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Global Modern Charcoal Dataset (GMCD): A tool for exploring proxy-fire linkages and spatial patterns of biomass burning

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ABSTRACT

Progresses in reconstructing Earth's history of biomass burning has motivated the development of a modern charcoal dataset covering the last decades through a community-based initiative called the Global Modern Charcoal Dataset (GMCD). As the frequency, intensity and spatial scale of fires are predicted to increase regionally and globally in conjunction with changing climate, anthropogenic activities and land-use patterns, there is an increasing need to further understand, calibrate and interrogate recent and past fire regimes as related to changing fire emissions and changing carbon sources and sinks. Discussions at the PAGES Global Paleofire Working Group workshop 2015, including paleoecologists, numerical modelers, statisticians, paleoclimatologists, archeologists, and anthropologists, identified an urgent need for an open, standardized, quality-controlled and globally representative dataset of modern sedimentary charcoal and other sediment-based fire proxies. This dataset fits into a gap between metrics of biomass burning indicators, current fire regimes and land cover, and carbon emissions inventories. The dataset will enable the calibration of paleofire data with other modern datasets including: data of satellite derived fire occurrence, vegetation patterns and species diversity, land cover change, and a range of sources capturing biochemical cycling. Standardized protocols are presented for collecting and analyzing sediment-based fire proxies, including charcoal, levoglucosan, black carbon, and soot. The GMCD will provide a publically-accessible repository of modern fire sediment surface samples in all terrestrial

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ecosystems. Sample collection and contributions to the dataset will be solicited from lacustrine, peat, marine, glacial, or other sediments, from a wide variety of ecosystems and geographic locations.

1. Introduction

Fire is a terrestrial phenomenon that influences ecosystem composition, distribution, structures, processes from local to global scales, and operates at multiple timescales (Bowman et al., 2009a; Conedera et al., 2009). Therefore, fire constitutes the most important terrestrial disturbance on the earth (Bond et al., 2005) and is responsible for shaping and modifying terrestrial ecosystems over millions of years (Bird and Cali, 1998; Bond, 2014). The different components of the fire regime, such as burned area, intensity, frequency, severity and seasonality (Bowman et al., 2009a; Krebs et al., 2010), are tightly related to weather and climatic conditions, fuel type and availability, ignition probability and human modifications, such as landscape fragmentation (Archibald et al., 2013). As a consequence, ongoing global warming, changing patterns of precipitation and anthropogenic activities are expected to deeply modify fire regimes at various spatiotemporal scales (Allen et al., 2014; Bedia et al., 2015; Knorr et al., 2016; Moritz et al., 2012b; Westerling et al., 2006; Yue et al., 2013).

Nevertheless, large uncertainties and biases remain in our understanding of the complex interactions between fire and other Earth system components, and challenges exist for integrating these interactions into Earth system models (Hantson et al., 2016b; Lehsten et al., 2009; Pfeiffer et al., 2013). Paleo-fire reconstructions constitute a unique opportunity to examine long-term variations in fire-climate-vegetation-human relationships. For example, charcoal-based fire reconstructions of the Quaternary have documented how fire regimes have changed in the past, both locally (Blarquez and Carcaillet, 2010; Colombaroli et al., 2014; Hawthorne and Mitchell, 2016; Maezumi et al., 2015; Vanniere et al., 2008) and regionally (e.g. Blarquez et al., 2015; Carcaillet et al., 2002; Daniau et al., 2012, 2013; Gavin et al., 2006; Power et al., 2008; Vannière et al., 2011). Many studies have examined how fire activity in different parts of the world have responded to climate changes (Ali et al., 2012; Colombaroli and Gavin, 2010; Daniau et al., 2012; Marlon et al., 2006), anthropogenic activities (Leys and Carcaillet, 2016; Power et al., 2010; Vannière et al., 2016), vegetation changes (Blarquez and Carcaillet, 2010; Clark et al., 2001; Fletcher et al., 2014; Higuera et al., 2009), and how paleofire-regime changes have contributed to carbon emissions toward the atmosphere (Bremond et al., 2011) and sequestration into soils (Carcaillet and Talon, 2001; DeLuca and Aplet, 2008). Both conversions might represent the same flux of burned biomass (Tinker and Knight, 2000), thus stressing the need of further reconstructions to improve the function of paleo-fires on the global carbon budget.

The Global Charcoal Database (GCD, www.paleofire.org) has supported cross-disciplinary research (Marlon et al., 2016b) as both a tool for multi-scalar analyses and as a repository for paleofire records. The database now contains records from upwards of 1076 sites with nearly 40% from Europe and 30% of records from the Americas, derived from six different depositional environments (i.e. lake, mire, bog, peat, soil, and marine) and over 120 individual approaches for classifying and reporting charred plant residues. The records can be analyzed individually or as spatiotemporal composites via a process of rescaling transformation and standardization (Marlon et al., 2008; Power et al., 2008, 2010) for multiscalar analyses (Blarquez et al., 2014; Marlon et al., 2013).

However, most currently available regional-to-global scale paleofire reconstructions reveal only changes in biomass burning relative to a study-specific base period, for example the past 200 or 500 years for a Holocene analysis. The wide range of incomparable units (Iglesias et al., 2014) employed in proxy measurement from diverse sediment archives have prevented the reconstruction of absolute quantities of biomass and an estimation of area burned. In addition, the myriad factors that determine quantities of charcoal accumulated in a given lake's sediment, for example, require systematic analyses across a broad range of environments, and have only been examined in a very few regional studies (Clark and Royall, 1996; Marlon et al., 2006). Thus, a standardized methodology, nomenclature and defined units are required to enable comparisons across records and locations, as well as methods for bridging modern fire metrics with fire historical reconstructions from sediment archives to make these independent data sources directly comparable.

Comparisons of recent sedimentary charcoal with fire scars from trees or historical fire events have helped improve quantitative reconstructions of past fire regimes (Brossier et al., 2014; Clark, 1990; Duffin et al., 2008; Gardner and Whitlock, 2001; Higuera et al., 2005, 2010; Marlon et al., 2012; Millspaugh et al., 2000; Oris et al., 2014; Pitkänen et al., 1999; Whitlock, 2001; Whitlock and Millspaugh, 1996a). Such calibration studies, however, are predominantly located in middle to high latitudes, leaving gaps in knowledge in many areas, especially tropical and sub-tropical savannas and forests, tundra, temperate grasslands, and Mediterranean ecosystems (Aleman et al., 2013; Duffin et al., 2008; Leys et al., 2015).

Moreover, taphonomic processes that influence charcoal records represent a challenge to quantitatively reconstruct past fire regimes. Some studies have explored charcoal production, dispersal and deposition (Higuera et al., 2007; Lynch et al., 2004; Ohlson and Tryterud, 2000; Tinner and Lotter, 2006), and have developed models of charcoal source area (Clark, 1988a; Clark et al., 1998; Higuera et al., 2007; Lynch et al., 2004; Peters and Higuera, 2007), but additional data-model comparisons covering all flammable ecosystems are needed. It has also been demonstrated that the size of the deposition site or body of water, of the watershed (Marlon et al., 2006) or even the vegetation burned can impact the accumulation of charcoal (Aleman et al., 2013; Leys et al., 2015; Marlon et al., 2006). Indeed, ignitability and flammability of vegetation depends on plant traits and community composition, plant biomass as well as stand (vertical) and landscape (horizontal) structures and fuel conditions. Understanding the link between vegetation, fire, and the production, transportation and deposition of charcoal particles has been a topic of interest for decades (Blackford, 2000; Clark, 1988a; Clark et al., 1998; Hudak et al., 2013; Lynch et al., 2004; Scott et al., 2000), but once again studies are limited to some ecosystems.

Despite the growing body of knowledge within the fire sciences, limited emphasis on issues of calibration at regional and global scales have thus emerged in the paleofire literature. Improving the ability to quantify paleofire proxies in terms of the specific fire variables which ecologists and land managers consider in conservation strategies, i.e. location, frequency, type (i.e. crown vs ground fire), biomass burned, emissions and burned area, are key targets for this modern charcoal dataset. There is also a need to conduct calibration studies using multiple independent proxy-fire measurements to better understand biomass burning and fire regime components.

To address these challenges, we propose a Global Modern Charcoal Dataset (GMCD) – a proxy-fire dataset that includes surface samples and short cores from locations across the globe using standardized extraction protocols and proxy analyses. Modern surface samples, from the past decades onwards and for which quantified fire is known, will enable direct comparisons of paleofire data to satellite-based fire products, model outputs, dendrochronological records, and historical records. Such comparisons will warrant the development of calibration protocols and models for expressing ecologically-relevant patterns of past fire activity derived from sedimentary records in absolute units of biomass or area burned (Aleman et al., 2013; Brossier et al., 2014; Leys et al., 2015; Whitlock and Millspaugh, 1996a). Analyses from such comparisons may also enable quantitative relationships to be determined between paleofire data and fire intensity, frequency, severity, and seasonality. Here we present standardized methods for collecting and analysing various fire proxies from sediments and biomarker analyses for the research community to produce open-access data accessible through the GMCD.

2. Proxy indicators of fire

A variety of indicators in sediments, from variations in black carbon to charred plant material, have been developed as proxy measurements of past fire activities and can be used to reconstruct patterns of biomass burning (Conedera et al., 2009; Whitlock and Larsen, 2002). Charcoal has commonly been used as an indicator of past fire and is a valuable proxy as it can be collected from lakes, soil and peat from around the world. However, charcoal morphology study that may inform about the type of burned vegetation is not yet a widely used technique in the paleo record and high latitude ecosystems tend to have greatly limited charcoal input over time (Hu et al., 2010). Alternate proxies – such as levoglucosan and black carbon – complement the charcoal record as they provide information from locations where charcoal is less abundant (high elevations and latitudes) and/or may provide information regarding the types of burned vegetation (Kirchgeorg et al., 2014).

2.1. Charcoal

Charcoal, which is a carbonaceous material produced by heating biomass during incomplete combustion (Jones and Muthuri, 1997), is commonly divided into two categories: macroscopic charcoal (particles $\geq$100 μm, and microscopic charcoal (particles $\leq$100 μm) (Whitlock and Larsen, 2002). However, in practice and for macroscopic charcoal analyses, several mesh sizes can be used during the extraction process or different size fractions identified during the counting. This potentially influences paleofire reconstructions, and homogenized and standardized protocols are needed (Iglesias et al., 2014, and section 4.2.1 this paper where we recommend a mesh size of 150 μm).

Charcoal particle sizes and morphologies are an important control on the transportation distances and the quantification of each size fraction informs about the source areas (Aleman et al., 2013; Carcaillet et al., 2001; Clark, 1988a; Clark et al., 1998; Duffin et al., 2008; Higuera et al., 2007; Lynch et al., 2004; Ohlson et al., 2013; Ohlson and Tryterud, 1999; Peters and Higuera, 2007; Pisaric, 2002; Tinner and Lotter, 2006). For example, smaller particles are assumed to be transported over longer distance compared to larger ones (Clark, 1988a; Crawford and Belcher, 2014; Whitlock, 2001). More recently, a particular focus has been on charcoal particle morphology. Indeed, charcoal morphotypes have considerable potential to provide information about fuel source consumed during biomass burning episodes (Jensen et al., 2007; Umbanhowar and Mcgrath, 1998; Aleman et al., 2013; Courtney-Mustaphi and Pisaric, 2014b). Individual particle measurements are thus valuable and will be included in the GMCD.

2.2. Black carbon

Black carbon (BC) is a fire-derived, highly aromatic-to-graphitic form of carbon that is produced by the incomplete combustion of biomass and fossil fuel (Jones and Muthuri, 1997) and is a collective term encompassing the carbonaceous products from almost the entire fire temperature range (Goldberg, 1985; Hedges et al., 2000). From partially charred organic material to highly graphitized soot, BC is divided into two different formation pathways: char and soot (Goldberg, 1985; Schmidt and Noack, 2000). In general, char is defined as carbonaceous combustion residues obtained by heating organic substances and formed directly from pyrolysis (Shafizadeh, 1982). The term soot is defined as only those combustion condensates that form at high temperature via gas-phase processes during incomplete combustion (Glassman, 1989). Char and soot have differing physico-chemical properties (Han et al., 2010; Masiello, 2004), principally characterized as different particle size. Soot is dominantly nanometer in size (Quénéa et al., 2006) and thus can be transported thousands of kilometers, while char has a wider particle size distribution in the environment, from micrometer (Odgaard, 1992) to centimeters (Bélanger et al., 2014) and the transportation is thus limited according to the weight/surface ratio of the particle (Clark, 1988a).

Charcoal differs from BC including char and soot, where these products are measured by chemical, thermal/optical, or optical methods, while charcoal specifically refers to the relatively larger combustion residues and is identified and quantified by various methods including but not limited to, slides of digested sediment, petrographic thin sections, and sieved sediment samples (Clark et al., 1996; Han et al., 2012b). Further, their chemical properties differ, resulting in different methods of measurement (Quénéa et al., 2006). Charcoal quantification then relies on optical measurements using stereomicroscopes or microscopes with manual counting or with the aid of an image analysis system (Ali et al., 2009; Beaufort et al., 2003; Clark and Hussey, 1996; Lynch et al., 2003).

