

# Climate and human influences on global biomass burning over the past two millennia

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Large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes. However, comparatively little is known about the patterns and driving forces of global fire activity before the twentieth century. Here we compile sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning for the past two millennia. We find that global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870. Global burning then declined abruptly after 1870. The early decline in biomass burning occurred in concert with a global cooling trend and despite a rise in the human population. We suggest the subsequent rise was linked to increasing human influences, such as population growth and land-use changes. Our compilation suggests that the final decline occurred despite increasing air temperatures and population. We attribute this reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management.

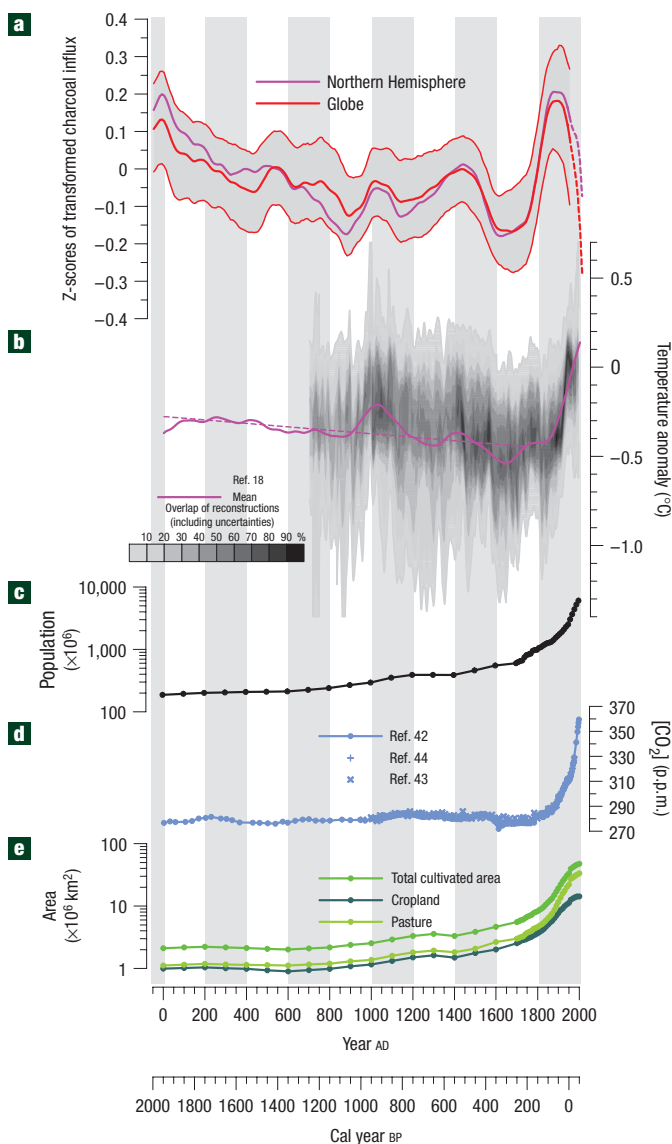
Fire is a key Earth system process affecting ecosystems, land-surface properties, the carbon cycle, atmospheric chemistry, aerosols and human activities. Humans manage fire intensively today, so it is easy to forget that fire is a natural process that has dominated the ecology of many terrestrial ecosystems throughout their history<sup>1–3</sup>. Empirical data on long-term changes in fire activity, particularly at broad spatial scales, however, are limited. Historical records<sup>4</sup>, remotely sensed data<sup>5</sup> and tree-ring data from the past few centuries<sup>6–8</sup> provide most of the information about the interactions of fire, climate, vegetation and people. Climate-change projections indicate that we will be moving quickly out of the range of the natural variability of the past few centuries. Charcoal records from lake sediments enable us to infer the impacts of climate changes and human activities on global biomass burning during periods when both have changed substantially. Although hundreds of such records have been developed during palaeoecological analyses<sup>9,10</sup>, until now no attempt has been made to analyse them for large-scale patterns and trends over the past 2,000 years.

We present global and regional reconstructions of biomass burned over the past 2,000 years (Figs 1 and 2) based on a global sedimentary charcoal data set (Fig. 3). We interpret temporal patterns in biomass burned, as indicated by changes in the input of charcoal to sediments, by comparison with independent reconstructions of human population and temperature changes,

and with climate simulations that mimic the broad features of reconstructed temperature changes.

