this time (Tinner and Lotter, 2001). In the mid-Holocene, (transitions 7, 8 and 9) there is coherence in most cases but these transitions are not present in all records. Nevertheless, they are geographically widespread, as they are identified in the marine and ice core records (Table II). Transitions 10 and 11 are identified in all regions, although only found in one of the analyses on European pollen records. Finally the Little Ice Age (transition 12) also had a widespread impact and appears temporally coherent. The exception is the marine IRD records, where sedimentological problems have been noted (Bond et al., 1997). The analyses on the European pollen databases also reveal transitions not seen in other records, in particular a transition around 2,000 cal yr BP and another around 1,000 cal yr BP (Table II). These transitions could represent extensive human modification of the European landscape or climate variability exclusive to the European continent. Alternatively, the climate impact at these times has not yet been recorded in some of these series. For example, Gajewski (1987) recorded a significant transition in pollen diagrams from varved-sediments in eastern North America at around 1000 years ago. The synthesis of these multi-proxy records reveals sufficient coherency that *it is reasonable to conclude that these are recording synchronous and widespread impacts on surface climates of a large portion of the northern hemisphere*. It is now necessary to develop more high-resolution records with high dating control to test this hypothesis of synchronicity.

The multimodal distribution of radiocarbon dates extracted from the EPD does not contain as clear a series of peaks (Figure 3b) as the North American record (Viau et al., 2002). There are several possible reasons for this. First, many data have not been submitted to the EPD; for example, only 20% of the sites in Berglund et al. (1996) were included in the EPD at the time the book was published (De Beaulieu, 1996). Based on the analysis of Parker et al. (2002) there should be more dates around 5,000 ^{14}C yr BP associated with the European elm decline. Next, the impact of human activity on the vegetation has been a preoccupation of many European palynologists and such events would be preferentially dated at the expense of vegetation transitions. Finally, our method of identifying modes requires that radiocarbon dates were preferentially taken at depths within a core that correspond to pollen transitions. Alternatives such as placing dates at regular intervals along the core would reduce the power of the methodology. Inspection of published diagrams indicates this is sometimes the case in European pollen diagrams although rarely are radiocarbon dates simply placed at even intervals down the core, as would be expected if they are being done only to develop an age-depth curve. Given the expense of dating pollen diagrams, there is a tendency among paleoecologists to date sections of more rapid change, as they wish to determine the most precise date for these transitions.

To determine the extent that analysts date zone boundaries, we inspected the 101 pollen diagrams from Berglund et al. (1996) where the authors had included a pollen diagram that showed the actual position of radiocarbon dates and also the zone boundaries. Three possibilities were identified: (a) a ^{14}C date not associated with a zone boundary (37% of the cases) (b) a zone boundary not dated by ^{14}C date (35%) and (c) a zone boundary dated with ^{14}C (29%) ($N = 374$ radiocarbon dates, 354 undated zones and 292 dated zones). Therefore, slightly less than half of the radiocarbon dates in this publication are associated with a zone boundary. However, in many cases, although the analysts dated levels that were not associated with zone boundaries, they also dated the zone boundaries in the same diagram. Of the 101 diagrams, there were 14 diagrams where the analyst did not date any zone boundaries but did date other levels using ^{14}C and 20 cases where zones boundaries are dated but there were no ^{14}C dates between zones. However, this is only a partial test, as some of the radiocarbon dates not associated with a zone boundary may nevertheless be associated with a change in the pollen diagram. Zones determined by the authors are supposed to reflect major transitions in the vegetation. Under our assumption, smaller changes are also reflecting a climate change (Gajewski, 1987) and would therefore contribute to identifying modal values. In fact the method is rather robust to violations of the assumptions. Viau et al. (2002) found that if the radiocarbon dates were randomly distributed through time, the method would identify this and not find a series of peaks, as we do in this paper. There is a "background level" of radiocarbon dates that may not be dating transitions, but as long as there is a *tendency* to date transitions, the method should identify these. We conclude that the assumption is not seriously violated, and to the extent that not only zone boundaries are dated, this should not overly affect the results.

The analysis of pollen assemblage zone transitions does show clear peaks. For this analysis to provide a valid test of our hypothesis, it is essential that each diagram be dated independently of the others. As we pointed out above, the protocols of the project stipulate that the zones were to be pollen assemblage zones, which, by definition, depend only on the data (Berglund, 1986; Birks, 1986). Although defining what constitutes a zone may be subjective and vary among analysts, there are sufficient pollen diagrams in the study to identify major transition periods in the vegetation, and therefore the climate, of Europe. Again, inspection of Berglund et al. (1996) indicates that zone boundaries were typically placed at transitions.

