Synchronous environmental and cultural change in the prehistory of the northeastern United States

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Climatic changes during the late Quaternary have resulted in substantial, often abrupt, rearrangements of terrestrial ecosystems, but the relationship between these environmental changes and prehistoric human culture and population size remains unclear. Using a database of archaeological radiocarbon dates alongside a network of paleoecological records (sedimentary pollen and charcoal) and paleoclimatic reconstructions, we show that periods of cultural and demographic change in the northeastern United States occurred at the same times as the major environmental-climatic transitions of that region. At 11.6, 8.2, 5.4, and 3.0 kyr BP (10^3 calendar years before present), changes in forest composition altered the distribution, availability, and predictability of food resources which triggered technological adjustments manifested in the archaeological record. Human population level has varied in response to these external changes in ecosystems, but the adoption of maize agriculture during the late Holocene also resulted in a substantial population increase. This study demonstrates the long-term interconnectedness of prehistoric human cultures and the ecosystems they inhabited, and provides a consolidated environmental-cultural framework from which more interdisciplinary research and discussion can develop. Moreover, it emphasizes the complex nature of human responses to environmental change in a temperate region.

climate change | data synthesis | paleoecology | prehistoric cultures

Paleoenvironmental research has demonstrated the role of climate in affecting the distribution and development of ecosystems (1, 2), but the impact of environmental changes on human populations remains contentious (3, 4). A growing literature documents the influence of catastrophic climate changes such as drought on past human societies, much of which has focused on environments where human vulnerability to climate change is most pronounced, such as in arid or tropical settings (e.g., 5, 6). To explore long-term human responses to environmental change in a temperate region, where the relationship between humans and environmental change may not be immediately evident, we integrate newly available and detailed environmental and archaeological records from the northeastern United States that span the initial human settlement of the region ~13.5 kyr BP to the arrival of Europeans 0.5 kyr BP (thousand calendar years before present). Our analysis identifies temporal correspondence between several key cultural transitions, fluctuations in human population, and climate-driven changes in terrestrial ecosystems, generating new insights into environmental factors that influenced cultural change in North American prehistory.

Since initial human occupation, the terrestrial ecosystems of the northeastern United States have undergone large changes in composition and structure, with much change concentrated at several, well defined transitions between climate phases, namely at 13, 11.6, 8.2, 5.4, and 3 kyr BP (7, 8). These transitions occurred when changes in insolation and ice sheet extent influenced the energy balance and ocean-atmosphere circulation, altering regional patterns of temperature and the timing and magnitude of precipitation (9–13). The arrangement of the major plant communities has been primarily driven by these changes in climate, and species have responded individualistically to different climate regimes (2, 14, 15). Thus, periodic transitions between climate regimes in the prehistory of the northeastern United States resulted in different vegetation communities which substantially altered ecosystem services that were used by prehistoric Native American populations (16–19).

By affecting the development and distribution of terrestrial ecosystems, it is likely that climatic change would also influence human population size as well as modes of prehistoric subsistence dependent on these ecosystems. Although the association of archaeological periods with different ecosystems has long been recognized (16, 17), new ideas of the postglacial climate evolution (13, 20) and more refined dating and specification of the vegetation development, including the presence of nonanalogue plant communities (2), present an opportunity to critically reevaluate the relationship between cultural and environmental change. Some previous paleoenvironmental and archaeological studies have suggested links between environmental and cultural change in the study region (18, 19, 21), but these have focused on a single cultural/environmental change while the availability of new databases, which can be used to quantify past environmental conditions and cultural and demographic changes, now permit a more comprehensive analysis.

