Wildfire responses to abrupt climate change in North America

J. R. Marlon[a,1], P. J. Bartlein[a], M. K. Walsh[a], S. P. Harrison[b], K. J. Brown[c,d], M. E. Edwards[e,f], P. E. Higuera[g], M. J. Power[h], R. S. Anderson[i], C. Briles[g], A. Brunelle[h], C. Carcaillet[j], M. Daniels[k], F. S. Hu[l], M. Lavoie[m], C. Long[n], T. Minckley[o], P. J. H. Richard[p], A. C. Scott[q], D. S. Shafer[r], W. Tinner[s], C. E. Umbanhowar, Jr.[t], and C. Whitlock[g]

[a]Department of Geography, University of Oregon, Eugene, OR 97403; [b]School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, United Kingdom; [c]Department of Quaternary Geology, Geological Survey, Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen, Denmark; [d]Royal British Columbia Museum, Victoria, BC, Canada V8W 9W2;[e]School of Geography, University of Southampton, Southampton SO17 1BJ, United Kingdom; [f]Alaska Quaternary Center, University of Alaska, Fairbanks, AK 99775; [g]Department of Earth Science, Montana State University, Bozeman, MT 59717; [h]Department of Geography, University of Utah, Salt Lake City, UT 84112; [i]Center for Sustainable Environments and [k]Ecological Restoration Institute, Northern Arizona University, Flagstaff, AZ 86011; [j]Centre for Bio-Archeology and Ecology (Unité Mixte de Recherche 5059, Centre National de la Recherche Scientifique) and Paleoenvironments and Chronoecology, Institut de Botanique, Université Montpellier 2, 163 Rue Broussonet, F-34090 Montpellier, France; [l]Departments of Plant Biology and Geology, University of Illinois at Urbana–Champaign, Urbana, IL 61801; [m]Département de Géographie et Centre d'Études Nordiques, Université Laval, Québec, QC, Canada G1V 0A6; [n]Department of Geography and Urban Planning, University of Wisconsin, Oshkosh, WI 54903; [o]Department of Botany, University of Wyoming, Laramie, WY 82071; [p]Département de Géographie, Université de Montréal, C. P. 6128 Centre-ville, Montréal, QC, Canada H3C 3J7; [q]Department of Earth Sciences, Royal Holloway, University of London, Egham, Surrey TW20 0EX, United Kingdom; [r]Division of Hydrologic Sciences, Desert Research Institute, Nevada System of Higher Education, 755 East Flamingo Road, Las Vegas, NV 89119; [s]Institute of Plant Sciences and Oeschger Centre for Climate Change Research, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland; and [t]Biology and Environmental Studies, St. Olaf College, Northfield, MN 55057

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It is widely accepted, based on data from the last few decades and on model simulations, that anthropogenic climate change will cause increased fire activity. However, less attention has been paid to the relationship between abrupt climate changes and heightened fire activity in the paleorecord. We use 35 charcoal and pollen records to assess how fire regimes in North America changed during the last glacial–interglacial transition (15 to 10 ka), a time of large and rapid climate changes. We also test the hypothesis that a comet impact initiated continental-scale wildfires at 12.9 ka; the data do not support this idea, nor are continent-wide fires indicated at any time during deglaciation. There are, however, clear links between large climate changes and fire activity. Biomass burning gradually increased from the glacial period to the beginning of the Younger Dryas. Although there are changes in biomass burning during the Younger Dryas, there is no systematic trend. There is a further increase in biomass burning after the Younger Dryas. Intervals of rapid climate change at 13.9, 13.2, and 11.7 ka are marked by large increases in fire activity. The timing of changes in fire is not coincident with changes in human population density or the timing of the extinction of the megafauna. Although these factors could have contributed to fire-regime changes at individual sites or at specific times, the charcoal data indicate an important role for climate, and particularly rapid climate change, in determining broad-scale levels of fire activity.

