Reconstructions of biomass burning from sediment charcoal records to improve data-model comparisons

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Abstract

The location, timing, spatial extent, and frequency of wildfires are changing rapidly in many parts of the world, producing substantial impacts on ecosystems, people, and potentially climate. Paleofire records based on charcoal accumulation in sediments enable modern changes in biomass burning to be considered in their long-term context. Paleofire records also provide insights into the causes and impacts of past wildfires and emissions when analyzed in conjunction with other paleoenvironmental data and with fire models. Here we present new 1000-year and 22,000-year trends and gridded biomass burning reconstructions based on the Global Charcoal Database version 3 (GCDv3), which includes 736 charcoal records (57 more than in version 2). The new gridded reconstructions reveal the spatial patterns underlying the temporal trends in the data, allowing insights into likely controls on biomass burning at regional to global scales. In the most recent few decades, biomass burning has sharply increased in both hemispheres, but especially in the north, where charcoal fluxes are now higher than at any other time during the past 22,000 years. We also discuss methodological issues relevant to data-model comparisons, and identify areas for future research. Spatially gridded versions of the global dataset from GCDv3 are provided to facilitate comparison with and validation of global fire simulations.

1. Introduction

Fire has long been recognized as an important ecological process because of its influence on species distributions and role in shaping other key ecosystem properties (Bond and Keeley 2005). Fire also affects regional and global biogeochemical and hydrologic cycles (Shakesby and Doerr 2006, van der Werf et al. 2006), geophysical processes (Morris and Moses 1987, DeBano 2000), and the climate system (Randerson et al. 2006, Ward et al. 2012, Saleh et al. 2014). Nevertheless, large gaps remain in our understanding of the interactions between fire and climate, despite an increasing need to manage fire and its emissions (Keywood et al. 2013).

Fire activity has been characterized at a wide range of spatial and temporal scales using field observations and historical data (e.g., Mouillot and Field 2005, Gavin et al. 2007), dendrochronological data (e.g., Falk et al. 2011), satellites (e.g., (e.g., Mouillot et al. 2014), ice cores (e.g., McConnell et al. 2007), and charcoal deposits in sediments, peat bogs, swamps, soils, and other environments (e.g., Whitlock and Bartlein 2004). Sedimentary records are unique among these data sources because of the broad temporal and spatial coverage they provide, which includes reconstructions of fire history at local to global spatial scales, and decadal to millennial temporal scales (e.g., Carcaillet et al. 2002, Brown 2005, Marlon et al. 2008, Iglesias and Whitlock 2014).

Results from paleofire research have helped lay a foundation for understanding the linkages among fire, climate, vegetation change, and human activities across a broad range of temporal and spatial scales. Fire-history data from sediment records highlight the importance of fire as a force of long-term global environmental change. Syntheses of data in the Global Charcoal Database (GCD), for example, reveal important variations in biomass burning during the last glacial period (Daniau et al. 2010), the last 21,000 years (Power et al. 2008, Daniau et al. 2012), and the last 2000 years (Marlon et al. 2008). With the increasing number of sites in the GCD, regional syntheses became possible, including long-term analyses of climate and human influences on burning in Australasia (Mooney et al. 2011, Williams et al. 2015), the Mediterranean (Colombaroli et al. 2009, Vanniere et al. 2011), the western US (Marlon et al. 2012), and the Americas more broadly (Whitlock et al. 2007, Power et al. 2012).

Here we briefly review the history of biomass burning reconstructions based on charcoal data, and introduce version 3 of the GCD (GCDv3, n=736), which improves on GCDv1 (Power et al. 2008) and GCDv2 (Daniau et al. 2012) by adding 57 records. We also present the GCDv3 in a new globally gridded format along with several broad-scale syntheses created using the open-source *paleofire* R package (Blarquez et al. 2014). The new gridded maps illustrate the spatial and temporal variability in fire activity over the past 22,000 years, highlighting recent departures from the long-term trends. The maps should be useful for modelers as well as others in the Earth sciences, particularly given the wide-ranging impacts of fire. Finally, we review several important limitations to charcoal-based records and identify promising future directions for the field.

2. Reconstructing Fire History with Sediment-Charcoal Data

Fire history research based on sediment-charcoal data has advanced rapidly in recent decades. Early analyses of sedimentary charcoal were typically conducted to support studies focused primarily on reconstructing past vegetation changes (Heusser 1995, Fuller et al. 1998, Haberle 1998, Behling 2001). A few early studies focused more directly on fire (Swain 1973, Burney 1987, Delcourt et al. 1998). In many cases, microscopic (<100μm) charcoal particles were tallied alongside pollen grains. Pollen and charcoal particles were converted to concentrations using the abundance of exotic markers of a known quantity added to each sample, and charcoal data were presented as ratios of the relative abundance of charcoal to pollen. Records were usually sampled at low temporal resolution due to the intensive labor and time required to analyze pollen. Samples represented broad spatial areas because microscopic charcoal can travel hundreds of kilometers (Clark 1988, Conedera and Tinner 2010). Variations in both pollen and charcoal abundances can influence the ratios, however, and so changes in pollen productivity could produce apparent changes in fire activity when none occurred. The differential production of charcoal from grass versus wood species could also alter charcoal/pollen ratios. Thus, early reconstructions based on microscopic charcoal-to-pollen ratios provided new and often useful insights, but the information was relatively coarse and potentially unreliable for inferring past regional fire activity.

Currently, most paleofire researchers analyze macroscopic charcoal particles (> 100μm) sampled contiguously from sediment cores to produce fire-history records that are more spatially and temporally precise (e.g., "local" histories at decadal time scales) compared to earlier methods. Macroscopic charcoal is typically quantified by simple particle counts or area measurements made using image analysis (Carcaillet et al. 2001b). However, particles can also be characterized using morphotypes. Two primary particle forms for non-arboreal charcoal exist: (1) cellular 'graminoid' (thin rectangular pieces; one cell layer thick with pores and visible vessels and cell wall separations) and (2) fibrous (collections or bundles of this filamentous charcoal clumped together). Arboreal charcoal can be characterized by three morphotypes: (1) dark (opaque, thick, solid, geometric in shape, some luster, and straight edges), (2) lattice (cross-hatched forming rectangular ladder-like structure with spaces between) and (3) branched (dendroidal, generally cylindrical with successively smaller jutting arms) (Jensen et al. 2007, Tweiten et al. 2009).

