**Title: “*The sedimentary and remote-sensing reflection of biomass burning in Europe* ”**

**Short running title:** Geospatial calibration for paleo-fire reconstructions

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# Abstract

Aim: We provide the first European-scale geospatial training set relating the charcoal signal in surface lake sediments to fire parameters (number, intensity and area) recorded by satellite MODIS sensors. Our calibration is intended for quantitative reconstructions of key fire-regime parameters by using sediment sequences of microscopic (MIC from pollen slides, particles 10-500 µm) and macroscopic charcoal (MAC from sieves, particles >100 µm).

Location: North–South and East–West transects across Europe, covering the mediterranean, temperate, alpine, boreal and steppe biomes.

Time Period: Lake sediments and MODIS active fire and burned area products were collected for the years 2012–2015.

Methods: Cylinder sediment traps were installed in lakes to annually collect charcoal particles in sediments. We quantitatively assessed the relationships between MIC and MAC influx [particles cm-2 year-1] and the MODIS-derived products to identify source areas of charcoal and the extent to which lake-sediment charcoal is linked to fire parameters across the continent.

Results: Source area of sedimentary charcoal was estimated to a 40 km radius around sites for both, MIC and MAC particles. Fires occurred in grasslands and in forests, with grass morphotypes of MAC well reflecting the burned fuel-type. Despite the lack of local fires around the sites MAC influx levels reached those reported for local fires. Both, MIC and MAC showed strong and highly significant relationships with the MODIS-derived fire parameters, as well as with climatic variation along a latitudinal temperature gradient.

Main Conclusions: MIC and MAC are suited to quantitatively reconstruct fire number and fire intensity on a regional scale. However, burned area may only be estimated using MAC. Local fires may be identified by using several lines of evidence, e.g. analysis of large particles (>600 µm), magnetic susceptibility and sedimentological data. Our results offer new insights and applications to quantitatively reconstruct fires and to interpret available sedimentary charcoal records.

**Keywords:** Fire regime, Fire ecology, Modis, Calibration in space, Palaeoecology, Micro- and macroscopic charcoal

# Introduction

Fire has long been a major ecological force on Earth, significantly shaping terrestrial ecosystems and leaving historical legacies on biodiversity (Bond, Woodward, & Midgley, 2005). Fire regimes vary significantly across the globe, depending on important ecosystem properties such as moisture, heat or fuel flammability. Important fire regime parameters include fire frequency, fire radiative power (FRP, i.e. intensity) and area burned. Fire frequency has been found to be indicative of a region’s fire-related land-use practices and population densities (Catry et al., 2010) but is also linked to regional fire-proneness and flammability (Pausas & Ribeiro, 2017). While fire intensity refers to the energy release of a fire, the area burned is related to fuel connectivity and is useful to calculate fire rotation periods (Bond & Keeley, 2005) as well as fire-related carbon emissions (van der Werf, Peters, van Leeuwen, & Giglio, 2012). However, quantitative data on fires and fire regime parameters on long time scales are scarce and mostly range from decades to little more than a century (e.g. Conedera et al., 1996; San-Miguel-Ayanz et al., 2012). Consequently, many open questions persist in regard to long-term fire ecology (Iglesias, Yospin, & Whitlock, 2015). For instance little is known about how different fire regime parameters influenced vegetation dynamics over millennia, by e.g. promoting fire-adapted ecosystems (Hill & Jordan, 2016) and what role humans played in shaping these relations. Answering such questions is important to assess future ecosystem responses to increased fire hazard as a result of climate change (IPCC, 2013).

In recent decades, satellites, such as Terra and Aqua, have acquired key fire data through the use of Moderate Resolution Imaging Spectroradiometer (MODIS) sensors, which have an optimized instrument design for fire detection. MODIS sensors are able to register fire number, intensity and area burned, but have only been operational since the early 2000s (Justice et al., 2002). Sedimentary records of charcoal, on the other hand, allow the reconstruction of past biomass burning and associated ecosystem responses over hundreds to tens of thousands of years. The reconstruction of fire sizes and intensities from charcoal data remains challenging, while significant progress has been made concerning fire frequency (Conedera *et al.*, 2009). In addition, a lack of understanding and consensus persists about charcoal source areas, adding difficulties to the interpretation and comparison of charcoal records (Conedera et al., 2009; Whitlock & Larsen, 2001). Combining specific MODIS products, such as the active fire and burned area products, with sedimentary charcoal influx [particles cm-2 year-1] is a promising new approach to enable quantitative calibration-based reconstructions of past fire frequency, intensity and size.

Here we present the first continental-scale charcoal calibration study for Europe that combines three years of annual charcoal influx monitoring with MODIS-derived active fire and burned area products from the same time period. The aim is to explore source areas of MIC and MAC particles and investigate the link between charcoal morphotypes and the fuel type burned. We then establish quantitative relationships based on regression analysis for microscopic (MIC, pollen slides) and macroscopic charcoal (MAC, sieves) influx that can be used to reconstruct key fire-regime parameters from down-core MIC and MAC charcoal records, refining existing fire-reconstruction approaches.