biomass burning | charcoal | comet | Younger Dryas

It is generally asserted that anthropogenic climate change will lead to widespread and more frequent fires (1, 2). Data from western North America in recent decades are consistent with this; they show that increases in the frequency of wildfire and the duration of the fire season are linked to increased spring and summer temperatures and earlier spring snowmelt (3). Changes in the pattern of precipitation are likewise affecting fire activity (4), as is the development of high fuel loads associated with long-term fire suppression (5). The effects of climate variability on fuels and fire regimes on multiple time scales have received much attention (6–8), and some research has linked shifts in fire regimes at individual sites to rapid climate changes (9). However, the broad-scale response of wildfires to large, abrupt climate changes in the past has received little attention (10, 11). One period of particular interest is the last glacial–interglacial transition (LGIT, 15–10 ka), when large and sometimes abrupt (i.e., decades to centuries) changes in climate and biota occurred in many parts of North America. In some regions, environmental changes at the beginning and end of the Younger Dryas chronozone (YDC) (12.9–11.7 ka) (12), in particular, were larger than those at any subsequent time (13). Such changes are similar in terms of the magnitude and rate of change to those projected for the future (14–16) and thus provide an opportunity to examine the response of fire regimes to rapidly changing environmental conditions in a variety of settings.

Investigating wildfire activity during the LGIT also allows us to test the recent proposal that a catastrophic extraterrestrial impact event at ≈12.9 ka had "continent-wide effects, especially biomass burning" (17). Firestone *et al.* (17) proposed that a comet exploded over the Laurentide ice sheet, producing a shock wave that would have traveled across North America at hundreds of kilometers per hour, and if multiple large airbursts occurred, could have ignited many thousands of square kilometers. Firestone *et al.* (17) also hypothesized that the event triggered global cooling, and that extreme wildfires destroyed forests and grasslands and produced charcoal, soot, toxic fumes and ash. These impacts, in turn, ostensibly limited the food supplies of herbivores, contributing to the extinction of North American megafauna and forcing major adaptations of PaleoAmericans (17), although this latter point has been disputed (18).

Even without invoking catastrophic events such as a comet impact, there are still reasons to expect a broad-scale response of fire activity in North America to the abrupt climate changes during the LGIT (19–21). At the beginning of the YDC (12.9 ka), North Atlantic meridional overturning slowed or shut down (21, 22). This led to abrupt cooling in the circum-North Atlantic region and general changes in atmospheric circulation around North America (23–25). Because atmospheric circulation affects temperature, precipitation and the position of storm tracks (26,

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[1]To whom correspondence should be addressed. E-mail: jmarlon@uoregon.edu.

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27), the particularly abrupt onset of the YDC was registered across the continent. A large, rapid climate reversal occurred in regions adjacent to the North Atlantic, whereas more distant regions registered changes in the progress of the LGIT (19, 28, 29). Other abrupt climate transitions focused on the North Atlantic, such as the onset of the Bølling–Allerød interval (14.7 ka), or short climatic oscillations, such as the intra-Allerød cold period (IACP) (≈13.2 ka), may also have had continent-wide impacts on climate.

Large-amplitude, rapid climate change affects fire regimes directly by altering the patterns of ignition and fire weather (30) and indirectly through vegetation composition (19, 31, 32), a major determinant of landscape flammability (33). The nature of the changes in ignition, fire weather, and vegetation composition will not be homogenous at a regional scale, but any rapid climate change, whatever its direction, imposes stress on an ecosystem and can trigger some change in the fire regime. Stress would result in increased mortality of the woody vegetation and a buildup of fuel, for example, as a result of pest outbreaks or physiological intolerance of new climate extremes (50). The rate at which such factors affect the fire regime varies, so a broad-scale change in fire activity would not necessarily exhibit absolute synchroneity, but some change should still be evident at most sites.

Charcoal and pollen from 35 lake-sediment records across North America [see supporting information (SI) Fig. S1 and Table S1] were used to assess changes in fire activity (defined here as biomass burned and fire frequency) and woody biomass during the LGIT. Variations in charcoal abundance or influx (particles/cm^2/yr) provide a record of past trends in biomass burning (34–37). Fifteen high-resolution macroscopic charcoal records (i.e., <50 years per sample and particles >100 μm) were further analyzed to reconstruct past fire episodes (defined as 1 or more fires occurring during the time spanned by a charcoal peak) (36, 38) and charcoal peak magnitude, an assumed metric of fire size, severity, or proximity (39) (*SI Methods*). The proportion of arboreal pollen (AP) in the lake sediments, which reflects the abundance of tree and shrub taxa on the landscape, was used to estimate the levels of woody biomass in the vegetation at the sites. AP can overestimate tree cover and mask shifts in trees and shrubs (40), so we consider it only a general indicator of available woody fuels. Records of charcoal influx, peak frequency, and AP were used to document trends in biomass burning (35, 36), fire-episode frequency (hereafter termed fire frequency), and woody fuel levels. These trends were compared with ice-core records of CO_2 (41) and $\delta^{18}O$ (21), the latter clearly illustrating abrupt climate changes, to explain the broad-scale changes in fire activity.