The present study provides a synthesis of paleoenvironmental and archaeological data for the entire prehistoric human occupation of sites across the northeastern United States from Maine to Pennsylvania (Fig. 1). This region has a high density of sedimentary pollen ($n = 63$) and charcoal ($n = 40$) records which provide a regional vegetation and fire history from the Paleoindian to the historic periods. To summarize vegetation change through time we calculated down-core squared-chord distances (SCD) across 500-year intervals from a subset of the highest quality pollen records ($n = 26$), where a positive change in SCD indicates a shift in vegetation composition (8, 22). Hydrogen isotope ratios from lake sediments provide a record of temperature (23) and lake-level variations provide a regional record of effective soil moisture (24).

The archaeological data consists of radiocarbon dates extracted from the Canadian Archaeological Radiocarbon Database [CARD; (25)], a searchable repository of over 35,000 archaeological and paleontological radiocarbon dates from Canada and the United States. Each datum includes a location (latitude, longitude, and elevation), the type and taxonomy of the material dated, and its associated cultural period as determined by the principal investigator. Using archaeological radiocarbon dates ($n = 1,887$) from within the study region (Fig. 1), we determined the timing of regional cultural transitions through the use of temporal fre-

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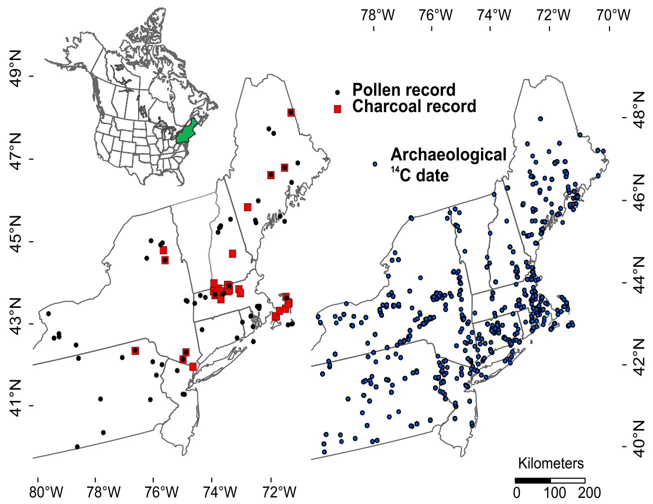

Fig. 1. Location of study region in relation to modern Canada and the United States (inset). Left: Location of sedimentary pollen (circles) and charcoal (squares) records; see Tables S1 and S2 for description of records and citations. Right: Location of archaeological radiocarbon dates used in this study; one point may contain multiple dates.

quency distributions of the calibrated dates (bin size = 250 yrs) associated with the different cultural periods. A cultural transition was objectively defined as the first time the majority of dates in a histogram bin consists of dates assigned to a later cultural period. To quantify the rate of cultural change through time we calculated the chord distance (CD) between adjacent histogram bins (26), where an increase in CD indicates a shift in the cultural composition of dates in a bin, with a maximum value reached when adjacent bins share no dates of the same cultural affiliation.

We interpret the temporal frequency distribution of archaeological radiocarbon dates as a proxy of relative population size (scaled from 0 to 1), based on research that has shown that a larger population will result in a greater deposition of cultural carbon (27–32). However, the distribution of archaeological radiocarbon dates can be influenced by taphonomic bias, resulting in an overrepresentation of younger material in the archaeological record (33). In a previous study using CARD to reconstruct relative population changes, Buchanan et al. (29) showed that even assuming a high rate of site destruction, relative peaks and troughs in frequency distributions of radiocarbon dates were robust. Surovell et al. (30) developed an empirical model to correct for taphonomic bias, which they argue is applicable to archaeological data, by comparing the frequency distribution of over 2,000 radiocarbon-dated volcanic deposits with the Greenland Ice Sheet Project (GISP2) SO_4^- record, interpreted as a continuous record of major global volcanic eruptions. However, in another analysis of prehistoric population numbers using CARD, Peros et al. (31) found that applying this taphonomic correction to their population estimates resulted in an improbably low contact-era population size, or an improbably high founder population size. These findings, coupled with additional exploration of CARD, led Peros et al. (31) to hypothesize that overrepresentation of older material, due to varying levels of archaeological interest and radiocarbon dating effort, may offset taphonomic bias at a continental scale. However, because this paper deals with a regional subset of CARD, and we are not yet able to quantify factors such as sampling and dating bias in the study region, we present population estimates made using both taphonomically-corrected and -uncorrected histogram curves.