# Methods

## Study area

Our study is based on a space-for-time calibration approach (Blois, Williams, Fitzpatrick, Jackson, & Ferrier, 2013), in which study sites are distributed across a wide range of environments. This approach allows us to capture the variability of charcoal influx over Europe, which may correspond to that of a given site over thousands of years. Hence, we selected the lakes to cover all important European biomes in the mediterranean, temperate, alpine, boreal and steppe realms (Fig. 1). At present, these biomes are characterized by different fire regimes exhibiting strong variability in regard to fire frequency, intensity, size and spread. For instance the boreal forests and the Mediterranean area are the only two biomes of Europe in which crown fires regularly occur. These fires are often intense and large, while in the other biomes (e.g. temperate, steppe or alpine) ground fires are small and less intense (Archibald, Lehmann, Gómez-Dans, & Bradstock, 2013). Besides covering all major fire-regimes and biomes of Europe, we also span the typical range of lakes studied in palaeoecology (see Table 1 for study sites details), with maximum depths of 16.7 m (SD=9.5 m), surface areas of 2–1,480 ha and altitudes ranging from sea level to 2065 m a.s.l.

## Lake-sediment sampling

We used two-cylinder sediment traps (type: EAWAG 130, see Appendix S1 of Supplementary Information) to collect charcoal particles close to the centre of each lake. The use of this type of sediment traps largely excludes sediment mixing due to taphonomical processes occurring on lake bottoms after charcoal deposition (Bloesch & Burns, 1980). The contribution of secondary charcoal (from erosion, re-deposition) is reduced, given that particles would have to be re-suspended in the water column above the openings of the cylinders (ca. 2 m above the sediment-water-interface). Starting in spring 2012, one sediment trap was placed in the water approximately at the deepest part of each study lake. The traps were emptied yearly (mean of 365 days (SD=25 days) for a period of three years (2012–2015). The repeated annual sediment collection allowed us to accurately estimate charcoal particle influx. To test how well charcoal influx from sediment traps can be compared to charcoal influx from lake-sediment cores, we took surface cores from three annually laminated lakes after the first year of sediment trap sampling.

## Sample preparation and charcoal analysis

Microscopic charcoal (MIC, 10-500 µm), which is counted on pollen slides, was prepared following standard pollen procedures (Moore, Weeb, & Collinson, 1991) and analysed following Finsinger & Tinner (2005) and Tinner & Hu (2003). Pollen grains were counted on the same slides as MIC to a minimal count of 500 grains. Preparation of macroscopic charcoal (MAC, >100 µm) followed the sieving method adapted from Whitlock & Anderson (2003) using a sieve size of 100 µm and excluding the use of hydrogen peroxide. We subdivided total MIC and MAC counts (tMIC, tMAC) further into wood and grass morphotypes for MIC, and wood, leaf and grass morphotypes for MAC. For morphotype classifications we considered length to width ratios (Umbanhowar & McGrath, 1998) combined with other morphological features (as in Colombaroli, Ssemmanda, Gelorini, & Verschuren, 2014). Loss-on-ignition analysis (Heiri, Lotter, & Lemcke, 2001) was used to infer the organic, carbonate, and inorganic content without carbonates at each lake and for each year. For a detailed description of sample preparation and charcoal morphotype identification, refer to Appendix S2.

## Satellite data and data handling

The global monthly fire location product (MCD14ML, collection 5.1, Justice et al., 2002, 2006; Giglio et al., 2003; Kaufman et al., 2003, consequently "active fire product") and the shapefile version of the MODIS burned area product (MCD45monthly, provided by the University of Maryland, collection 5.1, Roy et al., 2002, 2005, 2008, consequently "burned area product") were used to identify fire number (amount of detected fire pixels), intensity (total Fire Radiative Power, tFRP in Watt m-2) and burned area (km2), respectively. Both products are derived from MODIS sensors on-board of NASA’s Terra and Aqua satellite platforms. Pixel size of the active fire product is about 1 km² and pixels are flagged as “fire pixels” if one or more active fires are detected within the pixel (Giglio, 2013). Fires of an area of 1000 m2 (0.1 ha) are regularly detected, while smaller fires <100 m2 are detected only under very favourable observing conditions, such as at nadir or with no smoke (Giglio, 2013). The spatial resolution of the burned area product is of 500 m, equivalent to an area of 0.25 km2. For the active fire product, corrections for temporal and spatial autocorrelations were carried out as suggested by Giglio (2013) and Oliveras, Anderson, & Malhi (2014). Stationary fires and false fire pixels (e.g. power plants and hot factory roofs, respectively) were removed following Giglio, Csiszar, & Justice (2006) and by using an urban area mask from the European Space Agency (ESA) Global Land Cover Map of 2009 (GlobCover 2009, Arino et al., 2012, Appendix S3 & S4). Additional land-cover information with 300 m spatial resolution was retrieved from GlobCover 2009 to assign each detected fire pixel to a land cover class. Three fire datasets were consequently created for both MODIS products, containing fire pixels in “open” (i.e. non-forested), “closed” (i.e. forested) and “combined” (“open” and “closed”) vegetation land-cover categories. Finally, areas for each land-cover class from GlobCover 2009 were calculated within the radii 3, 15 and 40 km around each study site to report the proportion of open vs. closed vegetation around all sites (Appendix S4).