Results and Discussion

Trends in Fire Regimes and Woody Fuels. The general trend of charcoal influx across all sites (as represented by a 3-segment linear regression, Fig. 1*C*) indicates a significant ($P < 0.01$) increase in biomass burning until the beginning of the YDC, no overall change during the YDC, and then a further increase in biomass burning thereafter ($P < 0.01$). A local regression curve, which does not assume a specific form for the trend, displays a similar pattern. The bootstrap confidence intervals around charcoal influx indicate that these trends are not induced by any particular record. Inspection of the records (Fig. 2 and Fig. S2), however, shows that there can be different responses at individual sites reflecting modulation of the regional-scale response by local factors. For example, whereas sites 4–9 in southern British Columbia (BC) all show increasing biomass burning from 15 to 10 ka, spatial patterns are complex in the Pacific Northwest, Sierra Nevada, and Northern U.S. Rocky Mountains (NRM). The 3 sites in Alaska (AK) show increasing burning during the Bølling–Allerød and stable levels during the YDC, but trends are variable after the YDC. Almost no spatial coherence is evident in the Southwest, Midwest, and East, although these regions have limited data. Thus, whereas the composite record strongly indicates broad-scale trends in biomass burning, heterogeneity is expected and apparent at local to regional scales.

The overall trend in fire frequency increases during the Bølling–Allerød (Fig. 1*D*, Fig. S3) and has no discernable trend thereafter. Some regions show coherent patterns in fire frequency, including AK (sites 1 and 2), the Pacific Northwest (sites 11, 13, and 14), and the NRM (sites 21–23, and 25) (Fig. S3), although the nature of the changes naturally differ between regions. Fire frequency is most variable after 11.7 ka; only sites 21 and 29 show little or no change after that time. In general, peaks in fire frequency tend to match local maxima in biomass burning (e.g., at 13.9, 13.1, 12.3, and 11.7 ka).

There are no empirical studies that link the absolute size of charcoal peaks to a specific fire characteristic, such as area burned or severity, so the peak magnitudes must be interpreted with caution (Fig. S3). However, in previous research, unusually large peaks have been linked to extreme fire years in the historical record when large areas burned at the regional scale (42, 43). For example, fires in 1910 that burned >400,000 ha in the NRM comprised the largest peak of the last 120 years at site 20 (42). Consequently, peak-magnitude data suggest that many large fire episodes occurred between 15 and 10 ka, and large or severe fire episodes were more likely after the end of the YDC than before it, as for example in the Pacific Northwest (sites 11–13), the NRM (sites 20, 23–25), and the Southwest (site 27) (Fig. S3). Fire frequency was also high at most of these sites after the YDC.

The woody biomass trend increases during the Bølling–Allerød, is stable during the YDC, and decreases thereafter (Fig. 1*E*). Trends at individual sites again vary regionally and with elevation (Fig. 2 and Fig. S2). Woody biomass declines at most sites in BC and increases in the Sierra Nevada, Southwest, and Northeast. Other regions show mixed patterns. Fire–fuel relationships among sites also show regional similarities. For example, trends in charcoal influx and AP are similar at mid- to high-elevation sites in the Pacific Northwest and NRM (sites 13, 15, 23, 24, and 25), where biomass burning and woody fuel levels generally increased together as open forests became more closed or alpine vegetation was replaced by parkland and then forest during the LGIT (8). In BC (i.e., at sites 5, 6, 7, 8, and 10), an inverse relationship in fire and fuels is apparent because biomass burning increased as closed mixed conifer forests were replaced by more open forests (44). Charcoal influx is often opposite to AP in the Midwest as well, where grass abundance (low woody biomass) is a good predictor of biomass burning (45). Important changes in woody fuel levels in AK are obscured in the AP trends, because AP does not show changes in the relative importance of shrubs versus trees. AP declines at site 3 at 11 ka, for example, despite a large increase in *Populus* at that time (63). Overall, the spatiotemporal variability in woody fuel levels and biomass burning makes it difficult to generalize about fire–climate–vegetation linkages at the continental scale, but the role of climate in determining both woody fuel levels and fire activity underpins the regional coherence in charcoal–AP relationships. The AP data do indicate that availability of woody fuels was not a limiting factor in determining levels of biomass burning at the beginning or end of the YDC.