2.3. Levoglucosan

Biomass burning also produces characteristic organic biomarkers including monosaccharide anhydrides (MAs) that persist in the environment and can be analyzed from terrestrial and marine sediments as well as from ice cores. These biomarkers include levoglucosan and its isomers, the mannosan and the galactosan that are only produced by cellulose combustion at temperatures of approximately 250 °C (Elias et al., 2001; Otto et al., 2006; Shafizadeh et al., 1979; Simoneit and Elias, 2000; Simoneit et al., 1999). These temperatures are similar to the low temperature of 150–350 °C for the production of char samples. In terrestrial sediments, MA concentrations can be high enough to determine the differences in types of vegetation burned due to the ratios between levoglucosan and its isomers, and can then be compared to the sediment charcoal fraction (Kirchgeorg et al., 2014).

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3. Data collection and calibration studies to contribute to the GMCD

3.1. Single surface samples and short cores

Terrestrial archives (lakes, peat, bog, and soil), marine sediment sequences and snow and ice records of fire activity can be contributed to the GMCD. Surface samples from the first centimeter of the archive can be taken without dating. In this case, only the sampling date, and no geochronological dating, is required as with other surface sampling approaches (Davis et al., 2013; Flower et al., 1997). Sedimentation rates, in marine and terrestrial archives can also be calculated using the established linkages between sediment rates and coring depth that have been utilized for early diagenetic models (Soetaert et al., 1996) or basin comparison techniques (Chiverrell et al., 2009; Crann et al., 2015) to estimate the 'recent' age of the superficial layer. These samples will be used to infer biophysical differences between the depositional environments and fuel types, and how these characteristics influence the way the different proxies are selectively archived, and thus observed. Primarily concentration data of these proxies can be recovered from these samples, but this information would enable developing models to take into account taphonomic processes relating charcoal concentrations to the depositional environment.

When possible, age-depth modeled short core stratigraphies associated with radiometric (^{210}Pb, ^{10}Be, ^{137}Cs) or relative dating, are also required to contextualize modern surface samples. This type of record is crucial for influx computation and for direct comparison with paleodata influxes. Recent proxy influxes can directly be compared to fire regime variables, such as burned area, fire intensity or fuel type recovered from remote sensing data, observations or surveys (Lentile et al., 2006). Quantitative calibration can thus be developed, and directly applied to paleoenvironmental data, such that past fire regime or carbon emissions can be reconstructed in units that are comparable to observations and model output, taking into account taphonomic processes.

3.2. Contributing to the dataset

New records will initially be collected through a network of working group members, however it is expected that the dataset will attract contributions from observers from a range of scientific disciplines, as well as from both specialists and non-specialists, from varying locations across the globe. If contributors have facilities to collect, process and analyze samples, then the data can be uploaded directly to the dataset at (http://www.gpwg.paleofire.org/gmcd/). The alternative is to connect with a designated regional laboratory and arrange metadata submission and shipping of samples for analysis. Those laboratories will use the same standard protocols and be located in a range of geographical regions. They will also aid in disseminating protocols and techniques to new contributors and contact details will be listed on the GMCD webpage as the project progress. The open access approach facilitates an international research network coupled with the flexibility of the web interface to rapidly develop and share data collection through a researcher community and citizen science approach where anyone can contribute to the dataset by collecting surface sediment samples. Individuals can register their interest, participate in upcoming virtual workshops and contribute to the dataset by visiting the current webpage (http://www.gpwg.paleofire.org/gmcd/).

Data can be acquired from new or existing sediments that have already been cored or analyzed, providing that adequate information is available. Additional core material or surface samples can be shipped to participating laboratories for analysis and data sharing (http://www.gpwg.paleofire.org/gmcd/). Alternatively, people can analyze, develop, and submit their own proxy-fire data to the GMCD. We thus emphasize the use of common and standardized methodologies for each of the proxy, open-data sharing, and cross-disciplinary collaboration. Other sampling methods for surface samples, such as sediment traps, soil, tauber traps etc … would be welcome in the database. However, preference would be given to samples from *in situ* archives (sediments, ice) as it will be more straightforward to study taphonomic processes, applicable to long-term records, from them.

Metadata are crucial and should be included for each site and record that will be added to the dataset. They provide important information (location, climate, vegetation type, land-cover etc. Table 1), which will be useful in the reconstruction and interpretation of fire regimes. Precise GPS location is particularly important to perform spatial analyses therefore latitude and longitude are required at the hundredth decimal. Table 1 presents the input parameters for the GMCD. The minimum amount of data required should clearly identify the site, sample and date, and critically provide information that is not possible or difficult to obtain afterwards through examination of maps or remote sensing. The surface sample and short core data and metadata collected from the standardized methods outlined below will be incorporated into the GMCD. Fig. 1 shows surface sample records (from 1950 CE to present) currently included in the GCD.

3.3. Integration with GCD

The Global Charcoal Database (www.paleofire.org) is the research database that currently holds records of long-term fire history (Marlon et al., 2016a; Power et al., 2008). The new GMCD module will integrate new data with existing modern core top samples from studies included in the GCD. Various metadata, highlighted in Table 1, will be introduced in a systematic way, using common units based on international standards, and possess the ability to integrate additional biomass burning metrics such as charcoal morphological classification (Colombaroli et al., 2014; Courtney-Mustaphi and Pisaric, 2014a, b; Enache and Cumming, 2006; Jensen et al., 2007; Walsh et al., 2010), charcoal size measurements (Aleman et al., 2013; Umbanhowar and Mcgrath, 1998), the quantification techniques - image analysis (Clark and Hussey, 1996) on thin sections (Clark, 1988b), pollen slide counts (Clark, 1988b), chemical digestion (Rhodes, 1998; Winkler, 1985), and the processing method used to isolate large charcoal particles (e.g., sieve sizes (Carcaillet et al., 2001)).

4. Standardized protocols

Currently within the GCD, there are numerous analytical techniques applied for data acquisition and a variety of proxies to quantify and reconstruct biomass burning. These include metrics and methods such as charcoal counts, concentration, influx, chemical assay, image analysis, reflectance, percentage dry weight, area and volume measurements, and point counts (Carcaillet et al., 2002; Conedera et al., 2009; Marlon et al., 2015; Weng, 2005; Whitlock and Larsen, 2002). As a consequence, each metric produced by a given analytical technique was determined by the research question, the depositional environment and the background of the researchers, resulting in records with charcoal quantities spanning over ten orders of magnitude that require mathematical standardization (Marlon et al., 2008). Therefore, there is an urgent need for a set of homogeneous defined methodologies that would enable comparisons across records and locations, and reduce uncertainties associated with differing laboratory techniques (Marlon et al., 2008; Power et al., 2008).

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Table 1
Metadata for inclusion in the GMCD.

Category	Sub Category
Site	Name; Site Type; Latitude; Longitude; Elevation; Region; Catchment Size; Flow Type; Biome; Country; Local Vegetation; Regional Vegetation; Landscape Description; Inflow/Outflow; Human Features (Presence or absence).
Core	Name; Water Depth; Coring Date; Core Type; Depositional Environment; Storage Address.
Sample	Type; Volume; Depth; Sampling Interval; Previous Analyses.
Charcoal	Charcoal Size; Quantification Method; Charcoal Units; Charcoal Quantity; Charcoal Morphology; Sample Size.
Additional fire proxies	Proxy Type; Quantification Method, Sampling Type.
Dating	Date Type; Age Error; Material Dated; Age Units; Calibration Method; Calibration Version; Reference Number; Dating Laboratory; Age Model; Age Model Method.
Fire Occurrence	Fire regime; Fire Events; Frequency; Intensity; Fuel Burned; Fire type(s).
Source	Publication(s); Charcoal Analyst; Author and Data Contributor; Data Source; Affiliation; Contact Details; Laboratory Analyzed; Funding.

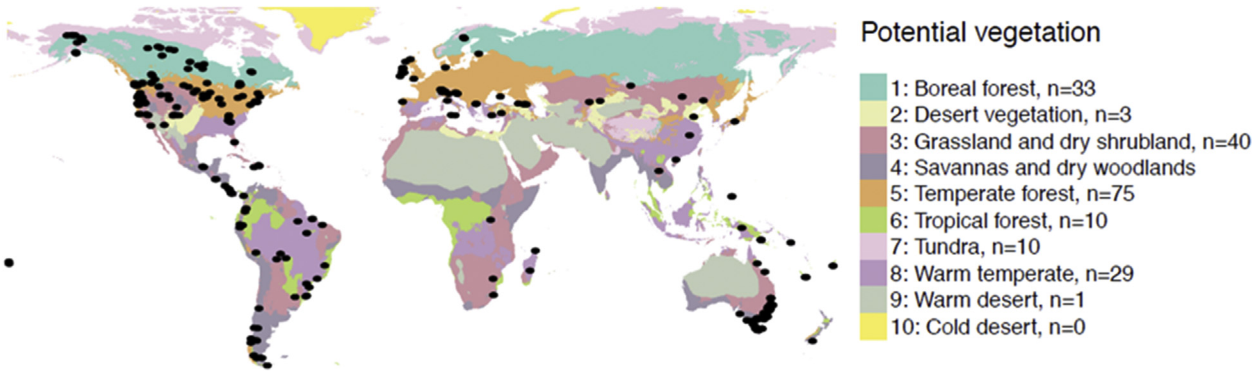

Fig. 1. World map of major potential vegetation biome distribution (Levavasseur et al., 2012), and the location of 20th century charcoal surface sample records currently included in the GCD (www.paleofire.org).

Fig. 2 shows the variety of analytical techniques and different charcoal size records currently in the GCD. Here, within the framework of the GMCD, we propose an accessible and straightforward set of methodologies that cover a range of depositional environments where fire proxies are captured. A harmonization of fire environmental variables, metrics and units from various disciplines will allow for increased meaningful and useful comparisons between data products and improved model parameterization. Fig. 3 shows a workflow diagram for the GMCD and Fig. 4 illustrates the varying methodological techniques for each proxy.

4.1. Site selection and sampling

4.1.1. Terrestrial records

A variety of sediment deposits contain charcoal and biomass burning products that preserve and represent a signal of recent burning surrounding depositional environments. Primary target sampling locations are small lakes or ponds with permanent water, little or no inflowing and outflowing streams, and low potential impact from physical and bioturbation (Conedera et al., 2009; Courtney-Mustaphi et al., 2015; Whitlock and Larsen, 2002). Samples should be ideally collected from the deepest or most central area of the lake or the calmest benthic zones where there is the least disturbance. Additional types of sites can be targeted for sampling, including small wetlands in forests namely “forest hollows” (Björkman and Bradshaw, 1996; Overballe-Petersen and Bradshaw, 2011), grasslands, and semi-arid areas (Rucina et al., 2010). In tropical peaty and palustrine areas, the target regions are usually in dense Cyperaceae zones, with minimal Poaceae and Typhaceaea, but avoiding collapsed floating vegetation mats, which may alter the preservation of high-resolution peat sediment records. Other basins, including those anthropogenically-modified may provide useful modern deposits of biomass burning products and can include, but are not limited to: dam reservoirs that are dredged infrequently, abandoned quarries, swimming holes, wells and water holes, flood protection basins, ponds, and craters, accumulating soil and sediments.

When analyzing a deposit it is always important to consider the deposition, transportation and disturbance of the sample, because these physiographical processes control the charcoal record and thus alter the performance of fire reconstructions (Bradbury, 1996; Carcaillet et al., 2007; Whitlock and Millspaugh, 1996b).

Surface sediments can be collected using a variety of techniques including a gravity corer (Glew et al., 2001), Eckman grab, piston corer (Wright et al., 1984), or other sediment sampler (Håkanson, 1982; Milbrink, 1971; Milbrink and Wiederholm, 1973). In peat and consolidated sediments a “Russian” corer (Jowsey, 1966) or organic soil plug corer can be used (Wardenaar, 1987). Depending on sedimentation rates, which vary site by site, the top 1 cm of stratigraphic depth is required, and can be isolated using a core extruder (Glew, 1988; Verschuren, 1993) or from the undisturbed tops or mud-water interface of other types of grab samples. We recommend that a minimum of 5–10 cm^3 samples be collected per site as these samples will be used for a variety of purposes: to quantify and measure macroscopic and microscopic charcoal pieces, to estimate the organic and carbonate content with loss-on-ignition (LOI) analysis (Dean, 1974; Heiri et al., 2001), any other complementary analyses, and as an archive sample for future work. Many laboratories may have archived surface sample material that could be used if the collection date is certain. If pollen analysis is also performed on the modern surface sample, the possibility arises to quantify microscopic charcoal within the same sample that will be useful for fire activity and taphonomic studies at multiple scales.