By using circular buffer areas around each lake with an increasing radius size (from 1–25 in 1 km steps and from 30–200 km in 10 km steps, including the 75 and 125 km radii), the fire number, tFRP and burned area per year within the different sized buffers were extracted from both MODIS products. We chose circular buffers because they are the most parsimonious shape for source areas, as wind directions in Europe are very variable. The time span of the satellite-derived data is equivalent to the time during which each trap was within the corresponding lake. We extracted annual values for each fire parameter within the different radii and calculated 2- or 3-year means, depending on how many years were available from the corresponding sediment traps. We compared these means to the matching charcoal influx means by using correlation and/or regression analyses.

For all correlations and regressions, charcoal influx data as well as satellite data were log(x+1) transformed to attain normal distribution of the residuals of the model (Juggins & Birks, 2012), which is necessary to fulfil the underlying assumptions of regression analyses. Weighted correlations (Pearson’s product–moment correlations) were calculated to explore the strength of the linkage between the variables. P-values for the correlation analyses were corrected for multiple testing bias using the Bonferroni correction method, where the p-values are multiplied by the number of comparisons. We used the inverse regression approach (Juggins & Birks, 2012; Appendix S5) to compute linear least square regressions with 95% confidence intervals. Weights (1–3) were included in the correlations and regressions, to consider differing numbers of years included in the means of both fire products and charcoal influx values. All calculations and dataset manipulations were done using the free software R (R Core Team, 2016) and R packages (list of full references in Appendix S6).

# Results and Interpretation

## Sediment traps and satellite data

From the initial 39 sediment traps, 29 were recovered every year, while eight traps were found in two years and one in one year only. Outliers were removed from the dataset when sedimentation rates were >3 standard deviations different from the mean and when external factors importantly affected sediment deposition to the traps (further details in Appendix S7). Differences between influx values from sediment traps and surface cores for the year 2012-2013 were small (-0.35 to +0.55 times the influx of surface cores, except when sample volume of the sediment core was <0.5 cm3; Appendix S8). Additionally, at the site Iffigsee, a major increase in sedimentation rates was registered after an avalanche-related erosion event in spring 2015 (data not shown). This may mean that secondary charcoal is captured by the traps, yet probably not as well as on the lake bottom. Because of the sophisticated sediment trap design (following Bloesch & Burns, 1980), we assume that influx from sediment traps reflects sediment influx. Unrelated to this issue, larger discrepancies between trap and sediment influx assessments may derive from dating uncertainties including age-depth modelling.

## Source areas and ignition sources for MIC and MAC

We estimated the source area of charcoal by assuming that it is indicated by the strongest correlations between charcoal and satellite data (Fig. 2a). In general, correlations between charcoal influx and MODIS products are higher for MAC than for MIC across all source areas and fire parameters. The highest correlation coefficients (r between 0.46-0.76) for tMIC and tMAC are found at 40 km radius (5,027 km2), suggesting regional provenance for both tMIC and tMAC. Furthermore, tMIC and tMAC influx values are highly and significantly correlated (r=0.82, p<0.00001, Fig. 3a), providing further support for a similar source area. However, a detailed comparison reveals that, at the 13 sites with the lowest charcoal influx, tMIC and tMAC influx do not show similar trends. tMAC influx remains constantly low in samples with low but increasing tMIC influx values (Fig. 3a). Common features of these sites are no fires within 5 km (mean minimum distance of fire: 24.5 km), high organic content of sediments (average of 39%) and a high percentage of forested surroundings (62.7% within 40 km compared to the overall mean of 35.5%, see Appendix S9).

Measurements of width and length of MAC particles in ten samples which cover the biomes studied (Fig. 1, black stars; bold in Table 1) show a peak of particle abundance in the lengths between 180 and 300 µm. Particle abundance declines until ca. 600 µm and particles >1000 µm only rarely contribute to tMAC influx (Fig. 3b). Even though our sites are distributed all over the continent and including very fire-prone areas, no fires were detected within 1 km around the lakes, neither on ground during fieldwork (e.g. burned grassland, forest) nor by the MODIS sensors (Table 1, last column). Longer MODIS time-series reveal that fire pixels occurred within 1 km distance of our study sites in years before the placement of the traps (data not shown), making it unlikely that an error in the land/water mask in the MODIS products is responsible for not registering fire pixels within 1 km during our study period.