The analysis of high-resolution macroscopic charcoal records focuses on decomposing temporal variations in particle measurements into low and high frequency signals. The low frequency signals were originally termed "background" (Clark and Patterson 1997), and were thought to primarily reflect non-fire processes within and around a site unrelated to fire occurrence, largely due to sediment redeposition. The background component was therefore explicitly filtered out and disregarded in analyses. Subsequent research, however, demonstrated that background charcoal contains important information about the relative amount of biomass burned through time (Haberle and Ledru 2001, Carcaillet et al. 2002), particularly when combined across multiple records. Thus, the collection of many records into a single repository, including those of insufficient resolution for local fire history reconstructions, became an important prerequisite for reconstructing variations in biomass burning at regional to global spatial scales.

Recent studies demonstrate that background charcoal corresponds well with independent evidence of area and/or biomass burned both at landscape scales (Higuera et al. 2011, Kelly et al. 2013) and regionally (Marlon et al. 2012). However, it is not possible to quantify absolute area burned in the absence of a calibration dataset, and the influences of non-fire-related processes such as erosion or vegetation change on biomass burning reconstructions remain poorly understood (Aleman et al. 2013). These limitations highlight a need for more calibration studies to understand how charcoal production and taphonomy relates to the area and amount of biomass burned across a range of vegetation types and climate conditions.

Another recent advance in fire research is the reconstruction of fire frequency based on peaks in sedimentary charcoal records. Fire frequency is an important component of the fire regime; but such analyses require datasets with decadal resolution that are relatively uncommon in the GCD. In order to reconstruct fire frequency, records must be sampled contiguously, have high temporal resolution relative to the expected mean fire return intervals, and have sufficient particle counts in each sample to separate peaks from "background" (Higuera et al. 2007, Higuera et al. 2010). In addition, relatively stable sediment accumulation rates are ideal because peak frequencies will vary with changes in sedimentation rates (Carcaillet et al. 2001a, Higuera et al. 2010). For these reasons, our analyses of the GCDv3, which are focused on broad-scale changes in fire, are limited to the reconstruction of fire activity or biomass burning rather than to changes in fire frequencies.

Many other methodological approaches to long-term fire history reconstruction are developing from a variety of combustion products in ice cores (Kehrwald et al. 2013), including the analysis of ammonium (NH_4^+) (Savarino and Legrand 1998), methane (Fischer et al. 2008), carbon monoxide (CO) (Wang et al. 2010), black carbon (Han et al. 2012, Lehndorff et al. 2015), vanillic acid (McConnell et al. 2007), and levoglucosan (Zennaro et al. 2014), as indicators of past fire activity. Laboratory and analytical methods are also advancing through the use of image analysis for counting charcoal and charcoal morphotypes (Enache and Cumming 2006b, Jensen et al. 2007, Thevenon and Anselmetti 2007, Gu et al. 2008, Moos and Cumming 2012).

Overall, the wealth of methods and approaches to fire research are providing a broad range of insights into fire, both as an ecological process and as an integrated component of the Earth system. Yet much work remains to understand the impact of wildfires and biomass burning emissions on climate, and vice versa (Keywood et al. 2013). Research on human-fire interactions using paleorecords is developing rapidly (Colombaroli et al. 2008, Perry et al. 2012, McLauchlan et al. 2014, Munoz et al. 2014), but applying insights from paleofire research to fire management and emissions reduction plans remains comparatively limited (Whitlock et al. 2003) (Cyr et al. 2009). By compiling diverse types of paleofire data in a central location and developing open-source analysis tools to explore those data, research can advance more quickly on these topics.

3. The Global Charcoal Database (Version 3)

The structure and contents of earlier versions of the GCD are outlined in Power et al. (2010). Here we review the database design and focus primarily on detailing new entries in GCDv3. Version 3 extends the total number of sites in the GCD to 736. It includes 679 sites from version 2 (Daniau et al. 2012) as well as new sites from recent regional syntheses from Australasia (Mooney et al. 2011), the Americas (Marlon et al., Power 2012#3017), and Europe (Vanniere et al. 2011).

3.1 Geographical distribution

Sites in GCDv3 come from five continents and exhibit a wide variety of temporal resolutions (Fig. 1). Most of the sites (436) are located in the Northern Hemisphere, which is due partly to its larger land area and partly to sampling bias; 300 sites come from the Southern Hemisphere. About 20% of Southern Hemisphere sites (178) are located in the tropics; most are located in forested regions, although sites increasingly come from grasslands, shrublands, and woodlands as well. The geographical distribution of the data reflects locations where fire research has traditionally focused and the presence of suitable locations for paleoenvironmental indicators. Sites are distributed between elevations of -9 to 4060 masl, with more than half (58%) below 500 masl; some records come from marine cores. Previous analyses of the distribution of GCD sites in climate space showed that the dataset has relatively broad coverage with respect to global biomes and climate gradients (Daniau et al. 2012). Many newly published fire history records exist that can potentially be incorporated into subsequent versions of the GCD (Brown 2005, Han et al. 2012, Harley et al. 2012, Iglesias et al. 2012, Daniau et al. 2013, Kelly et al. 2013, Quintana-Krupinski et al. 2013, Tan and Huang 2013, Cordeiro et al. 2014, Courtney Mustaphi and Pisaric 2014, Dunnette et al. 2014, Higuera et al. 2014, Iglesias and Whitlock 2014, Neumann et al. 2014, Walsh et al. 2015) and many more are in development that will fill important spatial gaps where fire is key, including Africa and the tropics.

3.2. Type of records, data entry and database structure

The majority of sites in the database are associated with a single record in which charcoal was quantified using a single method. Yet, 96 sites in GCDv3 have more than one charcoal record, typically because charcoal was quantified using multiple metrics or laboratory techniques.

