Holocene fire activity during low-natural flammability periods reveals scale-dependent cultural human-fire relationships in Europe

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Highlights

- We report sedimentary charcoal composites for the Central European lowlands (CEL).
- Holocene fire activity shows convergence and divergence across three spatial scales.
- Divergence in low-flammability periods reflects cultural fire use in land management.
- Since 8,500 cal. BP, humans affected CEL-biogeochemical cycles beyond the local scale.

Abstract

Fire is a natural component of global biogeochemical cycles and closely related to changes in human land use. Whereas climate-fuel relationships seem to drive both global and subcontinental fire regimes, human-induced fires are prominent mainly on a local scale. Furthermore, the basic assumption that relates humans and fire regimes in terms of population densities, suggesting that few human-induced fires should occur in periods and areas of low population density, is currently debated. Here, we analyze human-fire relationships throughout the Holocene and discuss how and to what extent human-driven fires affected the landscape transformation in the Central European Lowlands (CEL). We present sedimentary charcoal composites on three spatial scales and compare them with climate model output and land cover reconstructions from pollen records. Our findings indicate that widespread natural fires only occurred during the early Holocene. Natural conditions (climate and vegetation) limited the extent of wildfires beginning 8,500 cal. BP, and diverging subregional charcoal composites suggest that Mesolithic hunter-gatherers maintained a culturally diverse use of fire. Divergence in regional charcoal composites marks the spread of sedentary cultures in the western and eastern CEL. The intensification of human land use during the last millennium drove an increase in fire activity to early-Holocene levels across the CEL. Hence, humans have significantly affected natural fire regimes beyond the local scale – even in periods of low population densities – depending on diverse cultural land-use strategies. We find that humans have strongly affected land-cover- and biogeochemical cycles since Mesolithic times.

1. Introduction

Major questions in the global debate on climate and environmental change are when, how and to what extent humans have affected land cover and global carbon cycles beyond their natural variability (Ruddiman et al., 2015; Strandberg et al., 2014; Waters et al., 2016). Fire is a key component of many natural ecosystems and biogeochemical cycles worldwide (Jaffé et al., 2013; Randerson et al., 2006) and closely linked to climate (Daniau et al., 2012). However, fire usage has also been key in human evolution (Bowman et al., 2009; Roebroeks and Villa, 2011) and an important tool in anthropogenic land cover change across the globe (Bowman et al., 2011), at least until the time of active fire suppression and the notion of fire being a threat to society (Marlon et al., 2008; Pyne, 2016). As fire risk and socioecological damage are currently increasing in many parts of the world, human-fire relationships are highly debated (Balch et al., 2017; Syphard et al., 2017; Ward et al., 2018). One of the assumptions accounting for humans as drivers of fire regimes is a close relationship between human population densities and fire, where humans act first as ignition triggers. Then, after reaching a certain threshold, humans act as fire suppressors by increasing landscape fragmentation or by taking active suppressive measures (Guyette et al., 2002; Lasslop and Kloster, 2017; Ward et al., 2018). Given the low population densities throughout the early and mid-Holocene (Kaplan et al., 2011; Klein Goldewijk et al., 2011), fire histories derived from sedimentary charcoal (CHAR) compilations have been primarily associated with climatic factors (Daniau et al., 2012; Marlon et al., 2013) and natural vegetation compositions (Blarquez et al., 2015). Only in the most recent centuries, humans seem to have influenced natural fire regimes on global to regional scales (Marlon et al., 2008; Pechony and Shindell, 2010).

However, local CHAR records and some regional CHAR compilations show divergent Holocene fire regimes in adjacent European regions that cannot be explained solely by natural factors (climate, vegetation) (Rius et al., 2011; Vannière et al., 2011). Instead, diverse local to regional fire regimes (characterized by fire frequency, seasonality, intensity, and amount of biomass burned) could indicate human fire use in diverse cultural subsistence traditions and land use practices at least since the last 7,000 to 3,000 years (Molinari et al., 2013; Rius et al., 2011; Vannière et al., 2016; Vannière et al., 2011). However, to what extent early hunter-gatherer and farming societies altered natural fire regimes and landscapes beyond the local scale remains poorly understood (Kaplan et al., 2016; Marlon et al., 2013; Ruddiman, 2013; Vannière et al., 2016). The impacts of future climate change, such as changing fire risk, will be highly variable at the regional scale and dependent on preconditions that have shaped a landscape. Considering cultural dependencies in human-fire relationships over multiple spatial scales relevant to political decision processes is important to (i) unravel the long-term interactions between natural and human drivers on fire regimes and the associated human impact on biogeochemical cycles (Arneth et al., 2017; van der Werf et al., 2013) and (ii) enable informed discussions on future land management and nature conservation efforts (Whitlock et al., 2018).