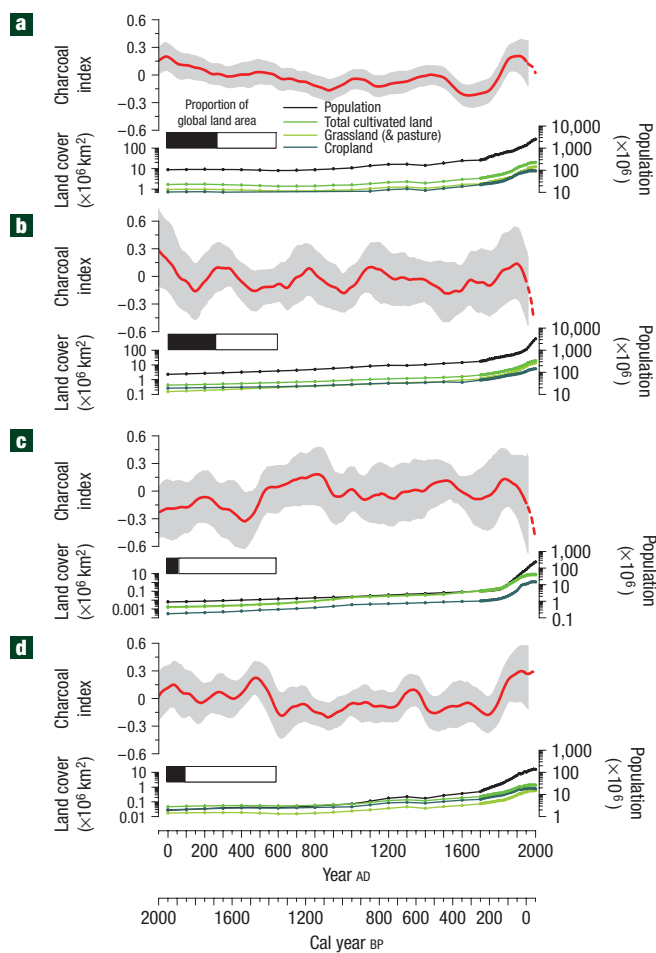
## CHARCOAL RECORDS OF BIOMASS BURNING

Charcoal accumulation in sediments has been shown<sup>11,12</sup> to reflect biomass burning within tens of kilometres of the sampling site. We developed regional and global composite stratigraphies based on 406 charcoal records from lake sediments and peats. Although there are geographic gaps, there is good coverage of climatic zones and of all the major biomes except grassland/dry shrubland (Fig. 3; Supplementary Information, Fig. S1), where low woody biomass limits charcoal production. Composite records were standardized and transformed (see Supplementary Information) to represent centennial-scale trends in charcoal accumulation rates or ‘influx’ (in units of quantity area<sup>-1</sup> yr<sup>-1</sup>) for the globe or a given region and to reveal the relative changes in biomass burned through time<sup>11</sup>. Interannual to decadal variations are not resolved, so these data do not record changes that might be attributable to higher-frequency climate variability or land management changes over the past few decades<sup>5,6</sup>. The strength of these data lies in their ability to provide a long-term observational record with site coverage that does not degrade substantially with increasing time from the present.



**Figure 1** Reconstructions of biomass burning, climate, population and land cover. **a**, Reconstruction of global (red line) and Northern Hemisphere (purple line) biomass burning with confidence intervals based on bootstrap resampling by site. A dashed line is used to represent increased uncertainty in late twentieth century changes in biomass burning. **b**, Reconstructions of Northern Hemisphere climate<sup>18</sup> with mean values (purple line) of available reconstructions, trend line (dotted line) for first part of record and overlap of uncertainty ranges of ten Northern Hemisphere temperature reconstructions after AD 700 (grey shading). **c**, World population from the HYDE 3.0 database<sup>30</sup>. **d**, Atmospheric CO<sub>2</sub> concentration<sup>42–44</sup>. **e**, Global agricultural land cover<sup>30</sup>.