Comparing MAC morphotypes to fires in “open”, “closed” and the “combined” land cover classes (Fig 2b & c), reveals that the grass morphotype is best related to fires under “open” but also shows significant correlations under “combined” conditions. This finding agrees with the closest fires around our study sites, which all occurred in Sicilian open lands, at 1-3 km distance (Table 1). In contrast, the MAC wood morphotype shows significant correlations with fires in all three land cover classes, including the “closed” one, however being predominantly better correlated to the “combined” one (Fig. 2c). The weaker correlation of the MAC wood morphotype with the “closed” class is partly explainable by the composition of the “open” and “closed” classes. Specifically the “open” category includes an important proportion of shrubland-vegetation with woody fuels (Appendix S4). All relationships with the leaf morphotype are non-significant (Appendix S10). This suggests that leaf charcoal might be more affected by factors unrelated to fuel and landscape types, such as e.g. particle fragmentation, a finding which is supported by the overall scarcity of the leaf morphotype in our samples. Both MIC morphotypes show significant and very similar correlation coefficients with fires in the “open” and “combined” land cover classes (Appendix S10).

Lastly, while the fire number parameter shows constantly highest correlation coefficients at 40 km radius, tFRP and burned area show strong relationships also at the extra-local scale or slightly above (2-3 or 10-15 km, Fig. 2 b&c). This is especially evident when we compare the “open” land cover class with the MAC grass morphotype (Fig. 2 b&c, Appendix S10). At regional scales of 40 km radius, changes in both mean tFRP and mean burned area seem to average out (Appendix S11).

## Linear regressions between charcoal influx and MODIS-derived fire parameters

We used the 40 km radius areas around our study lakes (strongest correlations for tMIC and tMAC, Fig. 2) to develop regressions for the estimation of fire number and tFRP from tMIC and tMAC influx (Fig. 4). At the radius of 40 km all regression models involving tMAC influx perform better than those with tMIC influx. Fire number explains most variance in the distribution of both tMIC (R2=0.36, r=0.62, p <0.01) and tMAC (R2=0.56, r=0.76, p <0.00001), followed by tFRP (tMIC R2=0.25, r=0.52 p-value <0.05; tMAC R2=0.42, r=0.66, p <0.001). Burned area correlations also reach highest values at a radius of 40 km, however, too many zero values (17) occurred to reliably calculate linear regressions. Hence, we used the second-highest correlation coefficients from the spatial correlation analyses at a radius of 180 km to develop the regressions. This resulted in an R2=0.20 (r=0.47, p >0.05) for tMIC and R2=0.39 (r=0.64, p <0.0001) for tMAC. The tMIC and burned area relationship is non-significant, thus not recommended for use. Additional regression equations for tMIC influx in areas (tMICia, [mm2 cm-2 year-1]), converted according to Tinner *et al.* (1998), are shown.

The resulting regression equations are:

log10(FN+1) = 0.659\*log10(tMICi+1) – 1.6577 (1 )

log10(FN+1) = 1.072\*log10(tMICia+1) + 0.2187 (2)

log10(FN+1) = 2.1802\*log10(tMACi+1) + 0.207 (3)

log10(tFRP+1) = 0.9349\*log10(tMICi+1) – 1.5111 (4)

log10(tFRP+1) = 1.5194\*log10(tMICia+1) + 1.1516 (5)

log10(tFRP+1) = 3.2172\*log10(tMACi+1) + 1.1002 (6)

log10(BA+1) = 0.7222\*log10(tMICi+1) – 1.2619 (7)

log10(BA+1) = 1.1624\*log10(tMICia+1) + 0.8012 (8)

log10(BA+1) = 2.6429\*log10(tMACi+1) + 0.712 (9)

where FN = fire number, tFRP = total fire radiative power [W m-2], BA = burned area [km2], tMICi = total microscopic charcoal number influx [particles cm-2 year-1], tMICia = total microscopic charcoal area influx [mm2 cm-2 year-1], tMACi = total macroscopic charcoal number influx [particles cm-2 year-1].

## Charcoal influx across Europe compared to MODIS products

To better understand spatial patterns of charcoal influx across biomes, we plotted the three-year mean of charcoal influx (untransformed) from our sediment traps on a map of Europe alongside with the corresponding untransformed means of fire number, tFRP and burned area from our northernmost to southernmost sites (Fig. 5). Both tMIC and tMAC influx increase dramatically with decreasing latitude (Fig. 5), the lowest values of tMIC and tMAC influx being three orders of magnitude smaller than their respective highest values. Overall, tMIC influx values are up to four orders of magnitude larger than tMAC influx values. For both tMIC and tMAC, the lowest influx is found in boreal and alpine sites, as well as in sites in the montane vegetation belt. In contrast, highest influx values are found only at Mediterranean sites. The MODIS-derived fire parameters within our outlined source area of charcoal (40 km and 180 km) also show a strong latitudinal gradient, with a major increase in fire number and tFRP towards southern Europe. Burned area is especially high around the Ukrainian site and in southern Europe (Fig. 5 c,d & e). Variability from North to South is less pronounced when mean FRP and mean burned area per fire are considered rather than fire number (Appendix S11).

The highly significant negative correlation (r=-0.64 for tMIC, r=-0.62 for tMAC, p <0.001) between tMIC, tMAC and the percentage of arboreal pollen from the same lake suggests a strong linkage of fire occurrence with vegetation openness (Appendix S9). Marginally significant correlations were found between tMIC particle influx and increasing inorganic content without carbonates, as well as with decreasing organic content (r=0.43, p=0.05 and r=-0.42, p=0.06, respectively, Appendix S9) pointing to weak erosional effects and possibly MIC re-deposition.