Evidence for Continent-Wide Wildfires at 12.9 ka. Firestone *et al.* (17) hypothesized that a comet impact at 12.9 ka ± 50 y triggered continental-scale wildfires across NA. One specific example has been proposed by Kennett *et al.* (46). However, the well-documented rapid climate changes of this time alone may have triggered increased fire at a regional scale. To separate these effects, we compared the response of fire during intervals of rapid climate changes at the beginning and at the end of the YDC. Fire-episode events that occurred during the transitions

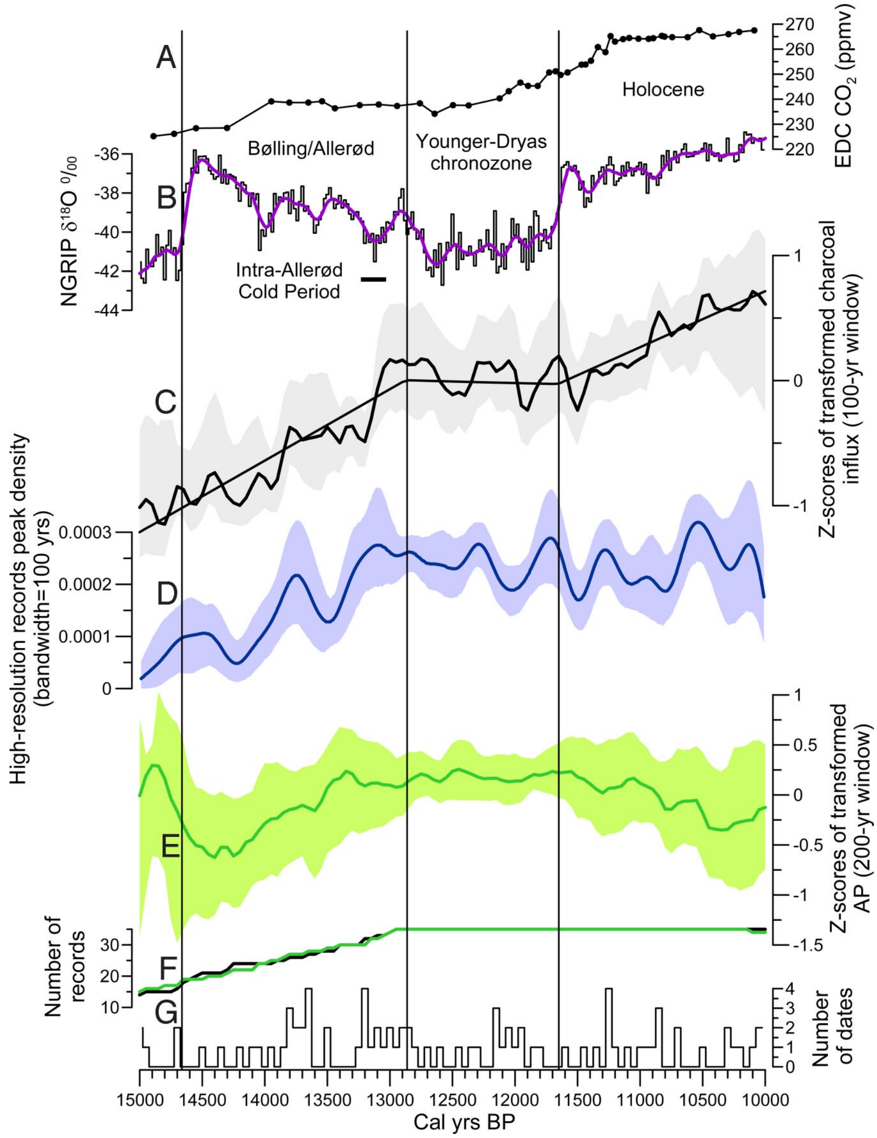

Fig. 1. Reconstructions of biomass burned, fire frequency, and woody biomass levels in North America. (*A*) The CO_2 ice-core record from Antarctica (41). (*B*) The NGRIP $\delta^{18}O_{ice}$ record, a proxy for North Atlantic temperatures (21). (*C*) Reconstruction of biomass burned based on 35 records; the straight lines are segmented regression curves, and the smooth curves are local-regression fitted values. (*D*) Reconstruction of fire frequency based on 15 high-resolution records, expressed as the density of peaks per site-year. (*E*) Trends in woody biomass based on 35 records. (*F*) Number of records contributing to the biomass burning (black) and woody biomass (green) trends. (*G*) Number of dates per 50-year interval in the 35 paleo records. Confidence intervals (95%) are based on bootstrap resampling of sites. Vertical lines mark the beginning (≈12.9 ka) and ending (≈11.7 ka) of the YDC.