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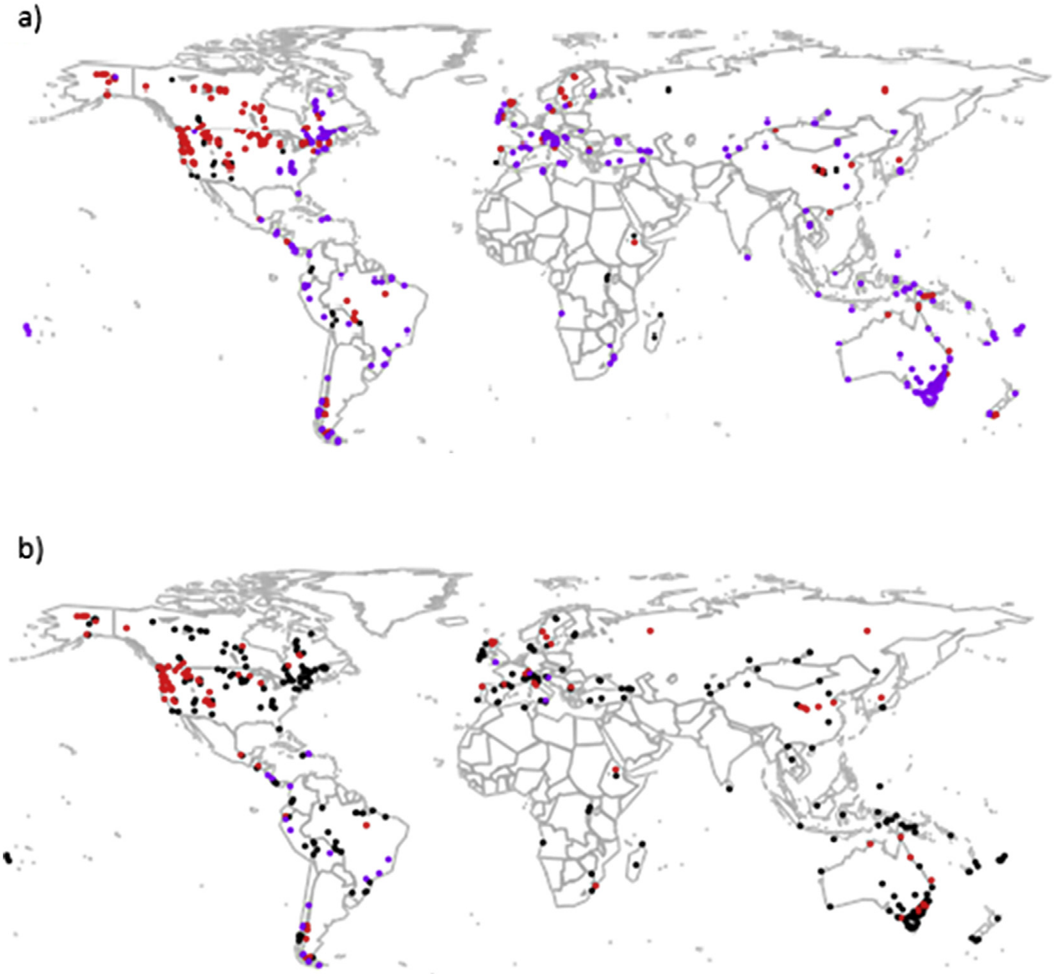

Fig. 2. World maps showing a) the varying analytical methods included from records within the GCD i.e. Sieved (black dots), Pollen slide (red dots) and All methods (purple dots), and b) different charcoal records included in the GCD i.e. Macroscopic (black dots), Microscopic (red dots) and All charcoal (purple dots). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1.2. Marine sediments

Microscopic charcoal analyses on marine surface samples can be done everywhere in the world (Suman et al., 1997). However, several variables can influence or alter the original signal detected from the regional microscopic charcoal. Variables include those related to the source area (size of the hydrographic basin) and the production of microscopic charcoal *in situ* (vegetation type, fuel amount, fuel flammability), but also those related to transport and sedimentation processes related to the distance from the coast, water depth, oceanic circulation, wind direction, river load and sediment discharge, precipitation, potential time lag between *in situ* production and marine deposition (Middelburg et al., 1999; Schmidt and Noack, 2000). To develop the calibration of fire proxy on those samples, we recommend to select samples from deep-sea cores with a known hydrographic basin source area, collected along a specific transect that covers different climate and biomes, and/or along a specific transect from the coast to the deep ocean. Fire proxy preserved in marine sediment surface samples should be analyzed from multicore, box or gravity, or piston corers presenting a good recovery of the sediment interfaces.

4.1.3. Snow and glacial ice

Surface snow and firn provide ideal locations for obtaining modern biomass burning samples. Snow pit samples can be collected from a range of locations, while shallow ice cores are more constrained by the glacier properties. Snow pits can be dug in seasonal snowpack while ice core are often dependent on multi-year ice. For either type of sample, the ideal location is the flattest possible surface near the top of the glacier or slope. Transects of snow pits along evenly-spaced elevations of a glacier can help augment the information gained from the uppermost sample to see if slope characteristics such as aspect or vegetation cover affect the samples. Snow pit sites should be located away from any rock walls that may cascade fresh snow and should also be away from wind-scoured areas to provide a more representational sample of recent flow fall. Locations with no obvious surface melt or wind scour are preferable to locations with disturbed upper snow layers.

Snow pit sample collection[2] provides a straightforward method without specialized tools other than a clean shovel, a tape measure, GPS, and low-density polyethylene (LDPE) sample bottles. Snow pits should be dug from the upper surface to as deep as possible. The time period covered by a snow pit will vary depending on accumulation and ablation. Ideally snow pits are selected from areas that are actively accumulating or are dug in spring. However anything that will be collected from or near the surface will be

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[2] https://science.nature.nps.gov/im/units/romn/monitor/snow/docs/Ingersoll_etal2009_ROMNSnowChemistryProtocol_FINAL_Web.pdf, https://www.nasa.gov/pdf/186123main_SnowPitProcedures.pdf.

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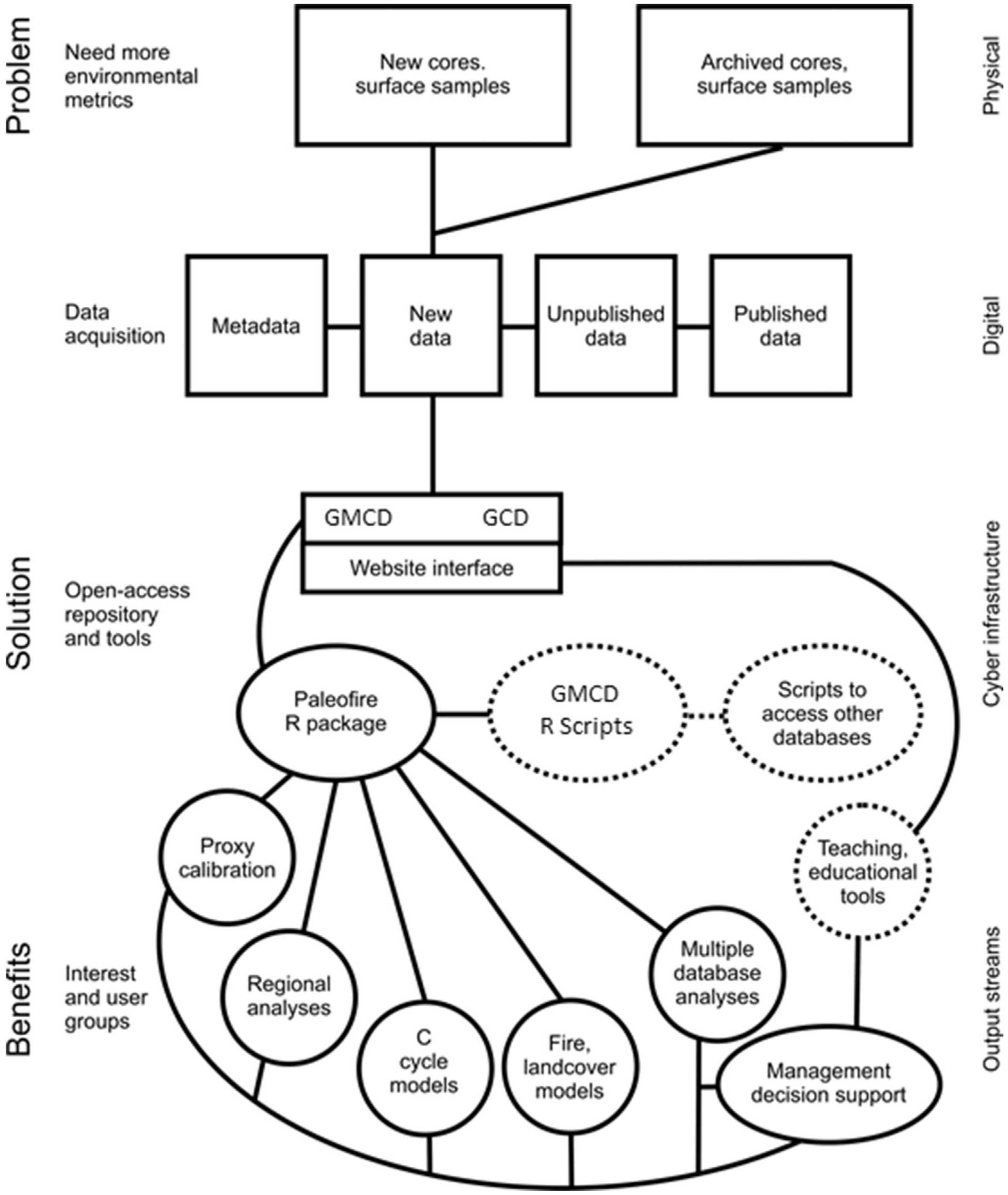

Fig. 3. Outline of how the GMCD fits into the knowledge, data and repository needs of the research community and foreseen outcomes. Dotted circles show potential outputs that have yet to be developed.

'modern'. Once the initial pit is dug, one wall should be scraped until it becomes smooth and perpendicular to the glacier surface. The exact location of the snow pit should be noted with the GPS. The tape measure should be attached to the snow surface and extend down into the snow pit until reaching the bottom. The LDPE sample bottles (pre-cleaned by rinsing three times in ultra-pure water) should be pressed into the vertical snow pit wall where the samples form a continuous sequence with no spaces between each sample with field depths of each sample recorded. An ideal sample size is 15 mL after melting that allows determining BC and/or levoglucosan in addition to other climate variables, but only 2–3 mL is required for replicate levoglucosan analyses.

Drilling ice cores is a more specialized procedure than digging snow pits, and thus, is more applicable to expeditions that already have the goal of drilling in a certain location. If researchers are in a position to drill a short (~10 m) ice core, then once the ice core is extracted from the glacier, it can be cut with a hand saw into ~10 cm sections which can be placed into pre-cleaned LPDE bottles and ideally transported back to the laboratory in a frozen state.

4.2. Macroscopic charcoal analyses

4.2.1. Extraction

Charcoal is extracted from a 1 cm^3 subsample, with the remaining 5–10 cm^3 sub-samples are reserved for additional analyses. The subsample is transferred to a Petri dish using commonly employed techniques of sieving and bleaching, adapted from those described by Mooney and Black (2003). If it is likely that charcoal particles may be included in carbonate aggregates or if the sediment is consolidated by carbonates, it may be useful to first remove carbonates with hydrochloric acid (HCl 0.1 M). Each subsample is treated with 40 mL of a 15% solution of sodium hexametaphosphate

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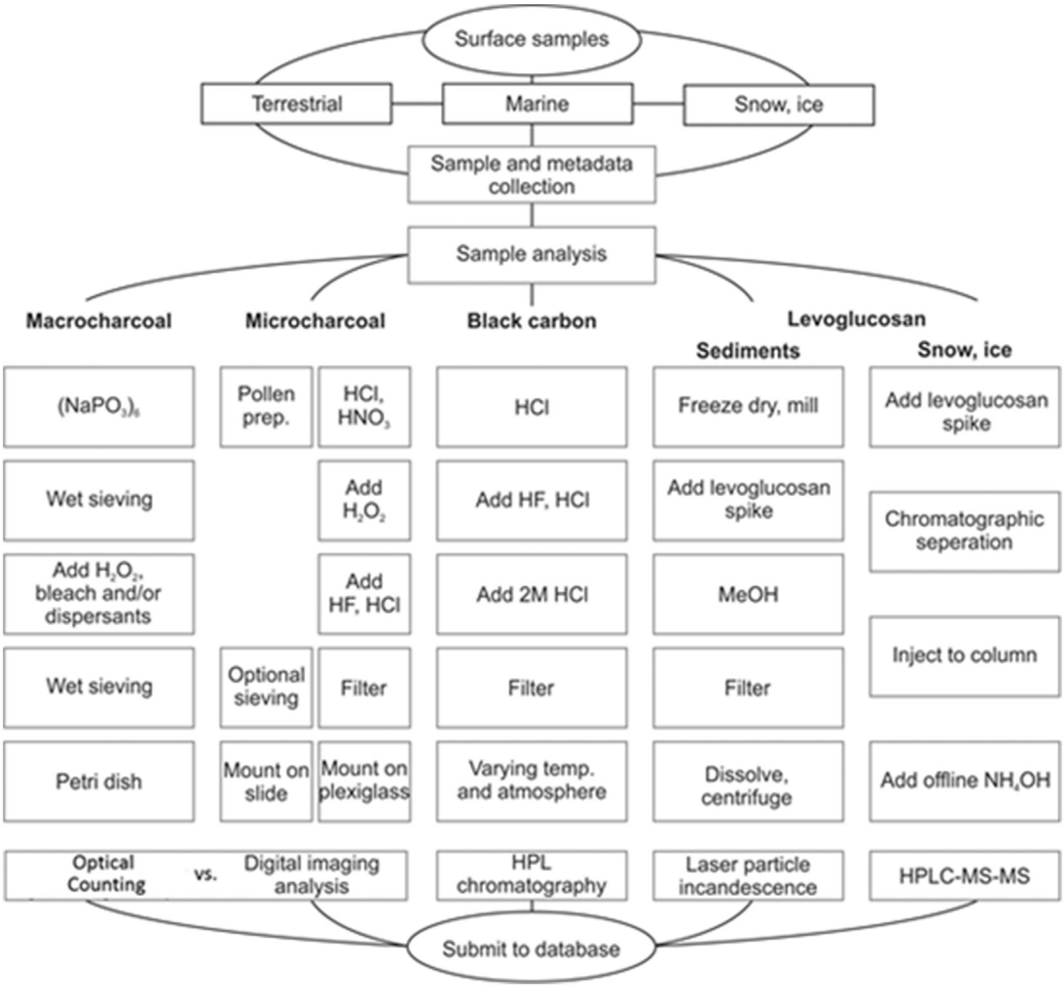

Fig. 4. Methodological flow of techniques and metrics for data acquisition and reporting to the GMCD.