# Discussion

## Regional versus local proxies of fire occurrence

Our data point to similar, regional source areas for tMIC and tMAC, as suggested by the high and significant correlation coefficients with the MODIS active fire and burned area products. This finding is unexpected considering that in contrast to MIC, a proxy for regional fires (20-100 km, Conedera et al. 2009), MAC is mostly used as a proxy for local (0-1 km) to extra-local (1-5 km) burning (e.g. Duffin, Gillson, & Willis, 2008; Higuera, Whitlock, & Gage, 2010; Kelly et al., 2013; Leys, Brewer, McConaghy, Mueller, & McLauchlan, 2015; Whitlock & Larsen, 2001). These findings have some implications for the reconstruction of local- to extra-local scale fire frequency from sediment charcoal. MAC series are often decomposed into a high-frequency “peak” and a low-frequency “background”; with peak residuals used as a proxy for local fires (e.g. Clark et al., 1996; Higuera et al., 2009). The peak component of MAC records is often attributed to a local signal from within 1 km distance (Gavin, Brubaker, & Lertzman, 2003; Higuera, Peters, Brubaker, & Gavin, 2007; Peters & Higuera, 2007). On the other hand, the low-frequency background component has in previous studies been attributed to various sources, including reworked (older) charcoal and fire activity within tens of kilometres (Conedera et al., 2009; Whitlock & Larsen, 2001). Our data strongly support studies that attributed background charcoal to overall fire activity (e.g. Marlon et al., 2008) emphasising the contribution of regional fires to MAC. However, the results of our study derive from rather open European vegetation conditions. It is conceivable that under densely forested conditions MAC source areas might be somewhat smaller (Kelly et al., 2013; Oris et al., 2014).

Our source area estimate for MIC fits quite well with previous calibration estimates (MacDonald *et al.*, 1991; Tinner *et al.*, 1998) and reviews (Whitlock & Larsen, 2001; Conedera *et al.*, 2009: 20–100 km) confirming it as a proxy for regional fire activity. On the basis of regional calibration studies, peaks in MIC are readily interpreted as increases in regional fire activity (Tinner *et al.*, 1998; Carcaillet *et al.*, 2001; Conedera *et al.*, 2009) and they are usually not considered to be evidence of local fires (but see Pitkänen *et al.*, 1999 if the standard pollen method is altered to capture large charcoal). Consequently, peak and background analyses were never applied to MIC (Conedera et al., 2009; Mooney & Tinner, 2011). In contrast to MAC, no correlation peak could be found for distances < 12 km for MIC, including the grass morphotype (Fig. 2a and Appendix S10), indeed pointing to a distinct regional provenience of MIC.

Empirical and theoretical studies show that particle size reflects the distance of a fire from the lake (Clark, 1988; Clark & Royall, 1995; Peters & Higuera, 2007). For instance, large particles are likely to be deposited close to the fire, while small particles can be transported far away. However, previous studies have shown that particle size alone may not be a good predictor of fire distance (Iglesias et al., 2015; Whitlock & Millspaugh, 1996), as fire intensity, area burned and wind strength and direction may greatly affect how far different-sized particles are transported (Pisaric, 2002; Tinner, Hofstetter, et al., 2006). Our results show that regional fires can produce tMAC peaks comparable to those identified as local fires (e.g. Fletcher et al., 2015; Millspaugh et al., 2000; Morales-Molino et al., 2015; Vannière et al., 2008). Thus, on the basis of tMAC particles >100-150 µm it might be difficult to correctly reconstruct important fire-regime parameters, such as fire frequency (IFF), mean fire intervals (MFI) and fire return intervals (FRI) that depend on the correct reconstruction of local fire occurrence. Analysing charcoal particles >600 µm (Fig. 3b) may contribute to a better detection of past local fire events. This suggestion is based on motion physics which determines that the chance of particles to be transported over long distances decreases with increasing size (Clark & Royall, 1995; Clark, 1988; Lynch, Clark, & Stocks, 2004; Peters & Higuera, 2007; Tinner, Hofstetter, et al., 2006). Support for such a procedure comes from image-analysis based calibration studies which show that the regional background of MAC can be reduced or completely eliminated by increasing the minimum size of particles (Tinner et al., 1998). Additional lines of evidence to determine if a fire is really local might be measurements of ferromagnetic material derived from burned soil (i.e. magnetic susceptibility measurements, Gedye, Jones, Tinner, Ammann, & Oldfield, 2000; MacDonald et al., 1991) and other sedimentological analyses including x-ray spectrometry (Colombaroli & Gavin, 2010; Fletcher et al., 2015). Since particles >250 µm are very rare in sediments (Whitlock & Millspaugh, 1996; Tinner et al. 1998), we recommend to use large sediment volumes (ca. 10-20 cm3 ) for the analysis of particles >600 µm, as also applied in plant macrofossil analysis (e.g. Tinner, Hu, et al., 2006).