into and out of the YDC were identified in both the high- and low-resolution records (see *Methods*) to determine whether fire episodes, regardless of magnitude, were more likely to occur (within ±50 y) at 12.9 ka than at 11.7 ka (Figs. 1*A* and 2). Because of high uncertainties in radiocarbon dating during the YDC, both 100- and 500-y window widths were used to identify fire episodes (Fig. 2). By using a 100-y window, 13 sites across the continent (Fig. 2) showed a peak (or increasing charcoal if no sample was within the window) at 12.9 ka. The peak was large (i.e., >90th percentile based on quantile regression) in the 9 low-resolution records, but it was not present in any of the 5 high-resolution records that registered a peak at 12.9 ka (±50 y) (Fig. S3), suggesting that the relatively high magnitude of fires at 12.9 in the low-resolution sites may be an artifact of the small number of samples in these records. The data also indicate that only 3 sites showed a peak only at 12.9 ka, whereas 12 sites showed a peak only at 11.7 ka, the abrupt end of the YDC (Fig. 2 and Figs. S1 and S3). Using a large 500-y window width greatly increased the number of sites recording fires ≈12.9 ka; however it also increased the number of fire episodes recorded at 11.7 ka (Fig. 2). It could be argued that poor dating control on some of the records prevented identification of fire episodes at 12.9 ka; however, when we limited our analysis to the 14 records with dates within ±300 years of 12.9 ka (Fig. 2), the results did not change. Peaks in charcoal influx were registered throughout the LGIT, particularly associated with abrupt climate changes, but there was no evidence of continent-wide wildfires at the beginning of the YDC.

Potential Controls on Fire Regimes and Woody Fuel Levels During the LGIT. The broad-scale trends in biomass burning, fire frequency and magnitude, and woody fuels during deglaciation are consistent with climate changes documented by ice cores, marine and lake sediments, speleothem, and other records from North America (21, 28, 47, 48). During the Bølling–Allerød, woody

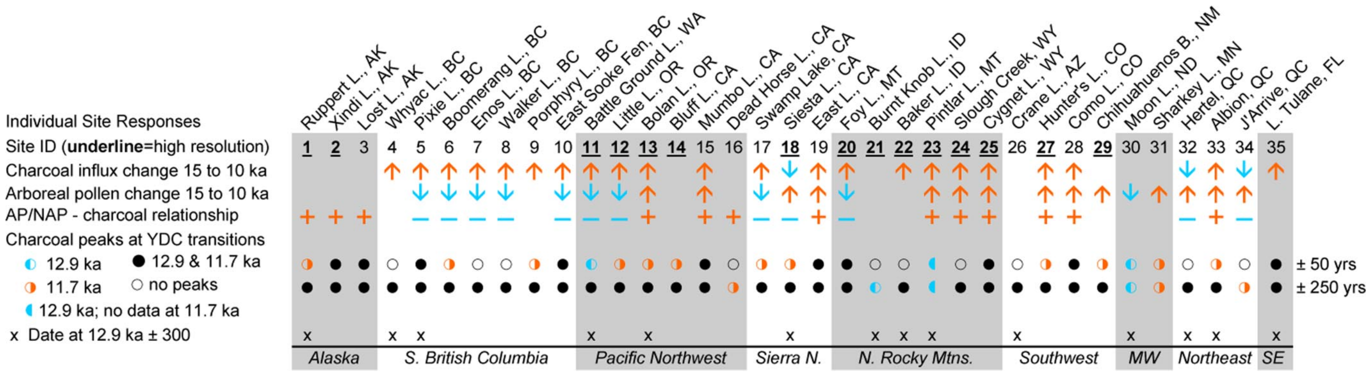

Fig. 2. Site summaries of changes in charcoal influx, arboreal pollen (AP), and charcoal–pollen relationships during the LGIT and of charcoal peaks at the beginning and end of the YDC. High-resolution site numbers are in bold type and underlined. Regions are identified by alternate shading. A ↑ (↓) indicates a general upward (downward) trend in charcoal influx. A + (−) indicates a positive (negative) relationship between charcoal and AP. Records that had a radiocarbon or tephra date within 300 years of 12.9 ka are marked by an x in the bottom row.

biomass, biomass burning, and fire frequency all increased (Fig. 1*E*), a likely consequence of warming and increased tree cover (40). A stepped increase in biomass burning is evident at 13.9 ka, coincident with a short period of warming and is matched by a peak in fire frequency.