The charcoal data and metadata from the GCDv3 are stored in several formats. The primary complete dataset is stored in a Microsoft Access relational database with four main and 23 supporting tables. The four main tables hold 1) site metadata such as site name and type, geographical coordinates, elevation, catchment size, data source, and dating type; 2) sample data, including depths, volume, and estimated ages; 3) charcoal data, including quantity, units, and quantification method; and 4) date information, including depth and type of dates, laboratory identification numbers, material dated, and associated errors. Additional tables include information such as the contact (i.e., the corresponding data contributor) and publications associated with each record, index tables (e.g., linking sites to publications and contacts), and full descriptions of codes used in the main tables. The original database was not designed to be a long-term archival repository but rather a research database, and is therefore currently being replaced with a new structure. A significant percentage of the site metadata, such as geographic characteristics and methodological details, remains undocumented, however, and requires completion if scientific questions that draw on such data are to be addressed.

In addition to the database format, the GCDv3 dataset is now available as part of the *paleofire* R package (Blarquez et al. 2014) for use with the R computer programming environment (R Development Core Team 2013). The R package currently lacks some of the metadata that are contained in the full database, but the site metadata, charcoal data and modeled ages are available. The complete GCD in the form of a relational database can be downloaded from the

GPWG.org and from the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Information (NCEI) website (URL: http://www.ncdc.noaa.gov/paleo/impd/gcd.html).

Records in the GCD come from diverse environments (Appendix, Tables 1, 2). Most of the sites in the database (n=390) are lacustrine, which are primarily natural lakes that are often of glacial origin but may also be of tectonic, volcanic, or thermokarst origin. Other records (n=197) are from terrestrial environments, such as bogs, marshes, mires, and fens. A smaller number of records were obtained from soils (n=52), and from coastal/fluvial (n=35) or marine environments (n=12). Depending on the objective of a particular study, some site types will be more suitable than others. Marine records, for example, are among the longest in the database, making them suitable for analyses of biomass burning during the last glacial cycle (Daniau et al. 2010). On the other hand, marine sites have large catchment areas, making them suitable for regional but unsuitable for fine-scale analyses of fire activity.

3.3 Charcoal quantification methods

Important differences exist in the types of quantification methods within the database. Taken together, the 736 sites in GCDv3 have 134,269 charcoal samples with estimated ages. For most of the sites, charcoal is quantified as concentration (n=402) or influx (n=212); 105 are expressed in terms of charcoal to pollen ratios or similar measures of relative abundance; and the remaining 17 sites have uncommon units, such as cumulative probabilities or presence/absence of charcoal. Influx is the preferred unit of measurement for most biomass burning reconstructions because it accounts for variations in sedimentation rates over time, which can vary widely. If concentrations, depths, and ages exist, then influx can be calculated prior to analyses. Charcoal-to-pollen ratios, which were common in early analyses, are now relatively rare due to the ambiguities inherent in their interpretation (Conedera et al. 2009).

Different laboratory methods are used to quantify charcoal (Table 3). The majority of charcoal records included in the database (436 sites) are quantified using the pollen-slide method (POLS); 271 sites by sieving method (SIEV); 14 sites using image analysis (IMAG); and 15 sites were quantified using other methods such as hand picking charcoal from soil samples, gravimetric chemical assay (Winkler 1985), and charcoal separation by heavy liquid preparation. Several records included were based on the cumulative probability of charcoal in alluvial fan deposits (Pierce et al. 2004), and several records employed other chemical, thermal, or optical treatments or some combination of these methods to quantify black or elemental carbon (Verardo et al. 1990).

3.4. Chronology

Accurate chronological dating of sediments is essential to paleo research. The quantity and quality of dating controls in GCDv3 records vary widely (Fig. 2). Some records have numerous, high precision AMS radiocarbon dates, while others have few dates and poorly constrained chronologies with high or unknown uncertainties. Five common types of dates exist in the GCD, including AMS ^{14}C, conventional ^{14}C, ^{210}Pb, pollen-based correlations, and stratigraphy markers (e.g., tephras). Methods used to develop long record stratigraphies are based on $^{234}U/^{230}Th$ ratios or orbital tie points. There are no major spatial patterns in the type of dating methods used, aside from the terrestrial/marine distinction, and the use of tephras in areas with volcanic activity (e.g. western coasts of the Americas). Differences in tephra dates among several records in the Pacific Northwest that use an ash layer associated with the eruption of Mt. Mazama around 7700 years before present (yr BP, where present is 1950 CE) (Bacon 1983) as a date in their depth-age models appear to need revision, as the eruption date was subsequently dated in multiple studies to 7627± 150 cal yr BP (Hallett et al. 1997, Zdanowicz et al. 1999). In general, radiocarbon dates (AMS or conventional) are the most common dating method reported in the GCD. The ^{210}Pb dating is used for dating uppermost sediments (i.e., spanning the past 150 years) because ^{210}Pb has the shortest half-life of the radioisotopes. When the sediment-water interface is retrieved during coring and is undisturbed, that core top sample is typically assigned the year in which the core was obtained; this sample is marked as “stratigraphic” in the legend of Figure 2, and accounts for the stack of orange-colored dots around 0 cal yr B.P. (i.e., 1950 CE).

4. Charcoal Data Standardization and Compositing

4.1. From raw data to standardized accumulation rates

Charcoal measurements can be obtained in a variety of ways, but the most common techniques employ particle counts, area measurements, or relative abundances (Power et al. 2010). The effects of local site characteristics such as lake size, watershed topography, and vegetation type on absolute charcoal influx values (Marlon et al. 2006), along with the diversity of quantification methods in common use (Conedera et al. 2009), results in values that vary over 13 orders of magnitude (Power et al., 2010), making it impossible at this time to directly compare metrics of biomass burned among sites. Charcoal records therefore must be standardized in order to examine relative changes in charcoal influx over time (Power et al. 2010). Once standardized, charcoal influx anomalies can be averaged from multiple records, even if the records are based on different methods, creating a composite series in which maxima, minima, trends, and other features can be identified and interpreted.