## Relationships between fuel-type burned and charcoal morphotypes

Highest correlation coefficients are found for the grass morphotype and the “open” fire dataset, irrespectively of MIC or MAC, which reflects the predominance of fires in non-forested areas in Europe (Korontzi, McCarty, Loboda, Kumar, & Justice, 2006, Fig. 5c, d & e). This relationship is further confirmed by the strong negative correlation between the percentages of arboreal pollen and tMIC and tMAC (Appendix S9). Other studies also found good agreements between MAC morphotypes and fuel type burned (e.g. Aleman et al., 2013; Leys, Commerford, & Mclauchlan, 2017). However there was no connection between MAC width to length ratios and the proportion of open landscape (Leys et al. 2017; Appendix S12), possibly because of the small sample number (10) available in this study.

## Quantitative fire history reconstructions

The regression equations linking tMAC influx and the three satellite-derived fire regime parameters (fire number, tFRP, and burned area) represent robust relationships that can be used to reconstruct past fire occurrence from fossil charcoal records. In the case of tMIC, the same is valid for fire number and tFRP but not burned area. That the best regression model is related to fire number for both tMIC and tMAC is surprising given that the majority of recent studies suggest significant relationships between charcoal and burned area or fire intensity (Duffin et al., 2008; Higuera, Whitlock, & Gage, 2010; Colombaroli & Gavin, 2010; Leys et al., 2015). Early calibration studies, where regional scales and/or long historical fire records were considered (MacDonald et al., 1991; Tinner et al., 1998) also identified fire number as a significant factor explaining charcoal abundance at regional scales, in accordance with present observations (Pausas & Ribeiro, 2017). Furthermore, this parameter is very sensitive to uncertainties in the amount of time contained within a sediment sample, possibly explaining why it was not significant in studies where only charcoal concentrations (and not influx) were calculated (Duffin et al., 2008; Whitlock & Millspaugh, 1996). Our results emphasize that charcoal calibration studies should only use influx data, which are achievable through annual trapping or accurate physical dating of surface sediments (Appleby, 2001).

The significant relationships between tMIC/tMAC and tFRP imply that tFRP may be reconstructed from charcoal influx data to estimate past regional fire intensity. Novel approaches such as using reflectance properties of charcoal particles are promising and might also be used to improve fire intensity reconstructions (Hudspith *et al.*, 2015). Highly significant correlations between tMAC influx and the MODIS burned area product suggest that our regression models may be also used for reconstructing past burned areas. A strong advantage of burned area is that it can be used to estimate area-specific fire rotation periods, i.e. the time it takes for fires to burn a specified area (Archibald et al., 2013; Bond & Keeley, 2005). In the fossil record, mean fire rotation periods for a certain period (e.g. 1,000 years) might be estimated for MAC samples by dividing the total area (102’000 km2) through the regression-inferred burned area for the 180 km radius and then calculating the average fire rotation periods for the chosen time interval. Given that in some biomes the fire regime is dominated by rare but large fires it is important to consider sufficiently long periods (Archibald et al., 2013). It remains to be tested how well this method performs when compared to other equivalent estimations of fire return intervals (Moreno et al. 1998).

# Conclusions

Our study shows that both MIC and MAC can be used to quantitatively reconstruct important fire parameters such as fire number, fire intensity, and burned area at the regional scale by using lake-sediment records. Both fire proxies show strong correlations with vegetation openness, highlighting the importance of human activities (e.g. agricultural fires to keep fields open vs. firefighting to protect forests) and/or feedbacks of vegetation on fire regimes (e.g. flammable maquis vs. nonflammable late-successional forests; see Henne *et al.*, 2015). Limitations of our approach include the study’s applicability to other climatic zones (e.g. tropics), periods with substantially different fuels (or vegetation types) and important differences in study sites (e.g. bogs and mires). For instance, non-analogue fire regimes may have existed in the past, e.g. during ice ages, or during periods with significantly less anthropogenic burning.

Further refinements may comprise the distinction between primary and secondary (or reworked) charcoal (Vannière et al., 2003) and the determination of minimum fire intensities of local fires using charcoal particle properties (Hudspith et al., 2015). Application to charcoal sequences available to a large community through the global charcoal database (Power, Marlon, Bartlein, & Harrison, 2010) would open new possibilities of applying our regression equations to sediment sequences, however only few studies provide reliable influx estimates based on accurate chronologies (Vannière *et al.*, 2016). Once high-quality influx studies should become standard, they might be used to carefully reconstruct past fire regime parameters. Together with long-term vegetation records (e.g. pollen or plant macrofossils) such reconstructions can provide crucial information regarding future ecosystem responses to increasing fire hazard under global change conditions. Additional applications may cover the estimation of past carbon emissions (van der Werf et al., 2012) originating from wildfires and the refinement of dynamic vegetation models involving fire disturbance scenarios (Colombaroli, Henne, Kaltenrieder, Gobet, & Tinner, 2010).

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Data Accessibility Statement: Charcoal influx values are available upon written request to the corresponding author and will be publicly available on an online data depository such as the Global Charcoal Database after completion of her PhD thesis.