A particularly steep increase in charcoal influx occurred at 13.2 ka (Fig. 1*C*); this is the largest and most rapid change in biomass burning during deglaciation. Burning was widespread but not continent wide (see site details in *SI Methods*). Furthermore, the change in fire regime is not unique: Several sites show similar peaks before the onset of the YDC, and many show an even larger peak at the end of the YDC. The widespread increase in fire activity (i.e., charcoal influx and peak frequency) at 13.2 ka appears ≈300 years before the hypothesized comet impact (17). Of the sites that do show fire activity at 13.2 ka, many are from regions distant from the proposed locus of the impact area over the Laurentide ice sheet, as well as from the proximal influence of the ice sheet on regional climates (e.g., in AK, the Southwest, Pacific Northwest, and the NRM). The timing and distribution of fire activity at 13.2 ka is consistent with the IACP—an abrupt short-term climate reversal recorded in the GISP $\delta^{18}O$ ice-core data (Fig. 1*B*). The IACP is associated with a rapid oscillation in North Atlantic temperatures that may have affected atmospheric circulation patterns across the continent (21, 23, 49) and increased the likelihood of drought as well as severe frost damage on some tree species (50). Any increase in vegetation mortality associated with such events would have added to the available fuels and facilitated an increase in fire.

During the YDC, ice-core $\delta^{18}O$ data indicate cool and variable temperatures in the North Atlantic region. Cooling is also evident in parts of western North America based on pollen and speleothem records (25, 28, 49), but climate patterns likely varied across the continent (27). The composite records (Fig. 1) show that biomass burning was higher but more variable than before 13.2 ka. Fire frequency and biomass burning had local maxima at ≈12.3 ka and at the end of the YDC (11.7 ka). Although there are fundamental and widespread changes in vegetation at the beginning (and end) of the YDC (19), the woody biomass trend shows little change during the YDC. This lack of change does not preclude change in specific regions e.g., Alaska (48) or at individual sites.

Biomass burning and fire frequency both decline at 11.7 ka but increase thereafter. Woody biomass, however, decreases from 11.7 to 10.0 ka. This contrast in behavior marks a shift in the relationship between fire and vegetation. Before 11.7 ka, woody biomass and fire activity generally change in parallel; after 11.7 ka, they change in opposite directions. Early-Holocene warming and enhanced seasonality facilitated the emergence of new vegetation communities and disturbance patterns (19, 32, 51). Low-elevation sites in the western US show the biggest changes, with declining woody biomass as forests became more open (44, 52) and more likely to burn (Fig. S2 and Fig. 2). High-elevation sites in the Pacific Northwest and NRM also show increasing fire activity but in association with increasing rather than decreasing woody fuel levels. New fire–fuel patterns also evolved in the Northeast after the YDC, with declines in biomass burning associated with increases in woody biomass.

Factors other than climate may have contributed to observed changes in fire regimes during the LGIT, including changes in atmospheric CO_2, the arrival of Clovis people between ≈13.4 and 12.8 ka (53), and the extinction of herbivorous megafauna (54). Changes in CO_2 affect vegetation productivity (55) and potentially fuel loads. Atmospheric CO_2 increased in stepwise fashion from the Last Glacial Maximum to the beginning of the Holocene (56) (Fig. 1*A*). The changes in woody biomass, fire frequency, and biomass burning are not coincident with changes in CO_2, although increasing CO_2 may have contributed to woody biomass production during the early part of the Bølling–Allerød. Clovis people appeared in North America between 13.4 and 12.8 ka, broadly coincident with the sharp increase in biomass burning at 13.2 ka, and then rapidly spread out across the continent (18). Paleoindians may have increased fire activity directly by setting more fires (57) or indirectly by reducing megafaunal populations. The decline in megafaunal populations, in turn, could have increased fuel loads and changed soil moisture regimes, both of which could have promoted fire (58, 59). There is some evidence for an association between megafaunal declines based on *Sporormiella* data and increased burning in the Northeast (58).