The charcoal syntheses presented here were standardized using a protocol (Marlon et al. 2008, Power et al. 2010) that includes: (1) transforming non-influx values (e.g., concentration expressed as particles cm^{-3}) to influx values (e.g., particles cm^{-2} yr^{-1}) by dividing the concentration values by sample deposition times (yr cm^{-1}); (2) homogenizing the variance using the Box-Cox transformation; (3) rescaling the values using a minimax transformation to allow comparisons among sites; and (4) rescaling values once more to Z-scores using a base period of 21,000 to 200 yrs BP. The base period ends at 200 yrs BP because of the large human impacts on ignitions and suppression during the 19th and 20th centuries, which if included would obscure variability in charcoal accumulation rates prior to this period. However, the transformed records do extend into the 20th century (-50 yr BP, where CE 1950 = 0 BP). The most important step of the transformation is the homogenization of the variance (Fig. 3), which serves to make small-scale variations visible while also reducing the importance of high-value outliers.

4.2. Compositing multiple standardized time series

The purpose of compositing multiple charcoal records is to identify shared features and trends in fire history that may exist in a given spatial or temporal domain (e.g., North America during the Holocene). Given that individual charcoal time series are typically highly variable, averaging multiple records can provide insights into changes in fire history that only manifest at broad spatial scales (e.g., the impact of a changing climate within a given region). The variability in a record comes from a variety of factors, including the stochastic nature of lightning-caused fires (Bartlein et al. 2008), site-specific factors such as topography, soils, and local vegetation that influence fire history, the complexities of charcoal production, transportation, and deposition , sediment sampling, and processing methods (Gavin et al. 2006). As a result, composite curves that are based on few records also tend to show relatively high variability (Fig. 4, top panel). As more records are included in the composite curve, the curve becomes smoother and the confidence intervals around the mean narrow (Fig. 4, middle and bottom panels), because averaging among many sites necessarily reduces peaks and other variations evident in individual sites.

Although charcoal records are typically composited to examine trends in fire history in a given geographic domain, composites can also be used to explore additional research questions. For example, combining all available records in the GCD from islands might yield insights into patterns of fire use associated with human colonization (McWethy et al. 2013). Alternatively, contrasting fire history from lakes versus peat bogs or marine records might yield insights into methodological questions about charcoal transportation and deposition. Compositing all records available during a particular time period may also offer insights into globally influential events like potential comet impacts (or lack thereof) (Marlon et al. 2009), volcanic events (Marlon et al. 2012), or into the effects of abrupt climate changes on fire (Daniau et al. 2010).

Irrespective of the research question, the process for compositing records is the same in each case. Each record is standardized as described above, but only after it is resampled to a common temporal resolution (“presampled”) in order to standardize the influence of each record on the final composite curve. Presampling can be done using simple binning techniques, but a preferred method is to fit a lowess curve to the series at regularly-spaced target points (e.g., at 20-year intervals); the latter smooths over uncertainties in the sediment data as well as in the age model, whereas binning creates artificial cut-off points between samples that are in reality uncertain. After presampling, the records are standardized using a common base period, and a lowess curve is again fitted to the pooled, transformed data using a fixed window width (e.g. 1000 years to generate a record of nominally "millennial-scale" variability). Composite curves in this paper were produced following these methods as implemented in the R *paleofire* package (Blarquez et al. 2014).

Two issues that are not addressed by the above standardization and compositing approach relate to age uncertainties and spatial representativeness. While compositing many records can highlight regional trends in biomass burning, the different temporal uncertainty in individual records can make it difficult to accurately determine the precise timing of changes, or to explore questions about synchroneity, for example. The number of radiocarbon dates or other chronological constraints in a record provide information about age uncertainties, and these dates are available in the GCD. However, formally assessing every age-depth model for the records in the GCD is a non-trivial task, and should ideally be undertaken with the researchers who produced each record. Smoothing and gridding data accounts for age uncertainty in the records informally because the process only reveals trends and shifts in biomass burning that are robust across multiple records. More detailed analysis will always be needed however, to address research questions about the sequence of particular changes, or the precise timing of specific events. Similarly, the varying spatial representativeness of individual records are not accounted for in the compositing method described here. The myriad factors that affect charcoal production, transportation, and deposition in sediments means that there is no universal relationship between charcoal quantities and area burned that can be applied to all records. The conversion of all units to z-scores therefore allows the detection of trends in biomass burning over time but removes any information that may exist about the specific magnitude of area burned recorded by different records that make up a composite curve.

5. The Gridded Charcoal Dataset

To efficiently visualize GCDv3 and facilitate comparisons with model output, we present a spatially gridded version of GCDv3 using dot maps (Figs. 5, 6) alongside composite time-series curves (Figs. 5, 6). Vertical gray bars on the composite graphs indicate the time periods reflected in the maps. Each dot on the map represents a composite charcoal series constructed from all records within a fixed distance of the dot, such that the area represented by each dot is the same. However, the dots are positioned on a regular latitude/longitude grid, and the area of each grid cell varies by latitude (i.e., cells near the equator cover larger areas than those near the poles); spacing dots in this way maximizes the compatibility of the gridded charcoal dataset with other global data products. On such a grid, the absolute distance between dots (or nodes) decreases with distance from the equator. We defined the radius used to identify sites contributing to a dot as half the distance between diagonally adjacent dots at the equator (e.g., ~395 km for a 5° x 5° grid). This radius ensures that all GCD sites contribute to at least one dot, but also causes sites to influence multiple dots, especially at high latitudes where dots are relatively close together in terms of absolute distance (Fig. 7). Finally, our gridding approach prevents interpolation into areas that are not represented in the GCD, which is desirable given the great spatial heterogeneity of fire regimes.