Results and Discussion

The archaeological chronology of the northeast is broadly divided into Paleoindian, Archaic, and Woodland periods based on changes in technology, settlement patterns, and artistic traditions, with the Archaic and Woodland periods typically divided into Early, Middle, and Late subdivisions which denote a particular change of material culture within this framework (34). Temporal frequency distributions of archaeological radiocarbon dates, stratified by cultural period as identified by the primary archaeological investigator, provide information on changes in relative population size and the rate and timing of regional cultural transitions (Fig. 2). The chronological overlap of the dates assigned to each cultural period and the CD metric show that some transitions were more gradual than others, although it is still possible to determine the most probable time around which each of these transitions was centered. The transition from Paleoindian to Early Archaic occurred around 11.25 kyr BP. The transitions from Early to Middle Archaic and Middle to Late Archaic were more abrupt, and are dated at 8.25 kyr BP and 5.25 kyr BP, respectively. A considerable overlap between the Late Archaic and Early Woodland occurs, with the first Early Woodland dates occurring as early as 5.25 kyr BP (the beginning of the Late Archaic), but it is not until 3.0 kyr BP that the majority of dates are associated with Early Woodland cultures. Cultural transitions into the Middle Woodland and Late Woodland occurred at 2.0 kyr BP and 1.0 kyr BP, respectively. Our reconstruction of human population level is consistent with archaeological interpretations of population size (21, 35–38), and suggests that the Late Archaic and Late Woodland were both periods of rapid population growth, and that population decreased at the Archaic-Woodland transition (3.0 kyr BP).

With the exception of the transitions into the Middle and Late Woodland, the latter of which denotes the adoption of maize agriculture (39), every cultural transition corresponds to a major transition in the climate and vegetation of the region (Fig. 2 and 7). At these transitions, changes in the spatial patterns of temperature and moisture availability caused shifts in vegetation composition; abrupt changes at 11.6, 8.2, and 5.4 kyr BP are marked by relative increases in SCD at these times (8). The climate transition at 3.0 kyr BP was not as abrupt, but nevertheless involved changes in temperature, moisture, and changes in the distribution and abundance of plant taxa (7, 20). For preagricultural populations in this region who subsisted on wild food resources, these transitions between climate phases altered the expected relationships between ecosystem processes and made their existing resource base less predictable (cf. 40), resulting in a shift in resource procurement strategy, technology, and/or population size.

Regional averages of pollen and charcoal records describe the changing ecosystems of the region associated with cultural periods and demographic change (Fig. 3). The Paleoindian period (13.5–11.25 kyr BP) was characterized by the pollen of tundra plants including sedges (Cyperaceae) as well as coniferous spruce (*Picea*) and pine (*Pinus*) and more frequent fires [higher charcoal Index, (CI)], the latter probably due to drier summers (41, 42). During the Early Archaic (11.25–8.25 kyr BP), oak (*Quercus*) increased, pine decreased, and charcoal remained high, consistent with the lake level and temperature data that document a shift toward a drier and warmer climate (Fig. 2). The environment during the Middle Archaic (8.25–5.25 kyr BP) was characterized by an increase in moisture availability (12), with more precipitation falling in the summer months (41), low fire frequency, high values of hemlock (*Tsuga*), and increases of other mesic taxa such as beech (*Fagus*) and hickory (*Carya*). During the Late Archaic (5.25–3.0 kyr BP), *Tsuga* decreased abruptly while the pollen percentages of mast trees (*Quercus*, *Carya*) remained high. Charcoal increased again during the Woodland period (3.0–0.5 kyr BP), possibly caused by an increase in anthropogenic burning (43) and aided by a gradual shift in the seasonality of precipitation, whereby more precipitation fell in winter and summers were once again relatively dry (41, 42). At the same time, chestnut (*Castanea*)