Here, we aim to provide (i) a long-term perspective of fire activity in the central European lowlands that allows assessment of the preconditions of current and future fire risk, and (ii) an analysis of the dependence of fire activity on natural and anthropogenic drivers. By comparing millennial-scale fire trends at nested spatial scales to known Holocene climate, land cover, and archaeological histories, we aim to determine and discuss when and how sociocultural characteristics such as foraging and agricultural land management have altered the natural occurrence of fire and affected regional biogeochemical cycles.

2. Study area and assumption

We analyze new sedimentary charcoal composites of the Central European Lowlands and the Baltic States (CEL, Fig. 1), a temperate region with a well-studied Holocene land-cover and settlement history (Marquer et al., 2017; Roberts et al., 2018; Trondman et al., 2015). Compared to other regions of the world, the CEL are a low-flammability landscape; currently, spring and summer fire events are rare and burned areas are small, usually < 5 ha (Archibald et al., 2013; FAO, 2007), except for Poland, where slightly larger and more frequent fires have occurred during the last three decades

(San-Miguel-Ayanz et al., 2012). The low flammability of the CEL is due to active fire suppression (Pyne, 2016), and several natural factors.

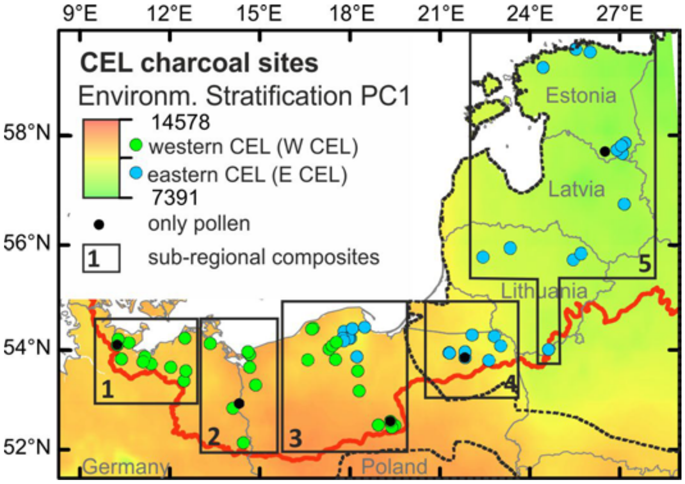

Fig. 1. Available sedimentary microcharcoal records in the Central European Lowlands (CEL). Sites are regionally grouped (eastern vs. western CEL) following the modern environmental stratification of Europe after Metzger et al. (2005) with green-to-brown temperature-related PC1 scores representing the modern climatic-ecological gradient. Black symbols represent pollen records used in land cover reconstructions. Black boxes frame subregional groups 1 – 5. The red bold line marks the extent of the Fennoscandian ice sheet during the last glacial maximum (LGM), after Stroeven et al. (2016). Black dashed lines enclose the current distribution of Norway spruce (*Picea abies*), after EUFORGEN (2018).

First, the generally humid climate of the CEL limits fires by reducing fire spread in wet fuel (Daniau et al., 2012; Flannigan et al., 2009; Pausas and Ribeiro, 2013) and droughts are rare compared to semi-arid, more fire-prone regions (Marlon et al., 2013). Lightning strikes (natural ignition triggers) occur at comparably low frequencies, i.e., <5 flashes km^{-2} yr^{-1} (Christian et al., 2003) and 44 % of the recorded fires in Poland between 1990 and 2006 were related to arson (FAO, 2007). Second, natural fires require sufficient and connected flammable biomass (fuel), even during prolonged shifts to dry conditions. Following a climatic gradient from more warm to more cool climate from the western to the eastern CEL, respectively (Fig. 1), the natural dominance of temperate mixed broadleaf trees decreases towards the eastern CEL and Norway spruce (*Picea abies*) becomes more abundant in the temperate hemiboreal zone (Caudullo et al., 2016; Giesecke and Bennett, 2004). Temperate mixed broadleaf forests of the western CEL rarely burn naturally, because of their high leaf moisture and less-flammable tree compounds (Bowman et al., 2011; Rogers et al., 2015). In the eastern CEL, the prevailing hemiboreal forests are mainly mixtures of broadleaf trees and Norway spruce. The long-term fire ecology of Norway spruce is still under discussion: similar to other conifers, the tree is easily flammable because of its resin-rich needles and canopy structure (Brown and Giesecke, 2014; Caudullo et al., 2016; Feurdean et al., 2017), but it is generally regarded as a fire avoider or even suppressor because it suffers in periods of frequent droughts and fires and its moist understory limits fire (Caudullo et al., 2016; Ohlson et al., 2011; Rogers et al., 2015). In contrast, Scots pine (*Pinus sylvestris*) is better adapted to dry soils and regenerates after a fires; its lighter canopy results in rapid drying of its understory and, hence, increased flammability (Houston Durrant et al., 2016; Rogers et al., 2015).