($Na_6P_6O_{18}$) (Bamber, 1982) or potassium hydroxide (KOH) to disaggregate the sediment in order to facilitate the separation of light organic matter from heavy mineral matters. Higher concentrations of ($Na_6P_6O_{18}$) can be used for very compacted sediments. The samples are allowed to disaggregate for 24 h and may be mechanically disaggregated by stirring on a gentle flat-bed shaker, before being washed with pure water through a sedimentological sieve. Choices for sieve sizes vary in the charcoal analysis literature. The GCD contains data derived from a range of sieve sizes, with sizes between 100 and 160 μm emerging as the dominant size range (Carcaillet et al., 2001). Although, these sieve size ranges have been examined in ecosystems with abundant woody fuels that burn, they have yet to be fully examined in ecosystems where grassy or herbaceous plants are the dominant fuels. The sieving mesh that is recommended and will be used by the regional designated laboratories is 150 μm. However a 100 μm (or less) mesh can be more suitable to track grass-dominated landscape burning (e.g. forest-savanna transitions (Colombaroli et al., 2014, 2016) or grassland (Duffin et al., 2008)), but more calibration studies are needed to precisely determine the optimal mesh-size for such analysis. The 100–150 μm mesh are composed of synthetic nylon that is resistant to UV and chemical treatments applied to charcoal samples, they are sold under the Nitex brand name, affordable and available worldwide. In any case, a sieve size no greater than 100–150 μm should be used as the frequency of charcoal fragments decreases exponentially as their size increases (Clark et al., 1998). To help distinguish dark organic matter from charred fragments, the material remaining on the sieve should be treated with 40 mL of undiluted domestic bleach, sodium hypochlorite (NaClO, for 5–10 min) or diluted hydrogen peroxide (H_2O_2, for a further 24 h) and allowed to stand (Schlachter and Horn, 2010).

After bleaching the samples can be rinsed if needed through the sieve and transferred to pre-labeled Petri dishes ready for visual counting or digital image analysis. Distinguishing charcoal particles from other black organic and inorganic material can be aided by bleaching (Schlachter and Horn, 2010) and physical manipulation. The characteristics in Table 2 can be used to help distinguish between such materials as some properties of charcoal are shared by sample contaminants and other naturally-occurring organic and inorganic materials. Fragments of freshly fractured charcoal are almost always jet-black and morphology classification should be based on the pre-fractured object.

4.2.2. *Digital processing*

Image analysis can be carried out in software such as ImageJ (open source) (Abràmoff et al., 2004) or Winseedle (Regent Instruments Incorporated, Quebec, Canada) which can be used to measure charcoal lengths and widths, the individual and total area of each particle and their number. We recommend counting and measurement of individual charcoal particles because it provides an opportunity to link both particle counts and particle areas to different metrics of fires, such as burned area or fire emissions; this will be the standard procedure within regional laboratories (see http://www.gpwg.paleofire.org/gmcd/for details). Using this

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Table 2
Common and readily observable diagnostic properties of charcoal preserved in depositional environments.

Property	Charcoal	Organic, mineral, or clastic
Chemical stability	Inert, stable	May react with acids, oxidizers, bleaches
Color	Black; Brown to black[a]	Any
Lustre	Bright, shiny, dull	Any
Fracture	Splintery, powdery, dry woody feel	Various; tearing, flexible, supple, energetic
Edge color once fragmented by analyst	Black, opaque	Any; brown, green, orange, yellow; translucent
Cellular features	Charred but preserved cell structures or frameworks	Preserved or decaying
Buoyancy in H_2O when dry	Pieces float	Density and shape dependent
Buoyancy in H_2O when saturated	Pieces readily sink	Density and shape dependent

[a] Roasting of plant material without fully charring produces brown material that is harder and fragments unlike similar organic matter in the samples. Comparing uncharred, charred, and roasted material from plant samples collected around the site can be used to contrast with subfossil material to improve identification and counts.

approach will help utilize paleorecords already in the GCD, many of which are based solely on particle counts, optimizing the ability to calibrate these modern samples with existing paleorecords (Carcaillet, 2007; Carcaillet et al., 2007; Leys et al., 2013). With image analysis, an image of the Petri dish is captured using a camera mounted on a stereomicroscope, then loaded into the software for analysis. Other software solutions can be used, but the basic workflow includes sample preparation, image acquisition, archiving, and data collection. Quality assurance is necessary, especially for samples with abundant non-charcoal black material that could introduce error. Users should strive for replicability and uncertainty estimates on charcoal quantities. A program of inter-laboratory inter-comparison and production of replicates will be done to estimate standard deviations and measurement uncertainties that may be necessary for data-model comparisons.

4.3. *Microscopic charcoal analyses*

Quantifying microscopic charcoal during pollen identification and counting from slides for pollen analyses (Faegri and Iversen, 1989; Stockmarr, 1971) has previously been a commonly used technique to quantify charcoal (Cwynar, 1977; Swain, 1973). However if using this technique, any fine sieving during pollen preparations should be noted as it may bias the remaining charcoal in the sample, as well as the mechanical trituration of sediment (Clark, 1984).

Marine samples can be processed following the sediment preparation protocol of Daniau et al. (2009) and slightly modified if necessary depending on the composition of marine surface samples. A chemical treatment of 5 mL 37% HCl, 5 mL 68% nitric acid (HNO_3 hot for 1 h at 70 °C), and 10 mL 33% H_2O_2 is performed over 24 h on approximately 0.2 g of dried sediment (less than 1 cm^3), followed by a chemical attack of 48% hydrofluoric acid (HF), and one HCl 25% and centrifugation to remove HF. This chemical treatment is used to remove carbonates, pyrites, humic material, labile or less refractory organic matter (OM), to bleach non-oxidized OM and to remove silicates. A dilution of 0.1 is applied to the residue. The suspension is then filtered onto a 47 mm in diameter membrane of 0.45 mm porosity. A portion of this membrane is mounted onto a plexiglass slide with ethyl acetate before gentle polishing with aluminium powder of 0.04 μm. The microscopic charcoal particles are identified under oil immersion using petrographic criteria in reflected light and quantified using image analysis in transmitted light following criteria listed above (Table 2), which permits both the counting of particles, morphometric measurements and morphological analysis of particles. This protocol could be developed in future on lake sediments as it has already been successfully tested on this type of sediment (AL Daniau, pers. com).

4.4. *Levoglucosan analysis*

Molecular markers help to augment the information obtained from charcoal analyses as they have the potential to determine what material burned in locations where charcoal is not present (Kaspari et al., 2015; Kehrwald et al., 2012; Zennaro et al., 2014). Levoglucosan has two isomers, mannosan and galactosan, and the ratio between these isomers may help differentiate what material burned in the past. Analyzing sediments with an ion chromatograph (IC) coupled to a mass spectrometer (MS) allows for the possibility of choosing between separating the three isomers or determining only levoglucosan based on the monosaccharide anhydrides (MA) concentrations. The MA concentrations correlate with charcoal counts in lake records, demonstrating coherence between the two proxy types (Elias et al., 2001; Kirchgeorg et al., 2014) even though levoglucosan has been suggested to be biased toward detecting a larger sampling area and relatively cool temperatures during combustion than the wide temperate range of combustion that produced charcoal.

Full method details for determining levoglucosan, mannosan and galactosan in lake sediments are described by Kirchgeorg et al. (2014). Briefly, samples are freeze-dried, milled and homogenized before spiking with an internal standard of 100 μL ^{13}C labeled levoglucosan. These samples are then extracted using a pressurized solvent extraction with MeOH, filtered on 0.2 μm Polytetrafluoroethylene (PTFE) filters, and dissolved into ultra-pure water and centrifuged. Blanks are prepared using the same procedure. The samples are injected into and IC-MS equipped with an electrospray ionization source in negative ionization mode using a CarboPac™ PA 10 column in series with a CarboPac™ PA 1 column. The IC-MS identifies levoglucosan, mannosan and galactosan using the mass/charge ratios 161, 101 and 113 where the mass/charge 167 identifies the ^{13}C labeled internal standard. Gas chromatograph mass spectrometer (GC-MS) techniques can also determine levoglucosan in marine and terrestrial sediments (Kuo et al., 2008; Louchouarn et al., 2009) and a high-performance liquid chromatography-mass spectrometry (HPLC-MS-MS) method may allow quantifying levoglucosan in sediment samples without requiring derivatizing the samples during their preparation (Hopmans et al., 2013).

Snow and ice core analyses use different methods than the sediment analyses as ice is a clean matrix and requires minimal sample pretreatment. Full details of HPLC-MS-MS methods for determining levoglucosan in ice samples are available in Gambaro et al. (2008) and modified in Zennaro et., (2015) and Zennaro et al. (2014). Samples are prepared in a Class 100 (or cleaner) clean bench or lab in order to avoid sample contamination. Samples consist of 675 μL of melted ice and 25 μL (35 ng) of labeled levoglucosan internal standard combined in a 700 μL pre-cleaned LDPE vial. The internal standard helps quantify the amount of levoglucosan in the samples. Chromatographic separation is achieved by injecting 300 μL of the sample in a C18 Synergy Hydro column. An offline post-column addition of an ammonium hydroxide solution helps improve the sample detection. The MS uses an electrospray ionization source, operates in the negative mode, and uses the mass transitions of 161/113 m/z for levoglucosan and 167/118 m/z for the

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levoglucosan standard (Zennaro et al., 2014). Levoglucosan concentrations in ice are often too low to allow separation between levoglucosan and its isomers mannosan and galactosan, such as in the case of continental sediments.

4.5. *Black carbon analysis*

Approximately 10–500 mg of sediment are required to work on black carbon (BC, or termed elemental carbon, EC), char, and soot (~10 mg dry weight) (Han et al., 2012a). The quantity of sample required is related to sediment type e.g. 50–150 mg lake sediments and ~500 mg loess sediments, because of the varying levels of total organic carbon. The quantification of BC, char, and soot includes two steps: chemical pretreatment followed by thermal/optical analysis (Han et al., 2007, 2009a). The pretreatment requires the sequential addition of: (i) 2 M HCl, (ii) a mixture of 48% HF and 6 M HCl, (iii) and 2 M HCl over 24 h to remove carbonate, minerals, metal oxides and some semi-volatile organic matter. The residues are then filtered onto a 47-mm Quartz filter (Waterman Inc.).

The residues from a punch of 0.526 cm^2 circular of the quartz filter are then subject to different conditions of temperature and atmosphere, producing eight carbon fractions: four organic carbon fractions (OC1, OC2, OC3, and OC4) in pure helium (He), three elemental carbon fractions (EC1, EC2, and EC3) in a mixture of 98% He2% O_2, and one pyrolyzed organic carbon (POC) produced in the pure helium atmosphere. The POC is monitored by a laser to assess its return to the initial value. We follow the quantification of BC (or EC), char, and soot by the definitions from the IMPROVE (Interagency Monitoring of Protected Visual Environments) protocol; it defines BC as the sum of EC1, EC2 and EC3 minus POC (Chow et al., 1993) and can be further separated where char = EC1-POC and soot = EC2 + EC3 (Han et al., 2007). This differentiation between char and soot helps investigate the transport of biomass burning products, their relationship with paleo-climate, and their indications of flaming and smoldering wildfires, etc. (i.e., (Gustafsson et al., 2009; Han et al., 2010, 2012b, 2016a, 2016b; Jeong et al., 2013; Lim et al., 2012).