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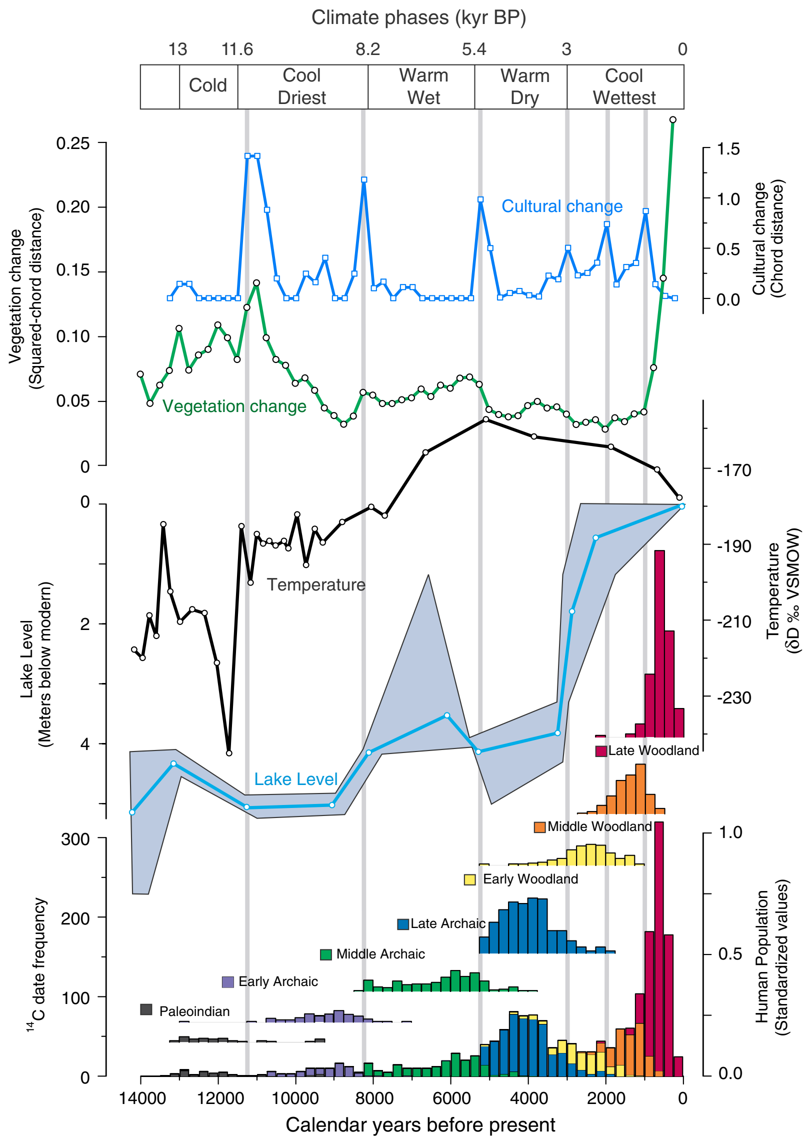

Fig. 2. Associations between archaeological, climate, and vegetation records for the study region from initial settlement (13,500 yr BP) to European contact (500 yr BP). A stacked temporal frequency distribution of archaeological radiocarbon dates (bottom) provides information on the timing of cultural transitions and human population fluctuations. Lake-level (24) and temperature (23) reconstructions for the region provide a record of late glacial and Holocene climate. The mean of between-sample SCD values from the highest quality pollen records in the study region provide a measure of vegetation change through time. The CD between adjacent bins of archaeological radiocarbon dates provides a measure of the timing and rate of cultural change. Climate phases and transitions derived from paleoenvironmental data are based on Shuman et al. (7). Gray vertical lines denote cultural transitions defined from the frequency of archaeological ^{14}C dates.