Given these natural background conditions in the CEL, we expect higher-than-average fire activity in times of dry climate and widespread pine-dominated forests. In times of fully established temperate broadleaf or spruce-dominated hemiboreal forests and wet climate, we expect lower-than-average fire activity. Human alteration of natural fire regimes should result in diverging fire activity trends over various spatial scales (Bowman et al., 2011; McWethy et al., 2013), as exemplified by (i) opposing fire activity trends in adjacent regions, and/or (ii) fire activity trends that contrast the expected natural flammability based on climate and vegetation trends.

3. Material and methods

3.1 Sedimentary charcoal composites

We compiled 61 (39 published and 22 unpublished) microscopic charcoal influx records (CHAR, number of particles cm^{-2} yr^{-1}) from lake sediment and peatland cores (Table S1). As 80% of the records derive from basins smaller than 90 ha, individual CHAR records represent fires with potential source areas within 100 kilometers of the sampling site (Adolf et al., 2018; Marlon et al., 2016) and thus integrate fire events of an extra-local area. We used only microscopic charcoal records from pollen slides, as few continuous macroscopic charcoal records have been published from this region (Feurdean et al., 2017; Marcisz et al., 2015; Pędziszewska and Latałowa, 2016). Evaluation of individual age-depth models considering amount and quality of age control points and type of calculation of age-depth models (see references in Table S2) showed a high diversity of age-depth models. To improve consistency, we recalculated age-depth models for 33 sites using CLAM in R (Blaauw, 2010) following the approach of Giesecke et al. (2014) and IntCal13 (Reimer et al., 2013). For 9 Baltic sites, we recalculated age-depth models using OxCal 4.2.4 and IntCal13 (Reimer et al., 2013) and for the remaining 19 sites, we used the original, high-quality age-depth models (i.e., based on more than 100 age control points, Table S2).

As the resolution and quantity of CHAR vary between sites, established statistical methods of data transformation and compositing allow the detection of common fire trends (Marlon et al., 2016; Power et al., 2008). All available charcoal flux records were transformed with the R paleofire package (Blarquez et al., 2014) using the boxcox, minmax and z-score transformations and a Holocene base period from – 50 to 11,500 years before 1950 AD (cal. BP) with the zero line representing the Holocene mean of all transformed records. Prior to resampling sites, transformed charcoal records were pre-binned in non-overlapping 100-year bins (i.e., at the approximate median resolution across all records). CHAR composite anomalies were calculated for groups over different spatial scales by fitting a robust locally-weighted scatterplot smoother (LOESS) to 1000-year windows using the transformed charcoal records (Blarquez et al., 2014; Daniau et al., 2012). Composite anomaly records are presented as medians and 95 % confidence intervals from 1000 bootstrap realizations (Figs. 2 – 4). Fig. S1 shows data availability for the 100-year bins.