# Biosketch:

Carole Adolf is currently a PhD student at University of Bern. She is interested in the use of geospatial data for the calibration of palaeoecological proxies and long-term ecosystem change in Europe and South America.

Willy Tinner is professor of Paleoecology at University of Bern. He uses biotic sedimentary time series (e.g. pollen, spores, macrofossils, charcoal) and modelling approaches to study the long-term interactions among climate, the biosphere and society.

Stefan Wunderle is head of the Remote Sensing Research Group, University of Bern and has a long experience in processing of satellite data for near real-time applications and generation of time series focused on Essential Climate Variables.

All three authors are members of the Oeschger Centre for Climate Change Research in Bern, Switzerland.

**TABLES AND FIGURES**

**Table 1:** Study site details

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Study Lake | Code | Country | Longitude  [°] | Latitude  [°] | Altitude (m asl) | Area  [ha] | Depth [m]  (trap pos.) | Sed. Acc. Rate [cm/year] | Closest Fire [km] |
| Lago dell‘Accesa | ACC | Italy | 10.895 | 42.988 | 111 | 16 | 37.5 | 0.26722 | >3 |
| Lago Piccolo d‘Avigliana | AVI | Italy | 7.393 | 45.053 | 288 | 61.1 | 12 | 0.21876 | >3 |
| Lago di Baratz | BAR | Italy | 8.225 | 40.681 | 24 | 60 | 12 | 0.28949 | >14 |
| **Blue Lake** | **BLU** | **Ukraine** | **33.203** | **48.454** | **87** | **24.4** | **14** | **0.25543** | **>6** |
| Černé jezero | CER | Czech Republic | 13.183 | 49.180 | 1007 | 18.4 | 24 | 0.08645 | >25 |
| Laguna Conceja | CONC | Spain | -2.814 | 38.926 | 857 | 29.4 | 27 | 0.317 | >4 |
| Lac du Crès | CRES | France | 3.931 | 43.655 | 39 | 6 | 15 | 0.68181 | >3 |
| Lago Enol | ENO | Spain | -4.991 | 43.271 | 1077 | 12.2 | 22 | 0.2109 | >5 |
| Étang d’Entressen | ENTR | France | 4.916 | 43.602 | 34 | 103.5 | 10 | 0.96082 | >3 |
| **Lagoa Escura** | **ESC** | **Portugal** | **-7.637** | **40.356** | **1679** | **2** | **12** | **0.12837** | **>7** |
| Laguna Grande de Estaña | EST | Spain | -0.531 | 42.027 | 669 | 18.8 | 17.4 | 0.28294 | >17 |
| Biviere di Gela | GELA | Italy | 14.346 | 37.019 | 0 | 150 | 5 | 1.73499 | >1 |
| Jezioro Gołyń Duży | GOL | Poland | 15.775 | 52.443 | 26 | 9.5 | 12 | 0.26919 | >22 |
| **Gorgo Basso** | **GORG** | **Italy** | **12.655** | **37.609** | **27** | **3** | **10** | **0.46109** | **>2** |
| Jezioro Gościąż | GOS | Poland | 19.339 | 52.583 | 76 | 42 | 21 | 0.90515 | >22 |
| **Gerzensee** | **GERZ** | **Switzerland** | **7.547** | **46.830** | **603** | **25.2** | **10.7** | **0.48991** | **>5** |
| Holzmaar | HOLZ | Germany | 6.879 | 50.119 | 422 | 20 | 20 | 0.91039 | >30 |
| Hromnické jezírko | HRO | Czech Republic | 13.444 | 49.850 | 332 | 2 | 13.4 | 0.12051 | >13 |
| **Iffigsee** | **IFF** | **Switzerland** | **7.405** | **46.386** | **2065** | **10** | **30** | **0.18208** | **>20** |
| Limni Kournas | KOU | Greece | 24.274 | 35.329 | 18 | 42.0 | 20.8 | 0.38119 | >12 |
| Mauensee | MAU | Switzerland | 8.073 | 47.170 | 500 | 51 | 8.1 | 0.43031 | >12 |
| **Lac du Mont d‘Orge** | **MNTOR** | **Switzerland** | **7.338** | **46.233** | **595** | **3** | **4.5** | **0.9641** | **>3** |
| **Lago Grande di Monticchio** | **MONTI** | **Italy** | **15.604** | **40.932** | **608** | **30** | **34.3** | **6.07044** | **>5** |
| **Lago d’Origlio** | **ORI** | **Switzerland** | **8.943** | **46.051** | **423** | **8** | **5.3** | **0.36809** | **>11** |
| Specchio di Venere | PANT | Italy | 11.986 | 36.816 | 8 | 19.4 | 10.5 | 0.50694 | >100 |
| Lago di Pergusa | PER | Italy | 14.308 | 37.518 | 677 | 50 | 3.5 | 3.41102 | >2 |
| Sarsjön | SAR | Sweden | 19.602 | 64.039 | 274 | 7.78 | 7.6 | 0.12706 | >18 |
| Stora Utterträsk | UTT | Sweden | 20.407 | 66.122 | 277 | 28.1 | 14.3 | 0.06392 | >7 |
| Vuolep Njakajaure | VUO | Sweden | 18.779 | 68.341 | 408 | 30 | 12.5 | 0.18863 | >110 |
| **Sisstjärnen** | **SISST** | **Sweden** | **14.920** | **60.645** | **216** | **9.6** | **11.5** | **0.0799** | **>21** |
| Hagsjön | HAGS | Sweden | 13.688 | 57.262 | 170 | 22.2 | 13.6 | 0.19125 | >40 |
| Snogeholmssjön | SNOG | Sweden | 13.726 | 55.561 | 33 | 246 | 4.5 | 7.57567 | >15 |
| Lago dello Scanzano | SCA | Italy | 13.370 | 37.924 | 547 | 97 | 15.8 | 3.48485 | >2 |
| Soppensee | SOPP | Switzerland | 8.081 | 47.090 | 593 | 24 | 27 | 0.19256 | >14 |
| Lej da San Murezzan | STM | Switzerland | 9.849 | 46.494 | 1773 | 78 | 44 | 0.14409 | >30 |
| **Suchar II** | **SUCH** | **Poland** | **23.018** | **54.087** | **140** | **2.5** | **10** | **0.09038** | **>5** |
| Laguna de Taravilla | TAR | Spain | -1.974 | 40.651 | 1113 | 2.1 | 10.6 | 0.13885 | >12 |
| Lago di Varese | VAR | Italy | 8.719 | 45.830 | 240 | 1480 | 23.1 | 0.31438 | >4 |
| Laguna Zóñar | ZON | Spain | -4.694 | 37.482 | 301 | 37 | 13.8 | 1.34528 | >10 |