expanded further north from the southern portion of the study region, while spruce (*Picea*) expanded across the northern part at the expense of other deciduous taxa (e.g., *Quercus*, *Carya*, and *Fagus*). Relative changes in population size occur at each environmental-cultural transition, with the population reconstruction corrected for taphonomic bias amplifying demographic changes in the Paleoindian and Archaic cultural periods. The close correspondence between changes in vegetation and climate, cultural transitions, and population levels suggests that environmental change greatly influenced the timing of cultural and demographic change in the northeast, at least until the adoption of maize agriculture around 1.0 kyr BP.

Several preagricultural periods of cultural and demographic change correspond with major and well documented shifts in climate and ecosystems. For example, the end of the Younger Dryas (~11.6 kyr BP) coincides with the Paleoindian-Archaic transition and the replacement of an open spruce-parkland with a more closed forest consisting mainly of oak (*Quercus*) and pine (*Pinus*) (19). A major shift in climate following the collapse of the Laurentide Ice Sheet at 8.2 kyr BP (44) resulted in a major change of moisture availability (12, 42) and the expansion of hemlock (*Tsuga*) and beech (*Fagus*) and the Early-Middle Archaic transition. A decline in hemlock (*Tsuga*) at 5.4 kyr BP (45) occurred at the same time as the Middle-Late Archaic transition and population increase. Although this transition has been associated with a pathogenic outbreak that greatly impacted hemlock (46), a reevaluation of the paleocological data suggests the effects of the pathogen may have been exacerbated by drier climatic conditions (7, 47). The Late Archaic is also the period during which mast-producing trees (*Quercus* and *Carya*), an important caloric source for humans and animals, reached their maximum abundance (Fig. 3). A previously identified population decline (21, 36–38) at the Archaic-Woodland transition (3.0 kyr BP) corresponds with gradual late-Holocene cooling and an increase in

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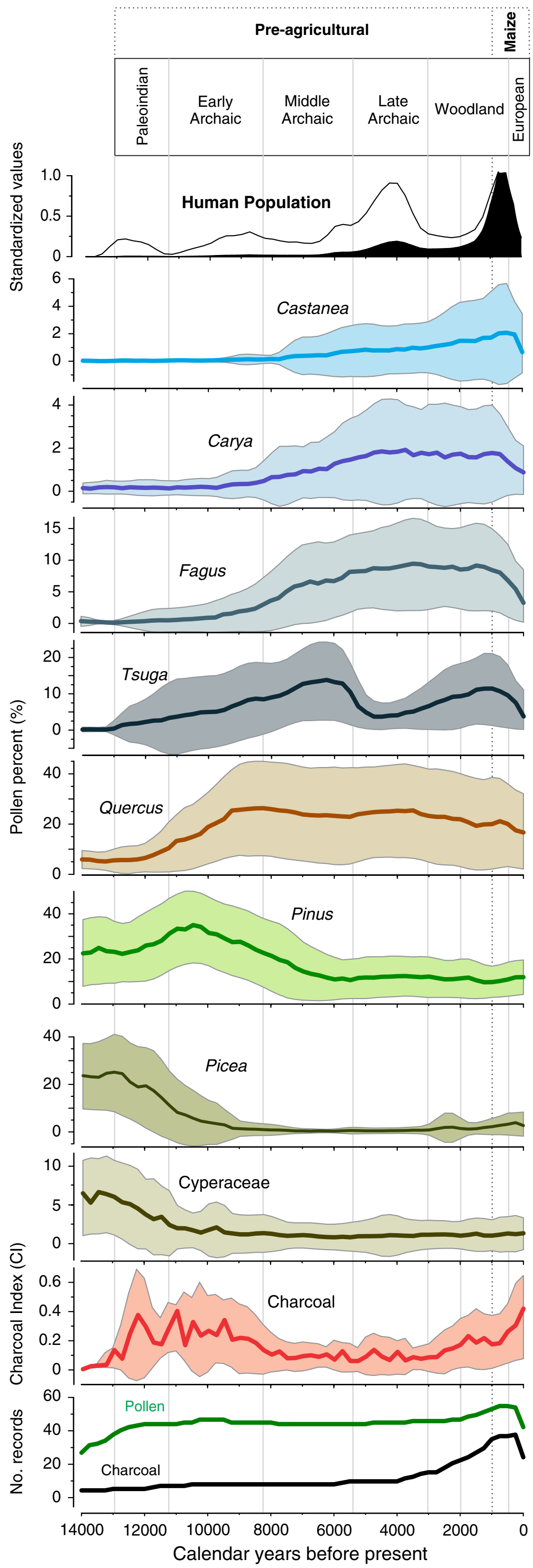