Recent instrumental developments also allow determining BC in snow at high resolution (Lim et al., 2014). The sample sites and collection procedures are the same for both levoglucosan and BC. To determine BC in ice core and aerosol studies a single particle soot photometer (SP2) uses laser-induced particle incandescence to determine BC based on optical properties. The SP2 can count up to 25,000 particles per second, depending in part upon the surrounding matrix, and therefore is a powerful technique for obtaining biomass burning records from ice even at sub-seasonal resolution (Kaspari et al., 2015).

5. Discussion

Surface sample datasets are commonly created when developing paleoenvironmental proxies. They allow the analysis of broad-scale spatial patterns with independent modern evidence of the same process i.e. a calibration procedure. There are multiple indirect proxies of past fire activity preserved in sediment records; yet, quantifying charcoal has emerged as an efficient and the most commonly applied technique for investigating biomass burning activity in the geologic record (Bird and Cali, 1998; Conedera et al., 2009). However interpreting charcoal records requires a mechanistic understanding of how processes occurring within any given fire regime, such as total burned area, fire frequency or type of biomass burned, are represented in the charcoal record. Improvements in quantitative interpretations of charcoal time series may thus emerge by examining fire-proxy relationships from a diversity of depositional environments, land cover, land uses and fire regimes. Spatial analyses of fire-fuel-charcoal relationships of various pyromes (Archibald et al., 2013) and taphonomic processes in all sedimentary contexts can improve calibration between ecosystem processes and proxy records (Aleman et al., 2013; Courtney-Mustaphi and Pisaric, 2014a; Duffin et al., 2008; Leys et al., 2015; Oris et al., 2014; Whitlock and Millspaugh, 1996a).

5.1. *Inclusion of non-charcoal fire-proxies: levoglucosan and black carbon*

The integrated signals of levoglucosan and black carbon provide an excellent comparison with syntheses of local charcoal reconstructions. For example, the major peak in levoglucosan concentrations in the North Greenland Eemian Ice Drilling (NEEM) ice core ~2.5 ky also exists as a minor peak in the high northern latitude charcoal compilation and is more prominent in regional North American and European charcoal syntheses (Zennaro et al., 2015). Combining these two proxies can help analyze the regional effects of local fires.

BC concentrations also augment the information obtained from charcoal records. BC including char and soot is ubiquitous in the environment via aeolian and fluvial transport. Because char and soot have different formation pathways, with soot generated in flames via gas-to-particle conversion while char is created as incomplete combustion residues in smoldering combustion, these two materials can be utilized to reflect different combustion conditions and thus may more clearly differentiate between wet and dry paleoclimatic conditions (Han et al., 2016a). This specificity is complementary to the local-to-regional wildfire reconstructions from charcoal records. Although it is not currently clear how far BC and its subtypes of char and soot can be transported in different climatic zones, it is generally acknowledged that soot can be easily uplifted by biomass burning convection, and can be transported over thousands of kilometers (Clark, 1988a; Han et al., 2009b; Masiello, 2004). Char is primarily deposited *in situ* (Ohlson and Tryterud, 2000) or over local to regional scales depending on fragment sizes and atmospheric turbulences (Clark et al., 1998; Higuera et al., 2007; Lynch et al., 2004). Thus, soot represents local-to-continental scale areas while char represents wildfires that are likely more stand-to-local. However, since char has a different quantification method than charcoal and includes all refractory combustion residues, char-based wildfires likely indicate larger spatial scale fires than are identified by macroscopic charcoal. These spatial and methodological mismatches are precisely the reason for developing and expanding the GMCD. BC records, and especially those differentiating between char and soot are still very sparse. However, the discrepancy in wildfire emissions produced by flaming and smoldering combustion has been extensively investigated (Chen et al., 2010; Christian et al., 2003; Ni et al., 2015; Yokelson et al., 1997). Smoldering and flaming fires can be distinguished in the paleorecord, from their production of char and soot, and their changes in abundance over time can be related to changes in climate (Han et al., 2016a). Taking into account this information on flaming and smoldering combustion with reconstruction compared to model-based global simulations can help to further explore the relationship between climate change and wildfire gas or particulates emissions.

5.2. *Standardized protocols: improving taphonomic considerations and quantitative biomass burning reconstructions*

Studies have investigated the relationships between sedimentary charcoal with fire regime variables such as fire frequency, severity or burned area, but these studies are geographically clustered to small basins in temperate and boreal ecosystems that

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experience low-frequency, high-intensity fires (Gardner and Whitlock, 2001; Higuera et al., 2005, 2010; Lynch et al., 2004; Ohlson and Tryterud, 2000; Oris et al., 2014; Pisaric, 2002; Whitlock and Millspaugh, 1996a). Calibration studies are now needed for more biomes and vegetation types because of the critical role that vegetation plays in determining fuel load, structure and distribution, which may affect charcoal taphonomy differently.

One aspect of calibration that has received little attention is how the size of charcoal particles analyzed compare across study sites, and whether there is preferential particle sorting during deposition due to, for example, basin morphology, drainage and runoff patterns, or vegetation differences across sites. Such data must be analyzed while controlling for differences in techniques used for extracting and analyzing charcoal particles, or else examined with standardized protocols, which data from the GMCD would provide. Variation in the accumulation rates of sediments in different depositional environments also contributes to uncertainties between time series from different sites (Bronk Ramsey, 2008; Parnell et al., 2008). The processing and quantification protocols and techniques also have a strong influence on the absolute value of charcoal count from sediment samples. For example, microscopic charcoal recovered from pollen-slide analysis generally are greater in abundance than abundances of macroscopic charcoal obtained by sieving samples when measured in the same sediment samples (Carcaillet et al., 2001).

Moreover, one of the main goals of the GMCD initiative is to increase the number of records in order to perform spatial analyses of charcoal accumulation from different lakes in the same area and compare these to measurements of biomass burning or other fire metrics (Higuera et al., 2007; Leys et al., 2015; Duffin et al., 2008). For example, this type of study can be used to identify spatial patterns of charcoal accumulation regarding (i) the physical properties of the landscape around the studied lakes (Davis and Sims, 2013), (ii) the spatial distribution of recorded fires (Itter et al., 2016), and (iii) the type of fuel burned during fires. If the spatial density of charcoal records is high enough (e.g. Higuera et al., 2007; Leys et al., 2015; Duffin et al., 2008), then modifications in charcoal accumulation can be identified. These changes can be identified using state shifts analysis by substituting time by space (e.g. Courtney-Mustaphi and Pisaric, 2014a; Stahle et al., 2016) or using spatial analyses (e.g. buffer distance, Leys et al., 2015). This approach can then be used to test if patterns of charcoal accumulation are similar within biome, region, or ecosystem.

An obvious limitation of this approach is the availability of sites (i.e. lakes, ponds etc …), with some regions being richer in such sites (e.g. boreal areas) than others (e.g. Tropical or Mediterranean areas). Furthermore, anthropogenic activities clearly modified the vegetation, disturbances regimes and the climate at different spatial scales. Fire regimes have thus been modified directly through land-use change and fire policies (prescription or suppression of fires), and indirectly through climate change, which probably modified the climate-vegetation-fire relationship. However, modern charcoal data are still useful to better understand charcoal accumulation and fire parameters relationships, and charcoal accumulation and the physical environment of the depositional area.

Finally, fire is one of the main terrestrial disturbance agent, having a large impact on the global carbon cycle as a driver of vegetation dynamics and a key source of atmospheric CO2 emissions. Therefore the proxies we described here are also used to inform about past emissions and carbon release into the atmosphere e.g. (Bremond et al., 2011; Van der Werf et al., 2013). The GMCD dataset will provide a unique opportunity to compare modern fire carbon emissions with the different fire proxies, and in relationship to vegetation and fire types. This will help to provide improved estimates of past fire emissions (Carcaillet et al., 2002).

It is also possible to link proxy-fire data with model outputs of environmental carbon cycling and aerosols to improve carbon inventories and emissions estimates (e.g. http://www.globalfiredata.org/ar6historic.html). Linking biomass burning metrics in a large geospatial dataset permits analyses of patterns in soil and sediment carbon stocks, of carbon fraction deposited as charcoal under environmental conditions, improving estimates of the carbon released by fire to the atmosphere and thus contribute to the carbon cycle modeling.

5.3. Data-model comparisons

At a global scale, the surface samples and short cores in the GMCD aspire to cover the full range of fire regimes, land cover gradients, human land use intensities and livelihood strategies. The GMCD will provide data about deposition of charcoal from the past century for calibration with modern observations and model-based simulations of fire, biomass, land cover, carbon emissions, and land use.

Our current day knowledge on global fire occurrence is largely based on remotely sensed burned area datasets (e.g. Giglio et al., 2013). However, these datasets are still very uncertain, with high commission and omission errors over large regions of the globe (e.g. (Padilla et al., 2015). Our knowledge of present day fire occurrence could be improved by a combined analysis of paleoreconstructions and other fire datasets. This is especially important because they are the basis of our understanding on patterns, magnitude and drivers of present day global fire occurrence (Bowman et al., 2009b; Le Page et al., 2010; Rabin et al., 2015). The satellite data have also raised questions about interpreting paleofire records in the pre-industrial environment (Van der Werf et al., 2013), and provided a basis for projecting fire activity into the future (Moritz et al., 2012a). Moreover, questions remain regarding how representative these relations are when applied to very different climatological and social conditions. Direct comparisons between the paleofire records and paleofire simulations motivate deeper analysis of the uncertainties and limits of both (Brücher et al., 2014). Charcoal quantities from the GMCD collected using standardized protocols calibrated using present-day satellite data can therefore offer critical insights into global fire activity.

Global fire models are also used to assess the spatiotemporal variability of biomass burning as a function of fire regimes, land cover gradients, and human land use intensities and livelihood strategies (Hantson et al., 2016a, 2016b; Prentice et al., 2011) and a standardized, calibrated GMCD can be used to validate, or at least evaluate, simulated fire metrics such as fire numbers, burned areas, fire severity (i.e. burned depth) and carbon emissions. Data from the GMCD will also enable us to compare model outputs of fire simulations with past fire reconstruction (Brücher et al., 2014). The global fire modeling community is actively exploring simulations of paleofire activity to understand the sensitivity of models to past climate changes as a way to gauge the ability of using these models to project future fire activity (Kloster et al., 2015; Pechony and Shindell, 2010). Current model weaknesses include constraining and evaluating the parameterizations – the functional representations of fire processes – and evaluating the output beyond the present-day (Bistinas et al., 2013; Kelley et al., 2013). Calibration of charcoal quantities using present-day satellite data would offer a critical way to expand the development and evaluation of fire models.

6. Conclusion

The GMCD was initiated to address key questions relating to the calibration of sedimentary charcoal and other biomass burning products useful to paleofire reconstructions. The creation of the Global Modern Charcoal Dataset (GMCD) is part of the Global Palaeofire Working Group (GPWG) who oversees the Global Charcoal Database (GCD, www.paleofire.org). There are four main aims of the GMCD project: 1) to develop a GCD module for surface sediment samples; 2) to develop standardized techniques for collection of surface samples and processing of charcoal in common international units; and 3) to identify new areas which currently lack charcoal records, aiming to cover all fire regions and biomes to provide a record of global pyrodiversity, and finally 4) to address issues of calibration between fire parameters and records of biomass burning. The standard approach developed within this GMCD initiative is the best way forward to increase capacity building and cross-discipline knowledge sharing within the fire science community. It will ultimately highlight regional diversity in fire regime and research practices while allowing a deeper understanding of the limitations and assumptions from various fire-product signals and create a global fire perspective in a rapidly changing world.

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References

Abràmoff, M.D., Magalhães, P.J., Ram, S.J., 2004. Image processing with ImageJ. Biophot. Int. 11, 36–42.

Aleman, J.C., Blarquez, O., Bentaleb, I., Bonté, P., Brossier, B., Carcaillet, C., Gond, V., Gourlet-Fleury, S., Kpolita, A., Lefèvre, I., 2013. Tracking land-cover changes with sedimentary charcoal in the Afrotropics. Holocene 23, 1853–1862.

Ali, A., Higuera, P.E., Bergeron, Y., Carcaillet, C., 2009. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. Quat. Res. 4C, 1–7.

Ali, A.A., Blarquez, O., Girardin, M.P., Hély, C., Tinquaut, F., El Guellab, A., Valsecchi, V., Terrier, A., Bremond, L., Genries, A., 2012. Control of the multimillennial wildfire size in boreal North America by spring climatic conditions. Proc. Natl. Acad. Sci. 109, 20966–20970.

Allen, M.R., Barros, V.R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., Dubash, N.K., 2014. IPCC Fifth Assessment Synthesis Report-climate Change 2014 Synthesis Report.

Archibald, S., Lehmann, C.E., Gómez-Dans, J.L., Bradstock, R.A., 2013. Defining pyromes and global syndromes of fire regimes. Proc. Natl. Acad. Sci. 110, 6442–6447.

Bamber, R., 1982. Sodium hexametaphosphate as an aid in benthic sample sorting. Mar. Environ. Res. 7, 251–255.

Beaufort, L., de Garidel-Thoron, T., Linsley, B., Oppo, D., Buchet, N., 2003. Biomass burning and oceanic primary production estimates in the Sulu Sea area over the last 380 kyr and the East Asian monsoon dynamics. Mar. Geol. 201, 53–65.