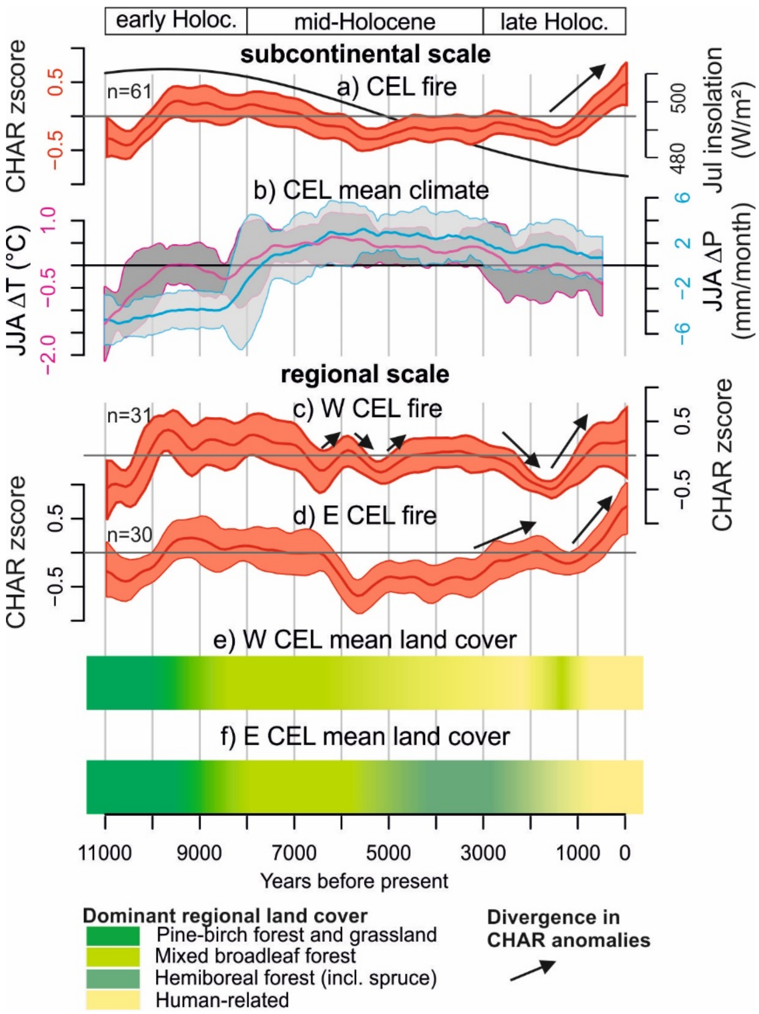

Fig. 2. Subcontinental and regional fire activity, climate, and vegetation trends during the Holocene in the Central European Lowlands and Baltic States (CEL). a) Subcontinental charcoal influx (CHAR) composite anomalies with the insolation curve for 55° N (Laskar et al., 2004); b) average CCSM3-TraCE21k (Liu et al., 2009) 1000-year LOESS-smoothed summer temperatures and precipitation relative to the Holocene average (JJA Δ T and JJA Δ P, respectively), averaged over all model grid cells that contain CHAR records; c) and d) regional CHAR anomalies of the western and eastern CEL (W and E CEL, respectively) CHAR composites, grouped after temperature-related PC1 of Metzger et al. (2005), with arrows indicating divergence from the expected natural and between the two trends; e) and f) generalized development of W and E CEL land-cover communities, respectively, according to pollen records (Figs. 3, 4) and literature review (see text). CHAR composites show the median and 95% confidence interval of LOESS smoothed, bootstrapped, and standardized microcharcoal influxes using *n* available sites (see Fig. S1 for sample availability per time).

CHAR composite anomalies relative to the Holocene average of all CEL sites represent fire activity, fire occurrence, or biomass burnt (Harrison et al., 2018; Marlon et al., 2016), with smaller confidence intervals reflecting greater agreement between records, especially when only few samples were available in a certain time window (Fig. S1). We interpret CHAR composite anomalies as being primarily derived from forest fires, with secondary sources being understory, grass, and crop residue burning (Whitlock and Larsen, 2001).

3.2 Spatial scale representation

We aim to identify the spatial extent of human fire usage in the CEL during the Holocene at nested subcontinental, regional, and subregional scales (Fig. 1), which have received little attention to date. The subcontinental CHAR composite (covering ~1,300 x 500 km) integrates all records. The two regional scale CHAR composites (~500 x 500 km) each represent half of the charcoal records as separated according to modern climate and vegetation gradients. The latter is represented by the natural spread of Norway spruce, whereas the climatic gradient is represented by the first principal component (PC1) of the modern environmental stratification (EnS) of Europe (Fig. 1), which represents temperature-related parameters of ecological relevance, such as altitude, slope, sunshine duration, and monthly temperatures (Metzger et al., 2005). We calculated the average EnS PC1 values of 14 spatial buffers (1 – 50 km around each site) in QGIS and grouped sites into the eastern and western CEL groups (E CEL and W CEL, respectively) according to the median of the data distribution (Figs. 1, S1a). Some northern central Poland sites were included within the E CEL group to account for the uneven spatial representation of records. Subcontinental and regional CHAR composites are shown in Fig. 2.

Five subregional CHAR composites (~200 x 400 km) represent spatial clusters of charcoal records from northern Germany, northwestern Poland/eastern Germany, north-central Poland and northeastern Poland, and the Baltic States (Figs. 1, 3, 4). This grouping is based on the west-to-east climatic-ecological gradients that affect fuel flammability and considers general knowledge of cultural histories (Fig. S2, Table S3). For example, the Lithuanian sites were grouped together with the Latvian and Estonian sites, because of the steep environmental gradient towards northeastern Poland (Fig. 1) and the closer cultural similarities of present-day Lithuania and the other Baltic States. Sample and site availabilities per 100-year bin are shown in Fig. S1 for all CHAR composite anomaly records at the subcontinental scale (n = 61; Fig. S1b), regional scale (W CEL, n = 31; E CEL, n = 30; Fig. S1b) and subregional scales (N Germany, n = 12; NW Poland/E Germany, n=8; N Poland, n = 20; NE Poland, n = 7; Baltics, n = 14; Fig. S1c), suggesting that further records are needed to approve or disprove the trends discussed below, especially those during the early Holocene in northeastern Poland.