Anomaly maps illustrate the gridding approach at six discrete intervals during the past 1000 years (Fig. 5, left panel) and 22,000 years (Figs. 6, left panel). Maps from each 100-year period during the past millennium and each 1000-year interval since the last glacial maximum (LGM) are provided in the Supplementary Information. The charcoal values are plotted on a 5° grid, and the dots are colored and sized to reflect the value and statistical significance, respectively, of the biomass burning anomalies (Fig. 5 and 6, right panels). The maps include data from three 100-year intervals (Fig. 5) and three 1000-year intervals (Fig. 6). Red dots on the maps indicate positive mean z-scores for sites in that location relative to their own long-term mean, which was calculated using a base period between 1000-200 years (Fig. 5) and 21,000-200 cal yr BP (Fig. 6). Blue dots on the map indicate negative mean z-scores. Because each dot shows changes in biomass burning relative to its own long-term average *for that location*, comparisons among dot colors on a single map (i.e., for a specific time) cannot be used to infer geographic patterns in biomass burning. For example, it is possible (or very likely, in fact) that for a given time period, a blue dot in Africa represents more biomass burning than a red dot in the Arctic. By contrast, changes in the color of a dot over time indicate meaningful temporal variability in the relative rate of biomass burning. A red dot in one time period that changes to a blue dot in the same location at another time period, for example, reflects an actual decrease in biomass burning over time at that location. One point of note is that it is possible in some cases for a recent time period to have less data than an older time period because samples from sediment cores are not regularly spaced in time, and core sections or tops are sometimes lost or destroyed in the field or during extraction. Most lake sediments provide continuous records, but soil and bog profiles often have hiatuses when sites dry out or peat is burned, and occasionally this happens in lake and marine sediments as well. Another reason that a site may have less data closer to present than in the distant past is when sedimentation rates decline over time. In this case, a section of the core the represents the most recent past may only have one or two samples, whereas sections of the same size further down core may contain many samples.

A diagnostic map of the gridded charcoal data shows the effects of summarizing all data within a constant specified distance from each dot (Fig. 7). Effectively, the gridding approach allows each site to influence an equivalent spatial area on the map. However, it is helpful to keep in mind that given the same number of sites at high latitudes and at the equator, the high-latitude sites will be more smoothed relative to those at the equator, which is evident in the diagnostic maps from different time periods. Another effect of using equal-area circles to construct the dot maps is that a circle can be centered quite far from shore but still encompass a site on land. Thus dots may represent terrestrial sites despite being plotted in the ocean on our maps (although in some cases they represent charcoal data actually collected from marine cores; see Figs. 1 and 7 for a comparison between location of sites and dots). Large (small) dots indicate biomass burning anomalies that are (not) significantly different from zero.

Global biomass burning during the past millennium (Fig. 5) shows a gradual long-term decline until the 17th century during the Little Ice Age (LIA, Mann et al. 2009), as observed in previous reconstructions (Marlon et al. 2008). This decline is more pronounced in the Northern than Southern Hemisphere (Fig. 5, top and bottom panels). After the LIA, global biomass burning increases gradually until the 19th century, then rapidly until the 20th century. Maximum levels of biomass burning in the Northern Hemisphere occur prior to maximum levels in the Southern Hemisphere, and both hemispheres experience sharp declines in biomass burning during the second half of the 20th century. The maps of biomass burning show the spatial heterogeneity underlying the composite curves. Biomass burning in central and eastern North America is highest from 1850-1950 CE, for example, whereas burning in western North America is highest during the most recent period (1950-2010 CE). In contrast, burning in western and southern Europe is generally higher 1000 years ago than it is in the past two centuries. Burning in southeast Asia is very high from 1850-1950 CE, and remains high in several locations for the period 1950-2010 CE where data are available.

The most recent upturn in fire activity globally, but particularly in the Northern Hemisphere reconstruction, is supported by a larger data set than GCDv1. Marlon et al. (2008) used GCDv1 to document the large decrease in biomass burning in the 20th century, but the reconstruction had large uncertainties in the trend over the last few decades. The addition of new records to versions 2 and 3 of the GCD, along with a finer-scale temporal focus now reveals the most recent increases in fire activity observed not only in the charcoal data, but also in several lines of independent evidence, including satellite and observational data (Giglio et al. 2013, Dennison et al. 2014).

Global biomass burning since the LGM, 21,000 years ago shows a long-term increase (Fig. 6), consistent with increasing temperatures, atmospheric CO_2 concentrations, and burnable biomass (Daniau et al. 2012, Martin Calvo et al. 2014). The reconstructions from GCDv3 (red lines) are very similar to those from GCDv2 (thin gray lines) for the globe, northern extratropics (>30° N latitude), tropics (>30° N latitude and <30° S latitude), and southern extratropics (<30° S latitude), with the exception of burning in the northern extratropics during the LGM, which registers as very low with the additional records in GCDv3 as compared with GCDv2 (Fig. 6). However, the northern and Southern Hemispheres show somewhat inverse patterns of burning during the Holocene, with fire increasing steadily in the northern extratropics during the Holocene, but declining in the early to mid-Holocene in the tropics and southern extratropics, before increasing in the late Holocene.

The gridded maps provide insight into the spatial variations in biomass burning since the LGM. Burning is generally higher in the past millennium than at any time since the LGM with the exception of central-western South America (Fig. 6), where some locations had higher than average burning during the mid-Holocene and below average burning in the past millennium. Levels of burning during the LGM in turn were generally lower than at later periods, with a few localized exceptions. Particularly high levels of biomass burning in the past millennium are observed in many locations in the Southern Hemisphere (e.g., New Zealand, central Africa, the Amazon, as well as in parts of the Northern Hemisphere (e.g., northeastern North America, southern California, and the southern Iberian Peninsula). The maps also reveal spatial coherence in regional biomass burning since the LGM, which likely reflects climate controls on fire in some cases and human controls on fire in others – the degree of coherence alone cannot distinguish causal mechanisms at this scale.

6. Using Charcoal Data in Model Validation

The development of the GCD is motivated by the need to understand the history of fire on Earth, and the linkages among fire, climate, vegetation, and human activities. As the GCD continues to expand, the expectation is that knowledge of fire histories will become more detailed. Analyzing charcoal-based fire history records with modern data from satellites (e.g. van der Werf et al. 2010, Giglio et al. 2013), fire scars (e.g. Girardin and Sauchyn 2008, Marlon et al. 2012), or historical records (e.g. Mouillot et al. 2006, Lamarque et al. 2010) is necessary to connect relative or qualitative variations in biomass burning from charcoal records (Aleman et al. 2013) to quantitative estimates of burned area or carbon emissions. To test hypotheses related to drivers of fire activity over longer time scales, however, research needs to integrate paleofire data with modeling approaches. As the spatial network of charcoal records become denser, there is increasing opportunity to identify locations where varying types of fire records overlap, and thus more opportunities to study changes in fire regimes that span multiple spatial and temporal scales.