Bedia, J., Herrera, S., Gutiérrez, J.M., Benali, A., Brands, S., Mota, B., Moreno, J.M., 2015. Global patterns in the sensitivity of burned area to fire-weather: implications for climate change. Agric. For. Meteorol. 214, 369–379.

Bélanger, N., Carcaillet, C., Padbury, G.A., Harvey-Schafer, A.N., Van Rees, K., 2014. Periglacial fires and trees in a continental setting of Central Canada, Upper Pleistocene. Geobiology 12, 109–118.

Bird, M., Cali, J., 1998. A million-year record of fire in sub-saharan Africa. Nature 394, 767–769.

Bistinas, I., Oom, D., Sá, A.C., Harrison, S.P., Prentice, I.C., Pereira, J.M., 2013. Relationships between human population density and burned area at continental and global scales. PLoS One 8, e81188.

Björkman, L., Bradshaw, R., 1996. The immigration of Fagus sylvatica L. and Picea abies (L.) Karst. into a natural forest stand in southern Sweden during the last 2000 years. J. Biogeogr. 23, 235–244.

Blackford, J., 2000. Charcoal fragments in surface samples following a fire and the implications for interpretation of subfossil charcoal data. Palaeogeogr. Palaeoclimatol. Palaeoecol. 164, 33–42.

Blarquez, O., Ali, A.A., Girardin, M.P., Grondin, P., Fréchette, B., Bergeron, Y., Hély, C., 2015. Regional paleofire regimes affected by non-uniform climate, vegetation and human drivers. Sci. Rep. 5.

Blarquez, O., Carcaillet, C., 2010. Fire, fuel composition and resilience threshold in subalpine ecosystem. PLoS One 5, e12480.

Blarquez, O., Vannière, B., Marlon, J.R., Daniau, A.-L., Power, M.J., Brewer, S., Bartlein, P.J., 2014. paleofire: an R package to analyse sedimentary charcoal records from the Global Charcoal Database to reconstruct past biomass burning. Comput. Geosci. 72, 255–261.

Bond, W.J., 2014. Fires in the Cenozoic: a late flowering of flammable ecosystems. Front. plant Sci. 5.

Bond, W.J., Woodward, F.I., Midgley, G.F., 2005. The global distribution of ecosystems in a world without fire. New Phytol. 165, 525–538.

Bowman, D.M., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., 2009a. Fire in the earth system. Science 324, 481–484.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R., Pyne, S.J., 2009b. Fire in the earth system. Science 324, 481–484.

Bradbury, J.P., 1996. Charcoal deposition and redeposition in Elk lake, Minnesota, USA. Holocene 6, 339–344.

Bremond, L., Carcaillet, C., Favier, C., Ali, A.A., Paitre, C., Bégin, Y., Bergeron, Y., Richard, P.J., 2011. Effects of vegetation zones and climatic changes on fire-induced atmospheric carbon emissions: a model based on paleodata. Int. J. Wildland Fire 19, 1015–1025.

Bronk Ramsey, C., 2008. Radiocarbon dating: revolutions in understanding*. Archaeometry 50, 249–275.

Brossier, B., Oris, F., Finsinger, W., Asselin, H., Bergeron, Y., Ali, A.A., 2014. Using tree-ring records to calibrate peak detection in fire reconstructions based on sedimentary charcoal records. The Holocene 24 (6), 635–645.

Brücher, T., Brovkin, V., Kloster, S., Marlon, J.R., Power, M.J., 2014. Comparing modelled fire dynamics with charcoal records for the Holocene. Clim. Past. 10, 811–824.

Carcaillet, C., 2007. Charred particles analyses. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 1582–1593.

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R., Carrion, J., Gaillard, M.-J., Gajewski, K., Haas, J., Haberle, S., Hadorn, P., 2002. Holocene biomass burning and global dynamics of the carbon cycle. Chemosphere 49, 845–863.

Carcaillet, C., Bouvier, M., Fréchette, B., Larouche, A.C., Richard, P.J.H., 2001. Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. Holocene 11, 467–476.

Carcaillet, C., Perroux, A.-S., Genries, A., Perrette, Y., 2007. Sedimentary charcoal pattern in a karstic underground lake, Vercors massif, French Alps: implications for palaeo-fire history. Holocene 17, 845–850.

Carcaillet, C., Talon, B., 2001. Soil carbon sequestration by Holocene fires inferred from soil charcoal in the dry French Alps. Arct. Antarct. Alp. Res. 282–288.

Chen, L.W.A., Verburg, P., Shackelford, A., Zhu, D., Susfalk, R., Chow, J.C., Watson, J.G., 2010. Moisture effects on carbon and nitrogen emission from burning of wildland biomass. Atmos. Chem. Phys. 10, 6617–6625.

Chiverrell, R.d.C., Foster, G.C., Thomas, G., Marshall, P., Hamilton, D., 2009. Robust chronologies for landform development. Earth Surf. Process. Landf. 34, 319–328.

Chow, J.C., Watson, J.G., Pritchett, L.C., Pierson, W.R., Frazier, C.A., Purcell, R.G., 1993. The DRI thermal/optical reflectance carbon analysis system: description, evaluation and applications in US air quality studies. Atmos. Environ. Part A. General Top. 27, 1185–1201.

Christian, T.J., Kleiss, B., Yokelson, R.J., Holzinger, R., Crutzen, P.J., Hao, W.M., Saharjo, B.H., Ward, D.E., 2003. Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels. J. Geophys. Res. 108.

Clark, J.S., 1988a. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quat. Res. 30, 67–80.

Clark, J.S., 1988b. Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in northwestern Minnesota. Quat. Res. 30, 81–91.

Clark, J.S., 1990. Fire and climate change during the last 750 yr in northwestern Minnesota. Ecol. Monogr. 60, 135–159.

Clark, J.S., Grimm, E.C., Lynch, J., Mueller, P.G., 2001. Effects of Holocene climate change on the C4 grassland/woodland boundary in the Northern Plains, USA. Ecology 82, 620–636.

Clark, J.S., Hussey, T.C., 1996. Estimating the mass flux of charcoal from sedimentary

Please cite this article in press as: Hawthorne, D., et al., Global Modern Charcoal Dataset (GMCD): A tool for exploring proxy-fire linkages and spatial patterns of biomass burning, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.03.046

records: effects of particle size, morphology, and orientation. Holocene 6, 129–144.

Clark, J.S., Lynch, J., Stocks, B.J., Goldammer, J.G., 1998. Relationships between charcoal particles in air and sediments in west-central Siberia. Holocene 8, 19–29.

Clark, J.S., Royall, P.D., 1996. Local and regional sediment charcoal evidence for fire regimes in presettlement North-Eastern North America. J. Ecol. 84, 365–382.

Clark, R., 1984. Effects o charcoal of pollen preparation procedures. Pollen et spores.

Clark, T.L., Jenkins, M.A., Coen, J., Packman, D., 1996. A coupled atmosphere fire-model: convective feedback on fire-line dynamics. J. Appl. Meteorol. 35, 875–901.

Colombaroli, D., Gavin, D.G., 2010. Highly episodic fire and erosion regime over the past 2,000 y in the Siskiyou Mountains, Oregon. Proc. Natl. Acad. Sci. 107, 18909–18914.

Colombaroli, D., Ssemmanda, I., Gelorini, V., Verschuren, D., 2014. Contrasting long-term records of biomass burning in wet and dry savannas of equatorial East Africa. Glob. change Biol. 20, 2903–2914.

Colombaroli, D., van der Plas, G., Rucina, S., Verschuren, D., 2016. Determinants of savanna-fire dynamics in the eastern Lake Victoria catchment (western Kenya) during the last 1200 years. Quat. Int.

Conedera, M., Tinner, W., Neff, C., Meurer, M., Dickens, A.F., Krebs, P., 2009. Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation. Quat. Sci. Rev. 28, 555–576.

Courtney-Mustaphi, C.J., Davis, E.L., Perreault, J.T., Pisaric, M.F., 2015. Spatial variability of recent macroscopic charcoal deposition in a small montane lake and implications for reconstruction of watershed-scale fire regimes. J. Paleolimnol. 54, 71–86.

Courtney-Mustaphi, C.J., Pisaric, M.F., 2014a. A classification for macroscopic charcoal morphologies found in Holocene lacustrine sediments. Prog. Phys. Geogr. 38, 734–754.

Courtney-Mustaphi, C.J., Pisaric, M.F., 2014b. Holocene climate–fire–vegetation interactions at a subalpine watershed in southeastern British Columbia, Canada. Quat. Res. 81, 228–239.

Crann, C.A., Patterson, R.T., Macumber, A.L., Galloway, J.M., Roe, H.M., Blaauw, M., Swindles, G.T., Falck, H., 2015. Sediment accumulation rates in subarctic lakes: insights into age-depth modeling from 22 dated lake records from the northwest territories, Canada. Quat. Geochronol. 27, 131–144.

Crawford, A.J., Belcher, C.M., 2014. Charcoal morphometry for paleoecological analysis: the effects of fuel type and transportation on morphological parameters. Appl. plant Sci. 2.

Cwynar, L.C., 1977. The recent fire history of barron township, algonquin park. Can. J. Bot. 55, 1524–1538.

Daniau, A.-L., Goñi, M.F.S., Martinez, P., Urrego, D.H., Bout-Roumazeilles, V., Desprat, S., Marlon, J.R., 2013. Orbital-scale climate forcing of grassland burning in southern Africa. Proc. Natl. Acad. Sci. 110, 5069–5073.

Daniau, A.L., Bartlein, P., Harrison, S., Prentice, I., Brewer, S., Friedlingstein, P., Harrison-Prentice, T., Inoue, J., Izumi, K., Marlon, J., 2012. Predictability of biomass burning in response to climate changes. Glob. Biogeochem. Cycles 26.

Daniau, A.L., Sánchez-Goñi, M.F., Duprat, J., 2009. Last glacial fire regime variability in western France inferred from microcharcoal preserved in core MD04-2845, Bay of Biscay. Quat. Res. 71, 385–396.

Davis, B.A., Zanon, M., Collins, P., Mauri, A., Bakker, J., Barboni, D., Barthelmes, A., Beaudouin, C., Bjune, A.E., Bozilova, E., 2013. The European modern pollen database (EMPD) project. Veg. Hist. Archaeobot. 22, 521–530.

Davis, J.D., Sims, S.M., 2013. Physical and maximum entropy models applied to inventories of hillslope sediment sources. J. Soils Sediments 13, 1784–1801.

Dean, W., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by Loss-on-ignition: comparison with other methods. J. Sediment. Petrol. 44, 242–248.

DeLuca, T.H., Aplet, G.H., 2008. Charcoal and carbon storage in forest soils of the rocky mountain west. Front. Ecol. Environ. 6, 18–24.

Duffin, K., Gillson, L., Willis, K., 2008. Testing the sensitivity of charcoal as an indicator of fire events in savanna environments: quantitative predictions of fire proximity, area and intensity. Holocene 18, 279–291.

Elias, V.O., Simoneit, B.R., Cordeiro, R.C., Turcq, B., 2001. Evaluating levoglucosan as an indicator of biomass burning in Carajas, Amazonia: a comparison to the charcoal record. Geochim. Cosmochim. Acta 65, 267–272.

Enache, M.D., Cumming, B.F., 2006. Tracking recorded fires using charcoal morphology from the sedimentary sequence of Prosser Lake, British Columbia (Canada). Quat. Res. 65, 282–292.

Faegri, K., Iversen, J., 1989. In: Faegri, K., Kaland, P.E., Krzywinski, K. (Eds.), Textbook of Pollen Analysis, fourth ed. Wiley, New York.

Fletcher, M.-S., Wood, S.W., Haberle, S.G., 2014. A fire-driven shift from forest to non-forest: evidence for alternative stable states? Ecology 95, 2504–2513.

Flower, R., Juggins, S., Battarbee, R., 1997. Matching diatom assemblages in lake sediment cores and modern surface sediment samples: the implications for lake conservation and restoration with special reference to acidified systems. Hydrobiologia 344, 27–40.

Gambaro, A., Zangrando, R., Gabrielli, P., Barbante, C., Cescon, P., 2008. Direct determination of levoglucosan at the picogram per milliliter level in Antarctic ice by high-performance liquid chromatography/electrospray ionization triple quadrupole mass spectrometry. Anal. Chem. 80, 1649–1655.

Gardner, J.J., Whitlock, C., 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. Holocene 11, 541–549.

Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87, 1722–1732.

Giglio, L., Randerson, J.T., Werf, G.R., 2013. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (GFED4). J. Geophys. Res. Biogeosci. 118, 317–328.

Glassman, I., 1989. Soot Formation in Combustion Processes, Symposium (International) on Combustion. Elsevier, pp. 295–311.

Glew, J.R., 1988. A portable extruding device for close interval sectioning of unconsolidated core samples. J. Paleolimnol. 1, 235–239.

Glew, J.R., Smol, J.P., Last, W.M., 2001. Sediment core collection and extrusion. In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments Volume 1: Basin Analysis, Coring, and Chronological Techniques. Kluwer Academic Publishers, Dordrecht, 73–10.