Fig. 3. Regional-scale pollen and charcoal records in relation to cultural periods and population size. The mean (line) and standard deviation (envelope) of pollen and charcoal records at 250-year intervals are shown. Charcoal records were rescaled between 0-1 to produce a CI. Solid gray vertical lines denote cultural transitions and dashed line indicates the approximate beginning of maize agriculture in the region (39). Changes in regional human population size, also rescaled from 0-1, were estimated from radiocarbon data (silhouette); this reconstruction was also corrected for taphonomic bias (line) using the empirical model developed by Surovell et al. (30).

lake level, driven by an increase in winter precipitation (i.e., deeper snowpack) (23, 24, 41).

More recent cultural and demographic changes are not as easily associated with major climate transitions. For example, the most significant increase in population occurred during the Late Woodland (1.0–0.5 kyr BP). This period is defined by the adoption of maize agriculture, a technology that would have facilitated population growth by increasing the amount of food energy available. Although agricultural production is related to climate, the relatively short length of the Late Woodland period combined with the coarse temporal resolution of many of the records used in this study makes it difficult to discern human-environment associations during this time. Higher-resolution paleoenvironmental studies from eastern North America have inferred changes in vegetation and climate during the late Holocene (48–50), and more detailed archaeological-environmental syntheses around this time would provide greater insight into the causes of the Archaic-Woodland population decline (21), the importance of climate change at the northern limits of maize agriculture (51), and the extent of human impact on the landscape (32, 52).

Given the complexity of human-climate interactions (3) and the multifaceted responses of ecosystems to past climate change (2, 9, 12) a unidirectional relationship from climatic change to a human response (5) may not always emerge. The resource base of prehistoric hunter-gatherers in a temperate region is controlled by the interaction of many ecological factors which are themselves associated in complex ways with environmental changes. Nevertheless, our work shows a close correspondence between periods of change in ecosystems and the archaeological record, and highlights the complex and multidirectional nature of human-climate relationships. The ecosystems from which prehistoric humans subsisted changed periodically in response to new climatic regimes, and as a result humans adjusted their toolkits accordingly by developing or adopting new or existing technologies. While human population numbers fluctuated in response to changes in the distribution and availability of food resources and site habitability, technological innovation, particularly maize agriculture, likely altered the dynamics of human-environment interaction. These findings provide new insights into the long-term interconnectedness of environmental change, human culture, and population in a temperate region, and convey a consolidated environmental framework from which further exploration of the factors that influenced North American prehistory can emerge.

Methods

Archaeological Data. Radiocarbon dates from the CARD (25) were extracted for the study region. Radiocarbon dates within the study region were not used in this analysis if they were not affiliated with prehistoric humans, if they were flagged as anomalous by the principal investigator, or if their cultural association was not specified. The remaining radiocarbon dates ($n = 1{,}887$) were converted to calendar years before present using the median probability provided by CALIB v.5.0.2 (53) and the IntCal04 dataset (54) or the Marine04 dataset for marine shells (55), with marine reservoir corrections following Dyke (56). To determine the timing and duration of cultural transitions, temporal frequency distributions of calibrated radiocarbon dates using 250-year bins were prepared. The CD (26) between adjacent bins was used as a metric for cultural change.