The nonlinear relation between radiocarbon and calendar ages may affect the analysis of frequency distributions of radiocarbon dates (Bartlein et al., 1995). However, we suggest that millennial-scale climate variations are indeed detectable in pollen data using uncalibrated radiocarbon dates. Bartlein et al. (1995) recognised that 2nd order errors, or ^{14}C plateaus, result mainly from solar output variability. The plateaus or shifts in radiocarbon production are themselves a common signal to several climate proxies, including marine and ice records (Bond et al., 2001). Indeed, changes in atmospheric ^{14}C occur at the same times as major climate shifts during the last deglaciation and the Holocene (Hughen et al., 2000; Bond et al., 2001). Therefore, a plausible explanation would be that millennial-scale climate variations occurred at or around these ^{14}C shifts. Given that these shifts in radiocarbon production can be *considered as a signal*, calibration *a priori* using this methodology would result in unnecessarily stretched or squeezed modes, which may bias the results and interpretation due to model sensitivity to sharp peaks. The only assumption used in this study is that palynologists tend to date pollen transitions prior to and independent of age-depth modeling. Therefore, these ^{14}C dates are not a random set of dates; they represent transitions in the sediments, as was demonstrated by simulation in the time and space domain in North America (Viau et al., 2002).

Our record for North America (Viau et al., 2002) combined with this study support the hypothesis that major vegetation changes also occurred at these preferred times of change. The close correspondence between the transitions within European pollen diagrams, North American pollen sequences, the Greenland ice core, North Atlantic sediments and other records provides compelling evidence that large-scale climate forcing of the European vegetation occurred during the past 14,000 years.

The particular climate sequence (i.e. a change from relative warmth to cold conditions at a particular transition) can vary regionally, but in response to the same global climate changes (Gajewski, 1993). Major transitions in the vegetation during the Holocene were caused by reorganizations of the atmospheric circulation that synchronously affected the surface climate in North America, Europe and the North Atlantic. Our study provides a challenge to paleoecologists to evaluate these results at a regional scale and to determine the nature of the vegetation and climate changes surrounding these transitions. It is also possible that climate changes may be causing human populations to migrate or change their technology in response to pressures on the ecosystems (deMenocal, 2001).

Several consequences arise from our results. First, they indicate that climate changes, now shown to be affecting plants and animals around the world at interannual to decadal scales (Parmesan and Yohe, 2003), also had influence at century to millennial scales despite human use of the land (Messerli et al., 2000). Climate changes impact cultural landscapes sufficiently to affect pollen production and differential species survival. Next, human evolution and development through the Holocene were tied to environmental fluctuations in spite of increasing technology (Berglund, 1991; Messerli et al., 2000). Finally, our results again indicate that climate changes impact the entire globe and not just marginal areas (Gajewski, 1987), with implications for understanding and adapting to the future.

This study shows a large-scale climate impact on the vegetation of Europe through the past 12,000 years. These were synchronous with changes in the vegetation of North America and with climate changes in the North Atlantic, not only in the Late Glacial but also throughout the Holocene (Nesje et al., 2004). Future work could improve on the methodology by identifying times-of-change objectively using complete pollen curves and determining the direction and magnitude of the regional climate changes associated with each transition. However, it is important to study not any particular taxon or event (e.g. spruce migration, elm decline), but any changes in the multivariate pollen diagram.

Although the results presented here show synchronous climate changes across Europe, this does not mean the actual climate variations (e.g. warming, drying) need be the same across the continent (Viau et al., 2002), as is frequently assumed. Although these variations appear to be synchronous, it would be an error to now use them for dating new sequences (Björck et al., 1998), as temporal differences may provide information about climate dynamics and vegetation response. That is, the variations around the modal values, which we assume result from random errors may provide ecological information at regional scales, if sufficient data exist to enable their study. Finally, these variations are only a small portion of total climate variations and future work should involve high-resolution records to record these. This study suggests that subtle climate variations are recorded in pollen diagrams. Because many such diagrams are now available over large regions, high-resolution pollen diagrams have great potential for future work at century to decadal scales.

Acknowledgments

This work is supported by the Natural Sciences and Engineering Research Council of Canada, and is a contribution of the Climate System History and Dynamics (CSHD) Project. We acknowledge the contributors to the European Pollen Database.

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(Received 1 October 2004; in revised form 5 December 2005)