The global sedimentary charcoal record (Fig. 1a) shows a long-term decline in biomass burning from AD 1 to about 1750, followed by a marked increase. A maximum, corresponding to the highest biomass-burning rate in the past two millennia, occurs around AD 1870. This maximum is followed by a sharp downturn in the composite record. At centennial scales, there is a local maximum in biomass burning at AD 1 that does not correspond to warmer temperatures, but the temperature reconstruction consists of only two records during this period. Biomass-burning minima

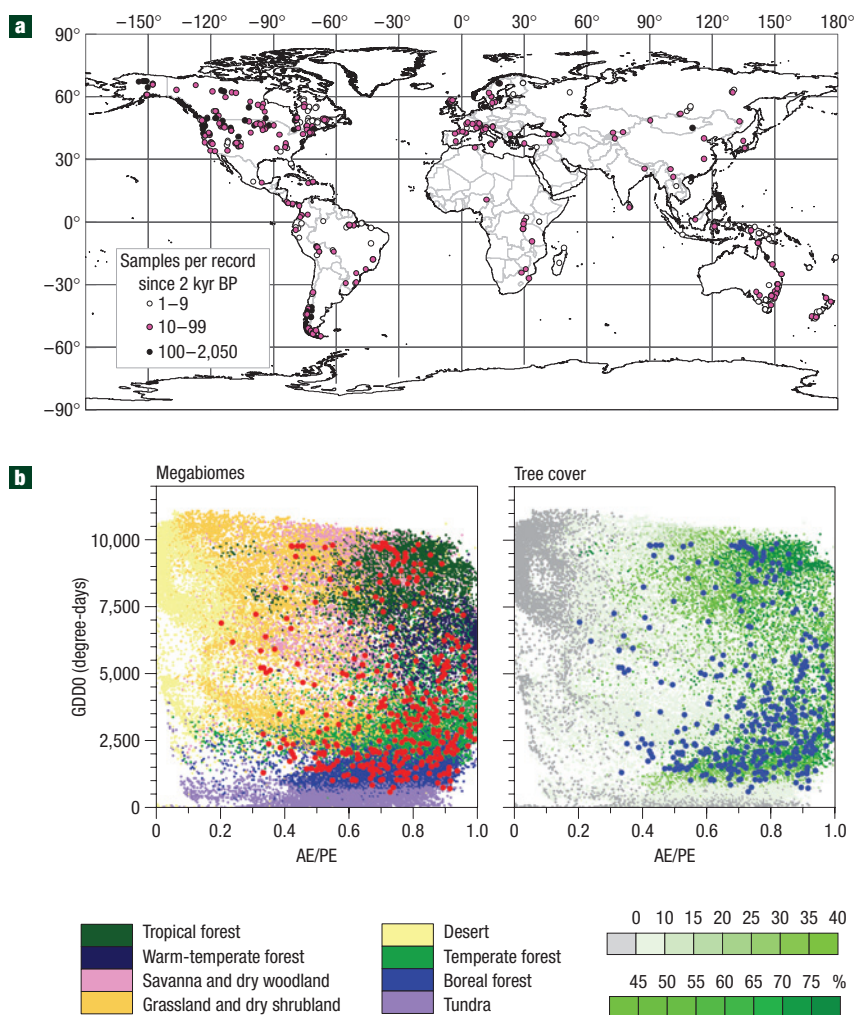


**Figure 2** Zonal changes in biomass burning, population and land cover. **a–d**, Changes in biomass burning (as in Fig. 1) with land-cover change<sup>30</sup>, and proportion of global ice-free land area, for northern extratropics (> 30° N) (**a**), tropics (30° N to 20° S) (**b**), southern extratropics (> 20° S) (**c**) and the northern high latitudes (> 55° N) (**d**). The composite records are based on at least 10 sites per region and thus should reveal the dominant patterns that reflect processes operating at large spatial scales (see Methods section).

occur about AD 400 and 900, and at 1700, during the ‘Little Ice Age’ (about 1400–1800). Our analyses (see Supplementary Information) show that these patterns in the global record are robust and unaffected by differences in record type or sampling resolution, changes in sedimentation rates and age model construction, or by the choice of statistical techniques used to construct the composite records.

The long-term decline in biomass burning before 1750 is most strongly expressed in the northern extratropics (Fig. 2), particularly in western North America and Asia (see Supplementary Information, Figs S11,S14). The long-term decline is also characteristic of records from Central and tropical South America (Fig. 4), although the decrease in biomass burning there occurs earlier (~1300) and persists longer than in other regions. In contrast, the tropics and southern extratropics show variable levels of biomass burning to ~1850, after which the records show a widespread decline in biomass burning (see Supplementary Information, Figs S8,S9).