To reconstruct paleo-population, we employ a method similar to that of Peros et al. (31) in which the frequency of radiocarbon dates is used to estimate population through time. We fit a spline (df $= 25$) to the temporal frequency distribution to smooth high-frequency variability that may result from the calibration process. Because we are only interested in relative changes in population, we rescaled the smoothed series using a minimax transformation. This transformation rescales a time series between 0 and 1 by subtracting the minimum value found in the record from each value, and dividing by the total range of values:

$$x' = (x - x_{\min})/(x_{\max} - x_{\min}), \qquad [1]$$

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where x is the initial value, x' is the transformed value, and x_{min} and x_{max} are the minimum and maximum values in series, respectively.

To test the robustness of relative changes in our population reconstruction, we applied the empirical model proposed by Surovell et al. (30) to correct for taphonomic bias, described as:

$$n_{\mathrm{orig}} = n_{\mathrm{obv}}/(5.73 \times 10^6(2{,}176.4 + t)^{-1.39}), \qquad \textbf{[2]}$$

where n_{orig} is the original number of radiocarbon dates at time t, n_{obv} is the observed number of dates at time t, and t is the time elapsed since the initial deposition of the dated material. This corrected population reconstruction was rescaled using Eq. **1** and plotted alongside the uncorrected reconstruction.

Pollen Data. To examine changes in vegetation across the study region, all available pollen records ($n = 63$) were extracted from Neotoma v.1.0 (Table S1 and 57). All chronologies were converted to calibrated years before present by calibrating the radiocarbon dates (median probability from IntCal04; 54) which were used in the original chronology. Age-depth models were developed by linearly interpolating between the calibrated radiocarbon dates. All pollen counts were converted to a percent of the total terrestrial pollen sum, and taxa with a maximum percent <1% were grouped into broader categories. All pollen records were interpolated at 250-year intervals; this interval is slightly less than the mean sampling resolution (310 ± 220 yr sample^{-1}) to avoid aliasing during interpolation. To create a regional-scale composite pollen record, we calculated the mean and standard deviation for major taxa at each interpolated level.

To quantify the magnitude of vegetation change through time, we calculated the SCD of the interpolated fossil-pollen spectra (27 taxa) across 500-year intervals (22). SCDs provide a measure of dissimilarity between two pollen spectra (58), where a larger SCD indicates a more significant shift in vegetation composition (22). The identification of peaks in SCD time series is sensitive to the quality of the pollen records (e.g., chronological controls, sampling resolution), so based on these criteria we selected a subset of 26 high-quality pollen records (see Table S1) which had (*i*) a total record length of ≥10 kyr, and (*ii*) at least one chronological control (on average) every 3 kyr, and (*iii*) a mean sampling resolution ≤400 yrs sample^{-1}. We then calculated the mean SCD at 250-year intervals from this high-quality subset to summarize vegetation changes across the region; results of this analysis are similar if all records are used (Fig. S1).

Charcoal. To examine changes in fire regimes, we extracted all available charcoal records ($n = 9$) across the study region from the Global Charcoal Database [GCD; (59)]. Additional charcoal records were provided by the Harvard Forest ($n = 20$), our files ($n = 4$), or digitized from the original publication ($n = 7$) to create a network of 40 records which span the study region (Table S2). Because charcoal records were prepared and presented differently in their original publication (e.g., influx, percent, and ratio) we rescaled each record between 0 and 1 using a minimax transformation. Rescaled values were then interpolated at 250-year intervals. To develop a regional-scale CI we calculated the mean and standard deviation at each 250-year interval.

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