Fire modeling efforts have advanced rapidly in the last decade (Arora and Boer 2005, Kloster et al. 2010, Kelley et al. 2014, Lasslop et al. 2014, Yue et al. 2014, Le Page et al. 2015), providing a better understanding of the varied impacts that fires have on humans, the biosphere, and the atmosphere (Harrison et al. 2010), as well as the mechanisms through which climate changes and human activities affect fire regimes. Simulations of fire activity using physically-based empirical relationships between flammability and its controlling variables, such as temperature and soil moisture, have helped identify the global drivers of modern burning (Arora and Boer 2005, Kloster et al. 2010, Pechony and Shindell 2010, Thonicke et al. 2010, Li et al. 2013, Pfeiffer et al. 2013). Fire modeling studies have also qualitatively compared paleofire trends with simulated global fire activity (Pechony and Shindell 2010, Kloster et al. 2012, Li et al. 2013), but quantitative testing of the physically based relationships that drive fire models – the mechanics of the models themselves – has only focused on modern climate conditions thus far. As a result, large gaps in knowledge exist about how fire, climate, vegetation, and humans interact under different climate conditions and over long timescales. Despite the fact that mechanistic global fire models remain largely untested outside modern climate parameters, these models are being used to predict the response of fires to ongoing climate change (Pechony and Shindell 2010, Kloster et al. 2012).

The fire modeling studies that have explicitly considered paleofire data provide examples of the challenges in comparing data and models. A study by Pechony and Shindell (2010) tested a global fire model scheme within a Global Climate Model simulation of the past millennium, for example, and found that at coarse spatial scales precipitation was the most important factor driving multi-centennial variations in fire activity in the model. However, the spatial patterns underlying these trends, and the extent to which finer-scale variations match paleofire evidence are unknown. Moreover, the finding that precipitation is more important than temperature in driving trends in fire activity globally contradicts analyses of paleodata (Daniau et al. 2012, Marlon et al. 2012, Power et al. 2012, Marlon et al. 2013), as well as satellite remote-sensing data (Bistinas et al. 2013), raising key questions about how temperature, precipitation, and their interactions affect variations in global biomass burning. Another fire modeling study (Brücher et al. 2014) compared model output to paleofire data from the GCD at regional scales from the mid-Holocene until the pre-industrial era in the 18th century. Kloster et al. (2015) go one step further to test the sensitivity of the same model to variations in fuel availability, fuel moisture, and wind speed, as well as their synergy for the same regions and time period.

The new approach to gridding GCD data presented here (and included in the *paleofire* R package) should help further paleofire data-model comparison studies. Whereas modeling studies to date have focused on global or regional trends, the growing number of records in the GCD allows for evaluation of model performance at finer spatial scales. Yet, site-specific variability is often high among charcoal records, and driver datasets for many global fire models may be of relatively coarse resolution. As a result it is ill-advised to compare model output to individual charcoal records. The gridded approach offers a flexible compromise that can be tuned in terms of spatial resolution depending on data availability, model driver datasets, and other factors. As an example, we present here a global map of simulated area burned using the CLIMBA model (Brücher et al. 2014), overlaid with gridded composite charcoal anomalies from the GCD. CLIMBA consists of the EMIC CLIMBER-2 (CLIMate and BiosphERe) (Petoukhov et al. 2000, Ganopolski et al. 2001) and JSBACH (Raddatz et al. 2007, Brovkin et al. 2009, Reick et al. 2013, Schneck et al. 2013), which is the land component of the Max Planck Institute Earth System Model (MPI-ESM, Giorgetta et al. 2013). Simulated area burned throughout the

Holocene was treated analogously to GCD data to produce a gridded map of area-burned anomalies at 6000 BP relative to present (i.e., 6,000 BP z-scores minus 0 BP z-scores).

Overall, data-model agreement is weak, with many grid cells disagreeing in terms of the sign of the anomaly estimated from the CLIMBA model versus GCD data (Fig. 8A). However, the exercise shows promise for some regions. In eastern North America, for example, site-level GCD data are difficult to reconcile with model output (Fig. 8B), but the gridded data product shows that both data and model generally agree that 6000 BP was a period of lower fire activity than present for the region (Fig. 8C). It is beyond the scope of this paper to evaluate the importance of this agreement, or the causes of data-model mismatch in other regions throughout the globe. Rather, we present the example as a proof-of-concept to motivate future studies. Important basic research topics to pursue include evaluation of spatiotemporal patterns in data-model comparisons, and a critical assessment of how uncertainties in both GCD data and fire model output contribute to the comparisons.

Using fire history data from the GCD to constrain fire model simulations, or conversely, using fire model simulations to understand variability in the fire history data from the GCD, requires careful consideration of the uncertainties associated with both data types. For paleofire records, quantifying and accounting for age uncertainties is a major concern, but progress is occurring on this front through the development of Bayesian age-modeling methods (Blaauw and Christen 2011, Goring et al. 2012). Uncertainties in charcoal records also come from the many natural processes related to charcoal production, transportation, and deposition, which interact to produce variability in charcoal accumulation over time. These processes are being studied through field experiments and calibration studies that will enable the development of higher quality fire-history reconstructions and a better understanding of uncertainties (Tinner et al. 2006, Higuera et al. 2011, Aleman et al. 2013). An important source of uncertainty in global fire models is the parameterization of the processes most directly controlling fire activity (e.g. human influence, climate influence, e.g.` Pechony and Shindell 2009, Pfeiffer et al. 2013). The sensitivity of simulated fire activity to such parameterizations needs to be tested to understand model uncertainty. Uncertainty in modern fire records arises from any extrapolation or interpretation beyond the available fire records (Mouillot et al. 2006) or to limits in the satellite data itself (Giglio et al. 2013). With detailed considerations of both the limits and uncertainties of all data sources and model parameterizations, connecting GCD to fire models represents the natural evolution in the effort to understand fires in the Earth system.

7. Future Recommendations

There are several research areas that, with further development, would facilitate rapid integration of fire data and a more comprehensive understanding of fire across spatiotemporal scales. Here we identify particular areas that would help address specific barriers to progress in paleofire research.