Increased burning in the tropics and western United States during the past three decades has been widely reported<sup>5,6,13,14</sup>. The



**Figure 3** Distribution of sites in geographic, climate and vegetation space. **a**, Locations of charcoal records and number of samples over the past 2,000 years (see Methods section). Mean sampling density is one sample per 70 years. **b**, Distribution of records in bioclimate space showing locations plotted against growing degree-days above 0 °C (an index of effective warmth during the growing season) and the ratio of actual to equilibrium evapotranspiration (an index of effective moisture)<sup>45,46</sup>, with remotely sensed tree cover<sup>47</sup> and modelled biome<sup>48</sup> shown for comparison.

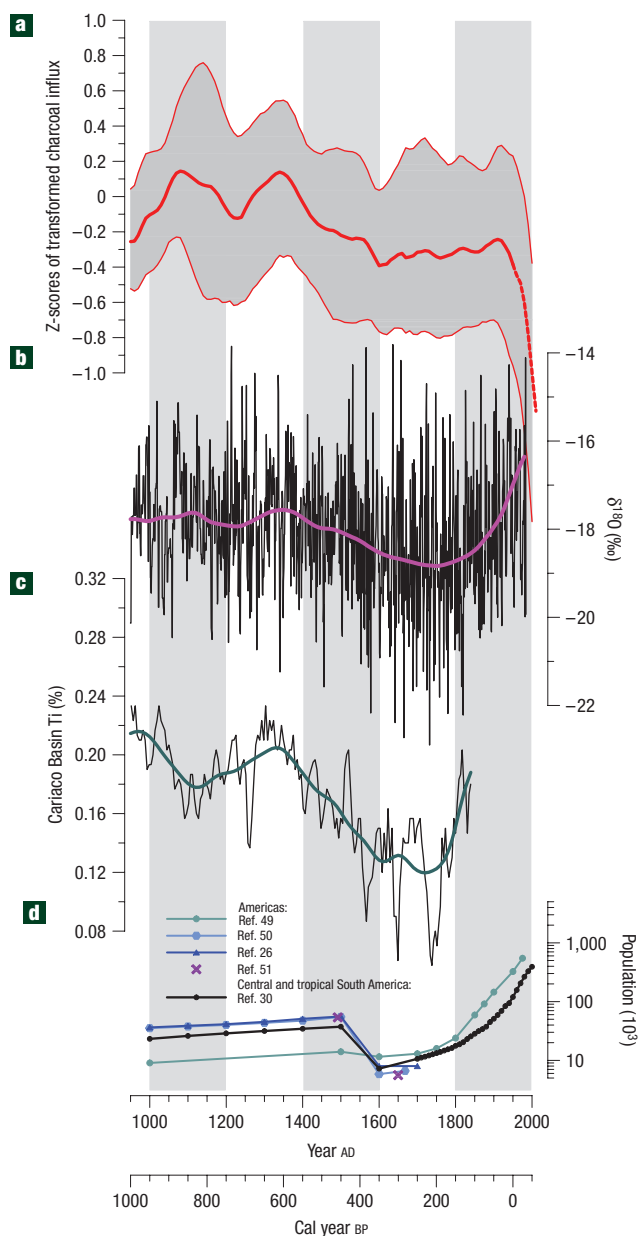
global charcoal record does not reflect this for a variety of reasons, including data coverage, methodological issues and chronological constraints in core-top sediments. For example, many of the charcoal records from the tropics do not span the most recent few decades. In addition, the geographic coverage of lakes and bogs in the tropics does not overlap well with the areas of most severe burning (Fig. 3). However, individual palaeofire records near areas of recent severe burning do show increasing charcoal levels towards present. For example, the only site in Kalimantan<sup>15</sup>, Indonesia, where extensive peat fires occurred, indicates high biomass burning in the past few decades. This is true in the western United States as well<sup>16,17</sup>. Additional data and regional syntheses are needed to resolve these patterns.