The 13.2 ka fire peak is registered at sites widely dispersed across the continent; it is not consistent with the progressive colonization of North America by Paleoindians. It also seems unlikely that people (or megafauna) would have caused an increase in burning across the full range of elevations represented by the sites and particularly at high-elevation sites (the fire peak is evident at 5 sites >2,000 m; see *SI Methods* and Table S1). Furthermore, most fire records show discrete peaks rather than permanent regime changes, as might be expected if humans or megafauna exerted a major control on fire regimes. It is possible, however, that the arrival of people and/or the extirpation of megafauna (18, 53, 54) played a role in permanently altering fire regimes at the sites that show a fundamental fire-regime shift prior to or at 13.2 ka. After 13.2 ka, fire-regime changes are not coincident with periods of increase in human populations. Thus, the spatial and temporal distribution of the fire signal point toward climate as the primary cause of increased fire activity at 13.2 ka.

In summary, fire records from North America show stepped increases in biomass burning during the LGIT. Abrupt climate changes are generally marked by a shift in the level of burning as well as an increase in the incidence of fires. No continent-wide fire response is observed at the beginning of the Younger Dryas chronozone, the time of the hypothesized comet impact. The results provide no evidence of synchronous continent-wide biomass burning at any time during the LGIT. The data indicate variability in the direction of changes in fire regimes among paleofire records, which may be due in part to noise and local variability (60), human activity, or megafaunal declines. The distribution of charcoal peaks across time and space, however, suggests that such patterns are more likely a result of spatially complex climate controls and/or vegetation changes. Although there is broad congruence between changes in climate, fire, and human populations at the beginning of the YDC, we find no convincing evidence that the observed changes in fire activity were caused solely by changes in human or herbivorous megafauna populations.

Methods

We used 30 lake-sediment records in North America from the Global Charcoal Database (GCD v. 1*†) and 5 records from authors that (*i*) were recording fire activity before, during, and after the YDC; (*ii*) had at least 5 data points and one date (radiocarbon or tephra) from 10 to 15 ka; and (*iii*) had pollen data from the same site. We did not include charcoal data from records that only sampled the beginning of the YDC because there is no baseline for analyzing changes in the fire regime with such data (46). We also excluded marine charcoal data (61) because there is no evidence that charcoal influx and peaks in influx in such records reflect recent fire activity from a consistent source region. Pollen data were obtained from authors or from the North American Pollen Database‡ (Table S1). We examined the chronologies for each record to ensure that the age–depth relationships were generally consistent throughout the LGIT and that no age reversals occurred during that interval. Under such conditions, age controls in lake-sediment records are sufficient to describe centennial-scale variations (see *SI Methods*).

For all analyses, charcoal concentration data (particles cm^{-3}) were converted to influx values (particles $cm^{-2}\ y^{-1}$) (see *SI Methods*). For the low-resolution records, millennial-scale (background) trends were identified by smoothing the data by using quantile regression (62). Any increase in charcoal influx above background within a defined interval (i.e., either ± 50 or ± 250 years) was considered a peak. High-resolution records were smoothed by using a decomposition technique (63) that separates peaks from background charcoal and allows the reconstruction of peak magnitude and fire frequency. Arboreal pollen proportions were obtained by dividing the sum of arboreal and shrub pollen percentages (AP) by the sum of the total terrestrial pollen percentages [AP/(AP + NAP)].

To display the general trends in the charcoal influx, the data were transformed to stabilize the variance and standardized to facilitate comparisons across a range of charcoal influx levels (37). To assess the significance in the trend, we fit a segmented linear regression model to these data, with breakpoints at the beginning and end of the YDC (see *SI Methods*). We also summarized the data by using ''lowess'' or local regression curves. Confidence intervals for the local regression curves were generated by a bootstrap approach in which individual records (not samples) were sampled with replacement over 1,000 replications. The approach reveals the sensitivity of the trends to the particular selection of charcoal and pollen records used here. Pollen data were also transformed (64) and summarized by using local regression curves. The peak frequency trends in the high-resolution records were summarized by a local-density (kernel smoothing) procedure.

*www.ncdc.noaa.gov/paleo/impd/gcd.html.

†www.bridge.bris.ac.uk/projects/QUEST_IGBP_Global_Palaeofire_WG/.

‡www.ncdc.noaa.gov/paleo/napd.html.

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