1. *Charcoal calibration studies in diverse environments*. A major limitation of biomass burning reconstructions is that they can only represent relative changes in burning from an arbitrary baseline. Calibration studies that relate variability in charcoal accumulation to fire regime characteristics from historical, fire-scar, satellite and other recent data

could allow additional information to be obtained from charcoal records. Given the complexities of charcoal production, transportation and deposition, it is unlikely that the absolute amount of biomass burning from a single paleofire time-series can be known, but with a better understanding of how charcoal abundances relate quantitatively to area burned or other fire-regime metrics, constraints on paleofire reconstructions can be established and integrated into models that can then provide quantitative estimates of variables like area burned and carbon emissions.

2. *Multiproxy studies of paleofire history*. Comparisons of paleofire data from multiple sources, such as charcoal, black carbon, and levoglucosan, are needed to better understand the roles of changes in area burned, fire frequency, fire type, and emissions in carbon cycling and the climate system. The combustion of vegetation produces a wide array of products, but many of these (e.g. ammonium and black carbon) are not specific to biomass combustion. As a result, developing methods for effectively comparing different types of data that imperfectly reflect fire emissions may improve our understanding of fire by providing convergent evidence for particular features, enhancing the temporal or spatial resolution of reconstructions, or refining our understanding of proxy source areas. By improving our ability to compare and integrate diverse sources of fire history information, we can more clearly identify and potentially offset the weaknesses of each particular data type.
3. *Data-model comparisons of paleofire history*. A primary motivation for the development of the GCD has been to create datasets for use in the development and validation of global fire models. Mechanistic and process-based simulations of fire activity at multiple spatiotemporal scales necessarily depend on an accurate understanding of the controls of biomass burning. The GCD can directly inform fire models on this point. Paleofire data-model comparisons are an emerging field in many respects. Spatiotemporal comparisons of GCD to fire model output will help move research forward into deeper analyses of how uncertainties associated with both the data and the models contribute to our collective understanding of paleofire history and implications for future model-based fire projections.
4. *Filling gaps in paleofire data*. Data collection from regions that are presently underrepresented in the GCD (e.g., Africa, the tropics, tundra and heathlands, and the boreal forests of Eurasia) is essential for learning how fire varied in response to climate forcings and human activity in the past, particularly in unique vegetation types and in biodiversity hotspots. Understanding fire-climate-vegetation interactions can supplement our knowledge from data-poor areas, but given the contingencies and legacies that land-use practices have on land cover and disturbance regimes (McLauchlan et al. 2014), having data from specific geographic locations is often necessary.
5. *Comparisons between charcoal data and other spatially-extensive datasets*. The development of large environmental datasets during the past few decades has opened up a new frontier in global change science. New research into the interactions among climate, vegetation, human activities and fire during the Holocene and in the more distant past can now be supported by large simulated and observed paleoclimate datasets, pollen datasets, and data on population growth, land-use, and land-cover change. Analyzing these datasets jointly with the GCD can provide insights into how changes in fire regimes affect rates of ecological change and biodiversity (Colombaroli et al. 2012), how fire

affects species migration (Edwards et al. 2015), or whether humans altered the climate system using fire in the early Holocene (Marlon et al. 2013).

In addition to the research needs above, several practices could aid in the development of high quality charcoal-based fire history reconstructions and facilitate data integration across labs, and therefore across different environmental contexts. The practices may be more useful to new researchers entering the field or establishing new labs.

1. *Continuous sampling of macroscopic charcoal data*. Although many researchers now sample lacustrine sediment continuously and quantify macroscopic charcoal, many continue to tally microscopic particles, or to sample discontinuously. Taking the latter approach may be necessary due to methodological, funding, or other constraints, but when it is possible, the former approach is more desirable. Research on charcoal particle size classes supports macroscopic particles (>100µm) as a reliable indicator of local (within 1-10+ kilometers of a study site) fire activity (Whitlock and Bartlein 2004), whereas smaller particles integrate biomass burning from a larger spatial domain (Conedera et al. 2009). If both macroscopic and microscopic particles can be tallied, they may provide complimentary evidence of past fire regime change. However, if only one particle size is collected, analysis of macroscopic charcoal usually provides a better signal for local fire reconstruction. While continuous sampling is more time and cost-intensive, it facilitates reconstructing event frequency, aligning multiple cores, detecting unique events, and examining rates of change.
2. *Separating woody and herbaceous charcoal*. In environments that may have had grasses as a fuel source, separate tallying of woody and herbaceous charcoal (e.g. Walsh et al. 2008) can be of great value (e.g. Daniau et al. 2013) in identifying temporal variability in fuel types. Additional charcoal morphotypes can be observed and classified as well (Enache and Cumming 2006a, Mustaphi and Pisaric 2014), but the application of these methods remains largely untested. In the meantime, separate tallies only of woody and herbaceous charcoal have already been shown to provide reliable information about fuel sources (e.g., Wooller et al. 2000, Walsh et al. 2008, Maezumi et al. 2015) and are recommended when possible.

3. *Data sharing and open-source code*. The importance of data sharing, and increasingly code sharing, is now widely recognized in the scientific community (Easterbrook 2014, Towards transparency 2014). Sharing data and code facilitates and encourages reproducibility, allows comparative data analysis, and promotes scientific progress in general (Herridge et al. 2015). Data sharing is also essential for addressing questions at broad spatial scales, evaluating alternative laboratory and analytical methods, and ensuring that limited research funds are used efficiently. Although sharing data and code introduces overhead costs for data management and archive maintenance, the benefits to individuals, the scientific community, and the public at large are increasingly recognized as far outweighing these costs. The research presented in this paper is just one example of the science that is possible with data and code sharing; we hope academic institutions, publishers, and funders continue to encourage and incentivize such practices (Kattge et al. 2014).

8. How to Access the Products

The complete GCDv1, v2 and v3 (this paper) Microsoft Access database with all available metadata is stored and available at gpwg.org. Supporting information about the Global Charcoal Database and the Global Palaeofire Working Group is also available at gpwg.org. Site metadata and the charcoal data are accessible through the *paleofire* package (Blarquez et al. 2014) for R (R Development Core Team 2013).