#### CLIMATE, POPULATION AND BIOMASS BURNING

Comparisons of global biomass burning with reconstructed and simulated climate conditions during the past two millennia show strong similarities until the Industrial Revolution, ~1750 (Fig. 1b, Supplementary Information, Fig. S5). Reconstructions

of Northern Hemisphere mean annual temperature from palaeoclimatic evidence<sup>18</sup> show a gradual cooling trend from 1 AD to 1750. Simulated temperatures show a similar decline<sup>19</sup> (see Supplementary Information, Fig. S5). Global and Northern Hemisphere reconstructed temperatures show local maxima around 1000 and 1400, corresponding to the local maxima in charcoal influx, and a pronounced decline from 1400 to 1700 (Fig. 1b).

Over the interval from 1 to 1750, world population and land-cover conversion to agriculture generally increased (Fig. 1c,e) with a very slight century-scale decrease related to the Black Death in Europe (about 1300 to 1400). Population growth and accompanying land-cover change therefore do not account for the apparent decrease in global biomass burning during the first phase of the composite record. Conversely, the correspondence between declining biomass burning and long-term cooling on hemispheric or global scales can be explained by the positive temperature dependence of fuel moisture (and hence flammability) and vegetation productivity (and hence fuel availability) in cooler climates.



**Figure 4** Comparison of biomass-burning reconstruction for Central and tropical South America with climate and population data. **a–c**, Biomass-burning reconstruction for Central and tropical South America (20° S to 30° N) for the past 1,000 years (**a**), with oxygen isotope data from the Quelccaya ice core<sup>31</sup> (**b**) and titanium concentration from a Cariaco Basin marine core<sup>32</sup> (**c**), both smoothed as the charcoal records. **d**, Population estimates for the Americas<sup>30</sup> derived from archaeological records<sup>26,27,30,49,50</sup>. The two crosses are estimates of the population of the Americas before and after European contact from ref. 51.

Biomass burning sharply increased around 1750; temperatures (Fig. 1b, Supplementary Information, Fig. S5), greenhouse-gas concentrations (Fig. 1d) and the rates of land-cover conversion and population growth (Fig. 1c,e) also began to increase. Increasing temperatures, rapidly increasing population and land-cover conversion and rising CO<sub>2</sub> (promoting an increase in biomass through CO<sub>2</sub> fertilization) could in principle all have contributed to the biomass-burning increase. However, after ~1870, a sharp

downturn in biomass burning occurs despite accelerated increases in temperature and CO<sub>2</sub>, strongly suggesting the involvement of human activity. The decades following 1870 coincide with the period of maximum expansion of population and agriculture (Figs 1c,e, and 2), so the biomass-burning decrease beginning then certainly cannot be explained by reduced human activity. Indeed, this has been the period of most rapid land-use change, characterized by large-scale conversion of native vegetation to croplands and the widespread introduction of domestic grazing animals such as cows and sheep<sup>20–22</sup>. We therefore suggest that the downturn can plausibly be explained as an effect of land-use change, resulting in landscape fragmentation and a generally less flammable landscape in many regions<sup>23</sup>. Active fire suppression since the early twentieth century has also presumably reduced total biomass burning in recent decades.

Records from the northern high-latitude regions (poleward of 55° N) show the general climate-induced decline and the post-1750 increase in biomass burning characteristic of the global signal but do not show the recent downturn in biomass burning (Fig. 2d, Supplementary Information, Fig. S10). This region has been much less affected by agricultural expansion than regions farther south (Fig. 2), and is influenced by high-latitude amplification of the global-warming signal leading to increased temperatures, dryness and greater fire activity<sup>24,25</sup>. The biomass-burning record from Europe (see Supplementary Information, Fig. S13), which has been subject to agricultural exploitation throughout the past two millennia, also fails to show the recent downturn, consistent with our explanation. The regions in which the downturn is most strongly expressed, including western North America (see Supplementary Information, Fig. S11), the tropics (Fig. 2b and Supplementary Information, Fig. S8) and Asia (see Supplementary Information, Fig. S14), are characterized by strong intensification of land management since the mid-nineteenth century. Although initial colonization may have been marked by an increased use of fire for land clearance, the expansion of intensive agriculture and forest management activities in these regions was associated with a reduced incidence of fire<sup>23</sup>.