Table 1: Study Sites (in bold: sites where additionally the length and width of macroscopic charcoal particles (>100 µm) were measured)

**FIGURE LEGENDS**

Figure 1: Location of study lakes within biomes of Europe. Black stars stand for sites where additionally the lengths and width of macroscopic charcoal particles (>100 µm) were measured. Modified map from Digital Map of European Ecological Regions (European Topic Centre on Biological Diversity (ETC/BD), 2009).

Figure 2: Correlations of fire number (FN, row 1), total fire radiative power (tFRP, row 2) and burned area (BA, row 3) with total micro (tMIC)- and total macroscopic charcoal (tMAC) influx (a). (b) MAC grass morphotype correlated with fires in “open” (i.e. non-forested), “closed” (i.e. forested) and “combined” (“open” and “closed”) land covers for FN, tFRP and BA. (c) MAC wood morphotype correlated with fires in “open”, “closed” and “combined” land covers for FN, tFRP and BA. All FN, tFRO and BA values are log10(x+1) transformed and are shown in dependence of source area (radius in km around each study lake). P-values were corrected for multiple testing using the Bonferroni correction. Spatial steps are: 1–25 km in 1 km steps, 30–200 km in 10 km steps, including radii 75 and 125 km.

Figure 3: a) Correlation between total microscopic charcoal (tMIC) influx and total macroscopic charcoal (tMAC) influx (influxes are log10(x+1) transformed). b) Particle size distribution of macroscopic charcoal (MAC) from 10 samples of biome-representing sites (black stars, Fig. 1).

Figure 4: Correlations and regressions between FN, tFRP, BA with total microscopic charcoal (tMIC) influx and total macroscopic charcoal (tMAC) influx with source area of 40 km radius for FN and tFRP and 180 km radius for BA. All values log10 (x+1) transformed. Significance levels for the correlation coefficients are Bonferroni-corrected.

Figure 5: Microscopic charcoal (a) and macroscopic charcoal (b) mean annual influx across Europe, values untransformed. A Sicily inlet is displayed respectively on the lower right corner (a.1, b.1). Categories were grouped using quantile partitioning. (c), (d) and (e) show the mean annual values from northernmost to southernmost sites for fire number (FN), total fire radiative power (tFRP) (both in 40 km radius) and burned area (BA, 180 km radius) for the study period. Red colour indicates fires in “open” (i.e. non-forested), turquoise colour indicates fires in “closed” (i.e. forested) land cover types.

# List of Titles in SI

Appendix S1: Figures and pictures of sediment traps

Appendix S2: MIC and MAC Sample Preparation

Appendix S3: Remote sensing products and fire parameters

Appendix S4: GlobCover 2009 land cover classes

Appendix S5: Inverse regression description

Appendix S6: References R packages

Appendix S7: Sediment Trap outliers

Appendix S8: Comparison of charcoal influx values between sediment traps and surface cores

Appendix S9: Relationships between charcoal influx and environmental variables

Appendix S10: Relationships between MIC and MAC morphotypes with open, closed and combined fire datasets

Appendix S11: Distribution of MODIS-derived fire parameters across Europe

Appendix S12: WL ratios compared to proportion of open landscape

Appendix S13: Comparison of MIC and MAC methods

Appendix S14: References Supplementary Information