9. Conclusions

The GCDv3 incorporates 736 charcoal records and can now be gridded globally for the modeling community to ease future data-model comparisons. Fire history reconstructions from the GCDv3 demonstrate that increases in biomass burning since the last glacial period were widespread, as are unusually high levels of burning over the past several decades. Present day burning inferred from the charcoal data is particularly high in western North America and southeastern Australasia. Detailed reconstructions of temporal variations in biomass burning during the past 1000 years reveal that a global biomass burning decline from 1000 to the LIA was more pronounced in the northern than Southern Hemisphere. In addition, variations in fire activity during the past 200 years show very different spatial patterns. In general, data-model comparisons with paleofire data provide a powerful method for testing hypotheses about interactions between climate and fire outside the range of modern climate conditions. Results from such data-model comparisons will highlight gaps and weaknesses in both data and models, allowing targeted refinements to be identified and prioritized. We identify five areas of focus to promote future progress in paleofire research, including (1) charcoal calibration studies in diverse environments, (2) multiproxy studies of paleofire history, (3) paleofire data-model comparisons, (4) filling gaps in paleo fire data, (5) comparisons between charcoal data and other large datasets, and (6) enhanced data extraction from existing cores, like continuous sampling and herbaceous charcoal identification.

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Figure Captions

	Lacustrine (LACU)	Bog (BOGM)	Unknown (NOTK)	Soil (SOIL)	Coastal (COAS)	Marine (MARI)
Concentration (CONC)	178	120	33	43	22	8

Influx (INFL)	157	37	9	3	4	2
Proportion (C0P0)	45	37	8	4	9	2
Other (OTHE)	10	3	2	2	0	0
Total	390	197	52	52	35	12

Table 1. Total number of sites by sediment and measurement type. The sediment types are lacustrine (LACU), bog (BOGM), unknown (NOTK), soil (SOIL), coastal (COAS), and marine (MARI). The measurement types stored in the database are concentration (CONC), influx, (INFL), proportions (e.g., ratio of charcoal particles to pollen grains), and other (OTHE).

	Lacustrine (LACU)	Bog (BOGM)	Unknown (NOTK)	Soil (SOIL)	Coastal (COAS)	Marine (MARI)
Small (SMAL)	194	100	4	13	15	0
Medium (MEDI)	33	22	2	9	7	0
Large (LARG)	14	2	7	1	0	12
Unknown (NOTK)	149	73	39	29	13	0
Total	390	197	52	52	35	12

Table 2. Total number of sites by sediment type and catchment size. Catchment sizes are small ($<10km^2$), medium ($>10.1km^2$ and $<500km^2$), large ($>500km^2$), and unknown (NOTK).

	Proportion (C0P0)	Concentration (CONC)	Influx (INFL)	Soil (SOIL)
Soil charcoal (CPRO)	0	0	0	1
Gravimetric (GRAV)	1	1	0	0
Hand Picked (HNPK)	0	7	0	0
Heavy Liquid Preparation (HVLQ)	0	4	0	0
Imaging Analysis (IMAG)	0	12	2	0
Oxidation Resistant Elemental Carbon OREC % of dry weight (OREC)	0	1	0	0
Pollen Slide (POLS)	81	259	98	0
Sieved (SIEV)	4	151	118	0
Total	86	435	218	1

Table 3. Total number of sites by quantification type and laboratory analysis method.

Figure 1. Location of paleofire sites and sampling density in the GCDv3.

Figure 2. Temporal and latitudinal distribution of dates used to develop chronologies for records in the GCDv3 over the past 22,000 years.

Figure 3. Example of untransformed and transformed charcoal influx (using the box-cox transformation) from Lago de Acessa, Tuscany, Italy (Vanniere et al. 2008). Number of particles per influx class is shown (left panels).

Figure 4. Three 3000-year biomass burning curves from eastern North America based on sites from an increasing number of adjacent grid cells show how the reconstructions become smoother and confidence intervals narrow as the number of sites and the spatial area included expand. Biomass burning reconstruction based on two adjacent grid cells containing a total of 19 records (top panel); three adjacent grid cells containing 40 records (middle panel), including the 19 from the top panel; and four adjacent grid cells representing a total of 59 records (bottom panel), including all previous. In all panels, red lines are based on 400-year smoothing windows, black lines based on 200-year windows, and bootstrap 95% confidence intervals from resampling by site are shown as gray bands.

Figure 5. Trends in biomass burning (left panel) for the Northern Hemisphere, globe, and Southern Hemisphere for the past 1000 years and spatially gridded biomass burning (right panel) for the period 1950-2010 CE, 1850-1950 CE, and 950-1050 CE. Vertical gray bars through the time series on the left panel correspond to the time intervals shown in the gridded dot maps on the right panel. The charcoal influx anomaly base period for all panels is 1,000-1800 CE. The smoothing window widths for the time-series (left panel) are 40 years (red line) and 20 years (black line). Bootstrap-by-site confidence intervals (95%) are filled in gray.

Figure 6. Trends in biomass burning (left panel) from 22 to 0ka from the GCDv3 (red) and GCDv2 (gray, Daniau et al. 2012) for the entire globe, northern extratropics (>30° N latitude), tropics (>30° N latitude and <30° S latitude), and the southern extratropics (<30° S latitude), along with spatially gridded biomass burning (right panel) for the periods 0-1ka, 5.5-6.5ka, and 20.5-21.5ka. Vertical gray bars on the left panel correspond to the intervals shown in the maps (right panel). The charcoal influx anomaly base period for all panels is 21ka-200 cal yr BP; the smoothing window width is 1000 years. Bootstrap-by-site confidence intervals (95%) are filled in gray.

Figure 7. Diagnostic maps for the globally gridded data showing the number of sites per grid cell at a) 0-1ka; b) 5.5-6.5ka; and c) 20.5-21.5ka.

Figure 8. Modeled (filled grid boxes, Brücher et al. 2014) vs. reconstructed (GCDv3) fire activity at global (a) and regional (b, c) scales. Both data and model represent millennial anomalies at 6ka relative to present (i.e., mean z-scores for 5.5–6.5ka minus mean z-scores for 500 cal yr BP to present). In all panels, green and pink symbols indicate GCD data that agrees or disagrees (respectively) with model output in terms of the sign of the 6–0ka anomaly. In (a) and (c) the data are gridded following methods presented in Section 5. In (b), anomalies for individual GCD sites are plotted, with symbols indicating positive (‘+’) or negative (‘o’) anomalies; records that do not span the full 6ka interval are shown (grey squares) but excluded from the analysis.

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