The record of global biomass burning over the past 2,000 years can be divided into four distinct intervals: (1) 1–1750, when climate drove the long-term downward trend in biomass burning; (2) 1750 to late nineteenth century, when population-driven land-cover changes along with increases in global temperatures produced the sharp increase in biomass burning, (3) late nineteenth to mid-to-late twentieth century, which includes the striking decrease in biomass burning that accompanies the decrease in the rate of land-cover change; and (4) the past several decades, which is beyond the resolving power of the global charcoal record, when increased biomass burning is reported in many tropical regions.

## FIRE AND ATMOSPHERIC CHEMISTRY

Ferretti *et al.*<sup>26</sup> showed an ‘unexpected’ trend towards more negative  $\delta^{13}\text{CH}_4$  values from AD 1 to 1700 in the Law Dome ice-core record, and invoked changes in biomass burning to explain this trend. They noted the similarity of their  $\delta^{13}\text{CH}_4$  record both to the Law Dome record of atmospheric CO concentration and to proxy-based reconstructions of Northern Hemisphere temperatures. Because fire is a major source of CO and the main natural source of relatively <sup>13</sup>C-enriched CH<sub>4</sub>, Ferretti *et al.* postulated a declining trend in biomass burning, and attributed it to long-term cooling of the land surface. Houweling *et al.*<sup>27</sup> expressed scepticism about this possibility and proposed an alternative scenario involving changing wetland emissions, plant emissions and early rice cultivation to explain the  $\delta^{13}\text{CH}_4$  trend, avoiding the implication of Ferretti *et al.* of high biomass-burning levels in pre-industrial time. Our results

however provide strong empirical support for the decline in biomass burning since 1 AD proposed by Ferretti *et al.*<sup>26</sup>.

Ferretti *et al.* also noted an especially steep fall in  $\delta^{13}\text{C}_{\text{H}_4}$  from 1500 to 1700, and invoked population decline in the Americas as an extra factor to account for it. The global charcoal record also shows a sharp decrease from 1500 to 1700, but global population did not fall during this period (Fig. 1c). South American population declined after 1500 (refs 28,29) (Fig. 4), but a comparison of biomass burning, population estimates for the Americas<sup>30</sup> and climate data from Andean ice cores<sup>31</sup> and Cariaco Basin titanium concentrations<sup>32</sup>, which is a proxy for Atlantic Intertropical Convergence Zone latitude and hence tropical precipitation trends, suggests that the largest decrease in biomass burning there preceded the population decline and followed regional climate trends (Fig. 4). The similarities between the global charcoal record and climate proxies suggest a continuing climatic control to at least 1750.

The peak in global biomass burning at ~1870 corresponds to a peak in black carbon around 1900 observed in Greenland ice; however, McConnell *et al.*<sup>33</sup> attribute this to a peak in industrial emissions. The separation of biomass and fossil components of the black-carbon record, however, rests on the interpretation of the accompanying vanillic acid record as a proxy for global biomass burning<sup>34</sup> and, in part, on the choice of scaling factors between vanillic acid and black carbon.

Our results strongly suggest that climate change has been the main driver of global biomass burning for the past two millennia. The decline in biomass burning after 1870 is opposite to the expected effect of rising  $\text{CO}_2$  and rapid warming, but contemporaneous with an unprecedentedly high rate of population increase. This suggests that, during the industrial era, a major impact of human activities has been to reduce biomass burning through the large-scale expansion of intensive grazing and cropping with associated landscape fragmentation, and also active fire management. However, in regions less dominated by intensive land management, wildland fire has remained at high levels or increased as the climate has warmed. In the future, it is plausible that the main impact of human activity on burning will be through anthropogenic climate change<sup>35</sup>. To assess this possibility, it will be necessary to improve our understanding of palaeoecological records of fire and to develop reliable models of the fire regime. Such models should include human as well as natural ignitions, account for the effects of land use as well as climate and be tested using palaeoecological and ice-core data<sup>36</sup>.

## METHODS

Analyses are based on 406 sedimentary charcoal records from the Global Charcoal Database (GCD version 1) (ref. 10), plus supplementary data from members of the Global Palaeofire Working Group that will be incorporated into GCD version 2. Only records from lakes, bogs and small hollows were included in our analyses (see Supplementary Information).