Goldberg, E.D., 1985. Black Carbon in the Environment. John Wiley & Sons, Inc., New York.

Gustafsson, O., Krusa, M., Zencak, Z., Sheesley, R.J., Granat, L., Engstrom, E., Praveen, P.S., Rao, P.S.P., Leck, C., Rodhe, H., 2009. Brown clouds over south Asia: biomass or fossil fuel combustion? Science 323, 495–498.

Håkanson, L., 1982. Lake bottom dynamics and morphometry: the dynamic ratio. Water Resour. Res. 18, 1444–1450.

Han, Y., Marlon, J., Cao, J., Jin, Z., An, Z., 2012a. Holocene linkages between char, soot, biomass burning and climate from Lake Daihai, China. Glob. Biogeochem. Cycles 26.

Han, Y.M., Cao, J.J., Lee, S.C., Ho, K.F., An, Z.S., 2010. Different characteristics of char and soot in the atmosphere and their ratio as an indicator for source identification in Xi'an, China. Atmos. Chem. Phys. 10, 595–607.

Han, Y.M., Cao, J.J., Posmentier, E.S., Chow, J.C., Watson, J.G., Fung, K.K., Jin, Z.D., Liu, S.X., An, Z.S., 2009a. The effect of acidification on the determination of elemental carbon, char-, and soot-elemental carbon in soils and sediments. Chemosphere 75, 92–99.

Han, Y.M., Lee, S.C., Cao, J.J., Ho, K.F., An, Z.S., 2009b. Spatial distribution and seasonal variation of char-EC and soot-EC in the atmosphere over China. Atmos. Environ. 43, 6066–6073.

Han, Y.M., Marlon, J., Cao, J.J., Jin, Z.D., An, Z.S., 2012b. Holocene linkages between char, soot, biomass burning and climate from Lake Daihai, China. Glob. Biogeochem. Cycles 26. http://dx.doi.org/10.1029/2012GB004413.

Han, Y.M., Peteet, D.M., Arimoto, R., Cao, J.J., An, Z.S., Sritrairat, S., Yan, B.Z., 2016a. Climate and fuel controls on North American paleofires: smoldering to flaming in the late-glacial-holocene transition. Sci. Rep. 6, 20719.

Han, Y.M., Wei, C., Huang, R.-J., Bandowe, B.A.M., Ho, S.S.H., Cao, J.J., Jin, Z.D., Xu, B.Q., Gao, S.P., Tie, X.X., An, Z.S., Wilcke, W., 2016b. Reconstruction of atmospheric soot history in inland regions from lake sediments over the past 150 years. Sci. Rep. http://dx.doi.org/10.1038/srep19151.

Han, Y.N., Cao, J.J., An, Z.S., Chow, J.C., Watson, J.G., Jin, Z., Fung, K., Liu, S.X., 2007. Evaluation of the thermal/optical reflectance method for quantification of elemental carbon in sediments. Chemosphere 69, 526–533.

Hantson, S., Arneth, A., Harrison, S.P., Kelley, D.I., Prentice, I.C., Rabin, S.S., Archibald, S., Mouillot, F., Arnold, S.R., Artaxo, P., 2016a. The status and challenge of global fire modelling. Biogeosciences 13, 3359–3375.

Hantson, S., Kloster, S., Coughlan, M., Daniau, A.-L., Vanniere, B., Brücher, T., Kehrwald, N., Magi, B.I., 2016b. Fire in the earth system: bridging data and modeling research. Bull. Am. Meteorol. Soc. 97 (6), 1069–1072.

Hawthorne, D., Mitchell, F.J.G., 2016. Identifying past fire regimes throughout the Holocene in Ireland using new and established methods of charcoal analysis. Quat. Sci. Rev. 137, 45–53.

Hedges, J.I., Eglinton, G., Hatcher, P.G., Kirchman, D.L., Arnosti, C., Derenne, S., Evershed, R.P., Kögel-Knabner, I., De Leeuw, J., Littke, R., 2000. The molecularly-uncharacterized component of nonliving organic matter in natural environments. Org. Geochem. 31, 945–958.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. J. Paleolimnol. 25, 101–110.

Higuera, P., Brubaker, L., Anderson, P., Hu, F.,S., Brown, T.,A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecol. Monogr. 79, 201–219.

Higuera, P.E., Peters, M.E., Brubaker, L.B., Gavin, D.G., 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quat. Sci. Rev. 26, 1790–1809.

Higuera, P.E., Sprugel, D.G., Brubaker, L.B., 2005. Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire. Holocene 15, 238–251.

Higuera, P.E., Whitlock, C., Gage, J.A., 2010. Linking tree-ring and sediment-charcoal records to reconstruct fire occurrence and area burned in subalpine forests of Yellowstone National Park, USA. Holocene 1–15.

Hopmans, E.C., dos Santos, R.A.L., Mets, A., Damsté, J.S.S., Schouten, S., 2013. A novel method for the rapid analysis of levoglucosan in soils and sediments. Org. Geochem. 58, 86–88.

Hu, F.S., Higuera, P.E., Walsh, J.E., Chapman, W.L., Duffy, P.A., Brubaker, L.B., et al., 2010. Tundra burning in Alaska: linkages to climatic change and sea ice retreat. J. Geophys. Res. 115.

Hudak, A.T., Ottmar, R.D., Vihnanek, R.E., Brewer, N.W., Smith, A.M., Morgan, P., 2013. The relationship of post-fire white ash cover to surface fuel consumption. Int. J. Wildland Fire 22, 780–785.

Iglesias, V., Yospin, G.I., Whitlock, C., 2014. Reconstruction of fire regimes through integrated paleoecological proxy data and ecological modeling. Front. Plant Sci.

Please cite this article in press as: Hawthorne, D., et al., Global Modern Charcoal Dataset (GMCD): A tool for exploring proxy-fire linkages and spatial patterns of biomass burning, Quaternary International (2017), http://dx.doi.org/10.1016/j.quaint.2017.03.046

5, 785.

Itter, M.S., Finley, A.O., Hooten, M.B., Higuera, P.E., Marlon, J.R., Kelly, R., McLachlan, J.S., 2016. A Model-Based Approach to Wildland Fire Reconstruction Using Sediment Charcoal Records arXiv preprint arXiv:1612.02382.

Jensen, K., Lynch, E.A., Calcote, R., Hotchkiss, S.C., 2007. Interpretation of charcoal morphotypes in sediments from Ferry Lake, Wisconsin, USA: do different plant fuel sources produce distinctive charcoal morphotypes? Holocene 17, 907–915.

Jeong, C.-H., Herod, D., Dabek-Zlotorzynska, E., Ding, L., McGuire, M.L., Evans, G., 2013. Identification of the sources and geographic origins of black carbon using factor analysis at paired rural and urban sites. Environ. Sci. Technol. 47, 8462–8470.

Jones, M.B., Muthuri, F.M., 1997. Standing biomass and carbon distribution in a papyrus (Cyperus papyrus L.) swamp on Lake Naivasha, Kenya. J. Trop. Ecol. 13, 347–356.

Jowsey, P., 1966. An improved peat sampler. New Phytol. 65, 245–248.

Kaspari, S., McKenzie Skiles, S., Delaney, I., Dixon, D., Painter, T.H., 2015. Accelerated glacier melt on Snow Dome, Mount Olympus, Washington, USA, due to deposition of black carbon and mineral dust from wildfire. J. Geophys. Res. Atmos. 120, 2793–2807.

Kehrwald, N., Zangrando, R., Gabrielli, P., Jaffrezo, J.-L., Boutron, C., Barbante, C., Gambaro, A., 2012. Levoglucosan as a specific marker of fire events in Greenland snow. Tellus B 64.

Kelley, D., Prentice, I.C., Harrison, S., Wang, H., Simard, M., Fisher, J., Willis, K., 2013. A comprehensive benchmarking system for evaluating global vegetation models. Biogeosciences 10, 3313–3340.

Kirchgeorg, T., Schüpbach, S., Kehrwald, N., McWethy, D., Barbante, C., 2014. Method for the determination of specific molecular markers of biomass burning in lake sediments. Org. Geochem. 71, 1–6.

Kloster, S., Brücher, T., Brovkin, V., Wilkenskjeld, S., 2015. Controls on fire activity over the Holocene. Clim. Past 11, 781–788.

Knorr, W., Jiang, L., Arneth, A., 2016. Climate, CO 2 and human population impacts on global wildfire emissions. Biogeosciences 13, 267–282.

Krebs, P., Pezzatti, G.B., Mazzoleni, S., Talbot, L.M., Conedera, M., 2010. Fire regime: history and definition of a key concept in disturbance ecology. Theory Biosci. 129, 53–69.

Kuo, L.-J., Herbert, B.E., Louchouarn, P., 2008. Can levoglucosan be used to characterize and quantify char/charcoal black carbon in environmental media? Org. Geochem. 39, 1466–1478.

Le Page, Y., Oom, D., Silva, J., Jönsson, P., Pereira, J., 2010. Seasonality of vegetation fires as modified by human action: observing the deviation from eco-climatic fire regimes. Glob. Ecol. Biogeogr. 19, 575–588.

Lehsten, V., Tansey, K., Balzter, H., Thonicke, K., Spessa, A., Weber, U., Smith, B., Arneth, A., 2009. Estimating carbon emissions from African wildfires. Biogeosciences 6, 349–360.

Lentile, L.B., Holden, Z.A., Smith, A.M., Falkowski, M.J., Hudak, A.T., Morgan, P., Lewis, S.A., Gessler, P.E., Benson, N.C., 2006. Remote sensing techniques to assess active fire characteristics and post-fire effects. Int. J. Wildland Fire 15, 319–345.

Levavasseur, G., Vrac, M., Roche, D., Paillard, D., 2012. Statistical modelling of a new global potential vegetation distribution. Environ. Res. Lett. 7, 044019.

Leys, B., Brewer, S.C., McConaghy, S., Mueller, J., McLauchlan, K.K., 2015. Fire history reconstruction in grassland ecosystems: amount of charcoal reflects local area burned. Environ. Res. Lett. 10, 114009.

Leys, B., Carcaillet, C., 2016. Subalpine fires: the roles of vegetation, climate and, ultimately, land uses. Clim. Change 1–15.

Leys, B., Carcaillet, C., Dezileau, L., Ali, A.A., Bradshaw, R.H., 2013. A comparison of charcoal measurements for reconstruction of Mediterranean paleo-fire frequency in the mountains of Corsica. Quat. Res. 79, 337–349.

Lim, S., Faïn, X., Zanatta, M., Cozic, J., Jaffrezo, J.-L., Ginot, P., Laj, P., 2014. Refractory black carbon mass concentrations in snow and ice: method evaluation and inter-comparison with elemental carbon measurement. Atmos. Meas. Tech. 7, 3307–3324.

Lim, S., Lee, M., Lee, G., Kim, S., Yoon, S., Kang, K., 2012. Ionic and carbonaceous compositions of PM10, PM2.5 and PM1.0 at Gosan ABC Superstation and their ratios as source signature. Atmos. Chem. Phys. 12, 2007–2024.

Louchouarn, P., Kuo, L.-J., Wade, T.L., Schantz, M., 2009. Determination of levoglucosan and its isomers in size fractions of aerosol standard reference materials. Atmos. Environ. 43, 5630–5636.

Lynch, J.A., Clark, J.S., Bigelow, N.H., Edwards, M.E., Finney, B.P., 2003. Geographic and temporal variations in fire history in boreal ecosystems of Alaska. J. Geophys. Res. 108. FFR8. 1-FFR8. 17.

Lynch, J.A., Clark, J.S., Stocks, B.J., 2004. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: interpreting fire regimes from charcoal records in boreal forests. Can. J. For. Res. 34, 1642–1656.

Maezumi, S., Power, M., Mayle, F.E., McLauchlan, K., Iriarte, J., 2015. Effects of past climate variability on fire and vegetation in the cerrâdo savanna of the Huanchaca Mesetta, NE Bolivia. Clim. Past 11, 835–853.

Marlon, J., Bartlein, P.J., Whitlock, C., 2006. Fire-fuel-climate linkages in the northwestern U.S. during the Holocene. Holocene 16, 1059–1071.

Marlon, J., Kelly, R., Daniau, A.-L., Vannière, B., Power, M., Bartlein, P., Higuera, P., Blarquez, O., Brewer, S., Brücher, T., 2015. Reconstructions of biomass burning from sediment charcoal records to improve data-model comparisons. Biogeosci. Discuss. 12, 18571–18623.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M., Prentice, I., 2008. Climate and human influences on global biomass burning over the past two millennia. Nat. Geosci. 1, 697–702.

Marlon, J.R., Bartlein, P.J., Daniau, A.-L., Harrison, S.P., Maezumi, S.Y., Power, M.J., Tinner, W., Vanniére, B., 2013. Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. Quat. Sci. Rev. 65, 5–25.

Marlon, J.R., Bartlein, P.J., Gavin, D.G., Long, C.J., Anderson, R.S., Briles, C.E., Brown, K.J., Colombaroli, D., Hallett, D.J., Power, M.J., Scharf, E.A., Walsh, M.K., 2012. Long-term perspective on wildfires in the western USA. Proc. Natl. Acad. Sci. 109, E535–E543.