We examined the distribution of data in terms of geographic, climatic and vegetation space to ensure that the data set could be considered a reasonable representation of global biomass burning. Given the unequal distribution of land between the Northern and Southern hemispheres, the charcoal data set is reasonably representative of the globe. Sixty-seven per cent of the sites are in the Northern Hemisphere, which represents ~74% of the ice-free land area. Nevertheless, some geographic regions are less well sampled than others (Fig. 3). To assess the global coverage of the GCD in terms of climate and vegetation, we plotted individual charcoal sites on top of climate, simulated biomes and tree cover data (Fig. 3). The charcoal sites provide a reasonably representative sampling of all the major climatic zones, and of forest biomes (see Supplementary Information, Fig. S1). Grassland/dry shrubland, savannas and deserts are under-represented (Fig. 3). There are few natural fires in desert regions; thus, this under-sampling is not important. The paucity of charcoal records from grassland and dry shrubland and from savanna reflects

the dominance of low-intensity ground fires in these regions and the smaller number of lakes present in dry regions. Such low-intensity fires do not consistently leave a charcoal record (although see ref. 37), and the total biomass burned is low compared with forests<sup>38</sup>. Thus, the under-sampling of these two vegetation types is unlikely to affect the composite global biomass-burning curve significantly.

The broad range of data types and charcoal quantification methods, as well as the skewed distribution of most charcoal records, motivated the transformation and standardization of the data before generating composite records. After testing the impact of several standardization and normalization techniques, we chose to use a modified version (see Supplementary Information) of the normalization and standardization procedure described by Power *et al.*<sup>10</sup>, which resulted in highly robust charcoal summarizations.

Charcoal data were normalized to stabilize the variance and standardized to make them comparable across a broad range of data types, sampling and processing methods. Records were smoothed by fitting lowess curves<sup>39</sup> to the data in a two-stage process that prevented records with the highest resolution from dominating the global signal, and that avoided interpolating data in the low-resolution records. This approach also minimizes the impact of the extreme values in sedimentary charcoal data, which enabled us to focus instead on the long-term trends in the data. Various sensitivity analyses were carried out to ensure that the composite records were robust to the use of influx versus concentration values, to the effects of changing sedimentation rates and to the differences in coverage among regions (see Supplementary Information).

We compared the reconstructed changes in fire regimes with climate proxy records of Northern Hemisphere temperature variations during the past 2,000 years<sup>18</sup>, and confirmed that these data series are statistically correlated during the interval from 1 to 1750 AD (see Supplementary Information). We used ten Northern Hemisphere temperature reconstructions based on multiple climate proxies. These reconstructions differ in (1) data type, (2) data origin (terrestrial and/or marine), (3) inclusion or exclusion of extratropical data sources, (4) the number of data points used in the final reconstructions, (5) temporal length, (6) seasonal specificity (summer versus mean annual temperature) and (7) statistical methods used to derive the reconstruction. Nevertheless, as shown in the Intergovernmental Panel on Climate Change Fourth Assessment<sup>18</sup>, the reconstructions show broad coherence over the past 1,300 years on centennial timescales, and the existence of multiple reconstructions makes it possible to derive confidence limits based on the degree of coherence between the available reconstructions. Here we use the mean of the ten available reconstructions, smoothed with a lowess curve. We also show the uncertainties in the reconstructions.

There have been some attempts to reconstruct historical changes in global mean temperatures<sup>40</sup>, and in Southern Hemisphere temperatures<sup>41</sup>. Given the paucity of data available from the Southern Hemisphere covering more than the past few decades, comparison of such data with the reconstructed fire histories is unwarranted. However, we did compare simulated global changes in warm-season temperatures and dry-season precipitation rates from the National Center for Atmospheric Research Climate System Model (see Supplementary Information, Fig. S5).

To explain the variations in global biomass burning, we also compared the charcoal data with population and land-cover data. World population and land-cover data were obtained from the HYDE 3.0 database<sup>30</sup> and were summarized using lowess curves in a manner similar to the charcoal and climate data. Confidence intervals (95%) are also shown (Fig. 1).

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#### Author contributions

S.P.H. proposed the idea of a 2000 year synthesis. J.R.M., M.J.P., P.J.B., F.J. and S.P.H. compiled the data. P.J.B. carried out the analyses with assistance from P.E.H., D.G.G. and J.R.M. All authors contributed to writing the paper.

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