Marlon, J.R., Kelly, R., Daniau, A.-L., Vannière, B., Power, M.J., Bartlein, P., Higuera, P., Blarquez, O., Brewer, S., Brücher, T., 2016a. Reconstructions of biomass burning from sediment-charcoal records to improve data–model comparisons. Biogeosciences 13, 3225–3244.

Marlon, J.R., Kelly, R., Daniau, A.-L., Vannière, B., Power, M.J., Bartlein, P., Higuera, P., Blarquez, O., Brewer, S., Brücher, T., 2016b. Reconstructions of biomass burning from sediment charcoal records to improve data-model comparisons. Biogeosci. (BG) 13, 3225–3244.

Masiello, C.A., 2004. New directions in black carbon organic geochemistry. Mar. Chem. 92, 201–213.

Middelburg, J.J., Nieuwenhuize, J., van Breugel, P., 1999. Black carbon in marine sediments. Mar. Chem. 65, 245–252.

Milbrink, G., 1971. A simplified tube bottom sampler. Oikos 260–263.

Milbrink, G., Wiederholm, T., 1973. Sampling efficiency of four types of mud bottom samplers. Oikos 479–482.

Millspaugh, S.H., Whitlock, C., Bartlein, P.J., 2000. Variations in fire frequency and climate over the past 17 000 yr in central Yellowstone National Park. Geology 28, 211–214.

Mooney, S., Black, M., 2003. A simple and fast method for calculating the area of macroscopic charcoal isolated from sediments. Quat. Australasia 21, 18–21.

Moritz, M.A., Parisien, M.-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., Hayhoe, K., 2012a. Climate change and disruptions to global fire activity. Ecosphere 3 art49.

Moritz, M.A., Parisien, M.-A., Batllori, E., Krawchuk, M.A., Van Dorn, J., Ganz, D.J., Hayhoe, K., 2012b. Climate change and disruptions to global fire activity. Ecosphere 3, 1–22.

Ni, H., Han, Y., Cao, J., Chen, L.W.A., Tian, J., Wang, X., Chow, J.C., Watson, J.G., Wang, Q., Wang, P., Li, H., Huang, R.-J., 2015. Emission characteristics of carbonaceous particles and trace gases from open burning of crop residues in China. Atmos. Environ. 123 (Part B), 399–406.

Odgaard, B.V., 1992. The fire history of Danish heathland areas as reflected by pollen and charred particles in lake sediments. Holocene 2, 218–226.

Ohlson, M., Kasin, I., Wist, A.N., Bjune, A.E., 2013. Size and spatial structure of the soil and lacustrine charcoal pool across a boreal forest watershed. Quat. Res. 80, 417–424.

Ohlson, M., Tryterud, E., 1999. Long-term spruce forest continuity–a challenge for a sustainable Scandinavian forestry. For. Ecol. Manag. 124, 27–34.

Ohlson, M., Tryterud, E., 2000. Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. Holocene 10, 519–525.

Oris, F., Ali, A.A., Asselin, H., Paradis, L., Bergeron, Y., Finsinger, W., 2014. Charcoal dispersion and deposition in boreal lakes from 3 years of monitoring: differences between local and regional fires. Geophys. Res. Lett. 41, 6743–6752.

Otto, A., Gondokusumo, R., Simpson, M.J., 2006. Characterization and quantification of biomarkers from biomass burning at a recent wildfire site in Northern Alberta, Canada. Appl. Geochem. 21, 166–183.

Overballe-Petersen, M.V., Bradshaw, R.H., 2011. The selection of small forest hollows for pollen analysis in boreal and temperate forest regions. Palynology 35, 146–153.

Padilla, M., Stehman, S.V., Ramo, R., Corti, D., Hantson, S., Oliva, P., Alonso-Canas, I., Bradley, A.V., Tansey, K., Mota, B., 2015. Comparing the accuracies of remote sensing global burned area products using stratified random sampling and estimation. Remote Sens. Environ. 160, 114–121.

Parnell, A., Haslett, J., Allen, J.R.M., Buck, C.E., Huntley, B., 2008. A flexible approach to assessing sychroneity of past events using Bayesian reconstructions of sedimentation history. Quat. Sci. Rev. 27, 1872–1885.

Pechony, O., Shindell, D.T., 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. Proc. Natl. Acad. Sci. 107, 19167–19170.

Peters, M.E., Higuera, P.E., 2007. Quantifying the source area of macroscopic charcoal with a particle dispersal model. Quat. Res. 67, 304–310.

Pfeiffer, M., Spessa, A., Kaplan, J.O., 2013. A model for global biomass burning in preindustrial time: LPJ-LMfire (v1. 0). Geosci. Model Dev. 6, 643–685.

Pisaric, M.F.J., 2002. Long-distance transport of terrestrial plant material by convection resulting from forest fires. J. Paleolimnol. 28, 349–354.

Pitkänen, A., Lehtonen, H., Huttunen, P., 1999. Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. Holocene 9, 559–567.

Power, M., Marlon, J., Bartlein, P., Harrison, S., 2010. Fire history and the Global Charcoal Database: a new tool for hypothesis testing and data exploration. Palaeogeogr. Palaeoclimatol. Palaeoecol. 291, 52–59.

Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R.H.W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P.I., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A.-L.,

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Daniels, M., Dodson, J., Doughty, E., Edwards, M.E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gavin, D.G., Gobet, E., Haberle, S., Hallett, D.J., Higuera, P.E., Hope, G., Horn, S., Inoue, J., Kaltenreider, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C.J., Lynch, J.A., Lynch, E.A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D.M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Sanchez Goñi, M.F., Shuman, B.J., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D.H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Clim. Dyn. 30, 887–907.

Prentice, I., Kelley, D., Foster, P., Friedlingstein, P., Harrison, S., Bartlein, P., 2011. Modeling fire and the terrestrial carbon balance. Glob. Biogeochem. Cycles 25.

Quénéa, K., Derenne, S., Rumpel, C., Rouzaud, J.-N., Gustafsson, O., Carcaillet, C., Mariotti, A., Largeau, C., 2006. Black carbon yields and types in forest and cultivated sandy soils (Landes de Gascogne, France) as determined with different methods: influence of change in land use. Org. Geochem. 37, 1185–1189.

Rabin, S., Magi, B., Shevliakova, E., Pacala, S., 2015. Quantifying regional, time-varying effects of cropland and pasture on vegetation fire. Biogeosciences 12, 6591–6604.

Rhodes, A.N., 1998. A method for the preparation and quantification of microscopic charcoal from terrestrial and lacustrine sediment cores. Holocene 8, 113–117.

Rucina, S.M., Muiruri, V.M., Downton, L., Marchant, R., 2010. Late-holocene savanna dynamics in the amboseli basin, Kenya. Holocene 20, 667–677.

Schlachter, K.J., Horn, S.P., 2010. Sample preparation methods and replicability in macroscopic charcoal analysis. J. Paleolimnol. 44, 701–708.

Schmidt, M.W.I., Noack, A.G., 2000. Black carbon in soils and sediments: analysis, distribution, implications, and current challenges. Glob. Biogeochem. Cycles 14, 777–793.

Scott, A.C., Cripps, J.A., Collinson, M.E., Nichols, G.J., 2000. The taphonomy of charcoal following a recent heathland fire and some implications for the interpretation of fossil charcoal deposits. Palaeogeogr. Palaeoclimatol. Palaeoecol. 164, 1–31.

Shafizadeh, F., 1982. Introduction to pyrolysis of biomass. J. Anal. Appl. Pyrolysis 3, 283–305.

Shafizadeh, F., Furneaux, R.H., Cochran, T.G., Scholl, J.P., Sakai, Y., 1979. Production of levoglucosan and glucose from pyrolysis of cellulosic materials. J. Appl. Polym. Sci. 23, 3525–3539.

Simoneit, B.R., Elias, V.O., 2000. Organic tracers from biomass burning in atmospheric particulate matter over the ocean. Mar. Chem. 69, 301–312.

Simoneit, B.R., Schauer, J.J., Nolte, C., Oros, D.R., Elias, V.O., Fraser, M., Rogge, W., Cass, G.R., 1999. Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles. Atmos. Environ. 33, 173–182.

Soetaert, K., Herman, P.M., Middelburg, J.J., 1996. A model of early diagenetic processes from the shelf to abyssal depths. Geochim. Cosmochim. Acta 60, 1019–1040.

Stahle, L.N., Whitlock, C., Haberle, S.G., 2016. A 17,000-year-long record of vegetation and fire from cradle mountain national park, tasmania. Front. Ecol. Evol. 4, 82.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollenet spores XIII (4).

Suman, D.O., Kuhlbusch, T., Lim, B., 1997. Marine sediments: a Reservoir for Black Carbon and Their Use as Spatial and Temporal Records of Combustion, Sediment Records of Biomass Burning and Global Change. Springer, pp. 271–293.

Swain, A.M., 1973. A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. Quat. Res. 3, 383IN1391–1390IN2396.

Tinker, D.B., Knight, D.H., 2000. Coarse woody debris following fire and logging in Wyoming lodgepole pine forests. Ecosystems 3, 472–483.

Tinner, W., Lotter, A.F., 2006. Holocene expansions of Fagus silvatica and Abies alba in Central Europe: where are we after eight decades of debate? Quat. Sci. Rev. 25, 526–549.

Umbanhowar, C.E., Mcgrath, M.J., 1998. Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. Holocene 8, 341–346.

Van der Werf, G., Peters, W., Van Leeuwen, T., Giglio, L., 2013. What could have caused pre-industrial biomass burning emissions to exceed current rates? Clim. Past 9, 289–306.

Vannière, B., Blarquez, O., Rius, D., Doyen, E., Brücher, T., Colombaroli, D., Connor, S., Feurdean, A., Hickler, T., Kaltenrieder, P., 2016. 7000-year human legacy of elevation-dependent European fire regimes. Quat. Sci. Rev. 132, 206–212.

Vanniere, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W., Magny, M., 2008. Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy). Quat. Sci. Rev. 27, 1181–1196.

Vannière, B., Power, M.J., Roberts, N., Tinner, W., Carrión, J., Magny, M., Bartlein, P., Colombaroli, D., Daniau, A., Finsinger, W., 2011. Circum-Mediterranean fire activity and climate changes during the mid-Holocene environmental transition (8500-2500 cal. BP). Holocene 21, 53–73.

Verschuren, D., 1993. A lightweight extruder for accurate sectioning of soft-bottom lake sediment cores in the field. Limnol. Oceanogr. 38, 1796–1802.

Walsh, M., Pearl, C.A., Whitlock, C., Bartlein, P.J., Worona, M.A., 2010. An 11 000-year-long record of fire and vegetation history at Beaver Lake, Oregon, central Willamette valley. Quat. Sci. Rev. 29, 1093–1106.

Wardenaar, E., 1987. A new hand tool for cutting peat profiles. Can. J. Bot. 65, 1772–1773.

Weng, C., 2005. An improved method for quantifying sedimentary charcoal via a volume proxy. Holocene 15, 298–301.

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313, 940–943.

Whitlock, C., 2001. Variations in Holocene fire frequency: a view from the western United States. Biol. Environ. Proc. R. Ir. Acad. 101B, 65–77.

Whitlock, C., Larsen, C., 2002. Charcoal as a fire proxy. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments Terrestrial, Algal, and Siliceous Indicators, vol. 3. Kluwer Academic Publishers, Dordrecht, pp. 75–97.

Whitlock, C., Millspaugh, S.H., 1996a. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. Holocene 6, 7–16.

Whitlock, C., Millspaugh, S.H., 1996b. Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. Holocene 6, 7–15.

Winkler, M.G., 1985. Charcoal analysis for paleoenvironmental interpretation: a chemical assay. Quat. Res. 23, 313–326.

Wright, J.H.E., Mann, D.H., Glaser, O.H., 1984. Piston corers for peat and lake sediments. Ecology 65, 657–659.

Yokelson, R.J., Susott, R., Ward, D.E., Reardon, J., Griffith, D.W.T., 1997. Emissions from smoldering combustion of biomass measured by open-path Fourier transform infrared spectroscopy. J. Geophys. Res. 102, 18865–18877.

Yue, X., Mickley, L.J., Logan, J.A., Kaplan, J.O., 2013. Ensemble projections of wildfire activity and carbonaceous aerosol concentrations over the western United States in the mid-21st century. Atmos. Environ. 77, 767–780.

Zennaro, P., Kehrwald, N., Marlon, J., Ruddiman, W.F., Brücher, T., Agostinelli, C., Dahl-Jensen, D., Zangrando, R., Gambaro, A., Barbante, C., 2015. Europe on fire three thousand years ago: arson or climate? Geophys. Res. Lett. 42, 5023–2033.

Zennaro, P., Kehrwald, N., McConnell, J.R., Schüpbach, S., Maselli, O.J., Marlon, J., Vallelonga, P., Leuenberger, D., Zangrando, R., Spolaor, A., 2014. Fire in ice: two millennia of boreal forest fire history from the Greenland NEEM ice core. Clim. Past 10, 1905–1924.

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