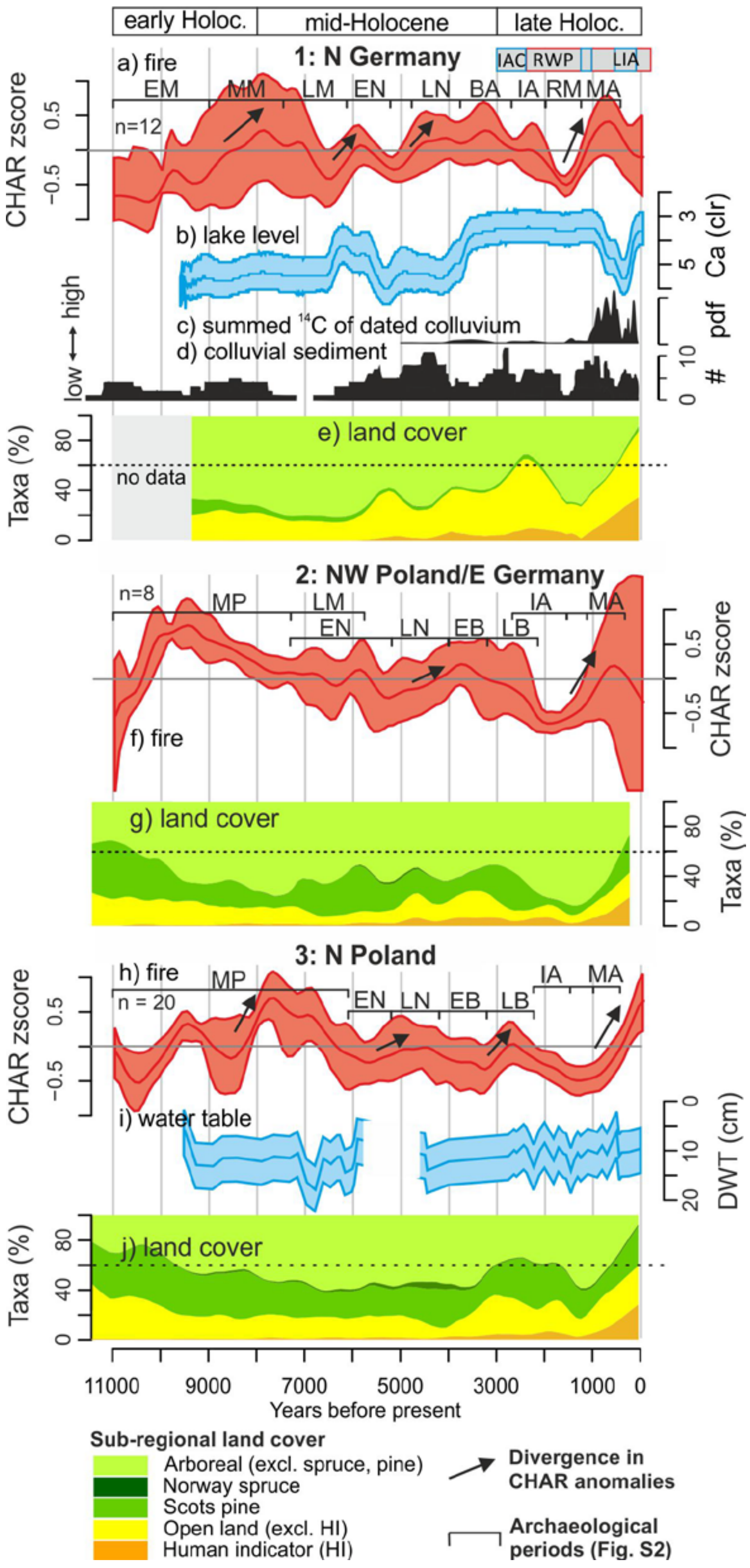

Fig. 3. Subregional Holocene fire activity, lake levels, soil erosion, and land cover reconstructions of the western CEL. a), f) and h) N Germany, NW Poland/E Germany and N Poland CHAR composites, respectively, (median and 95% confidence interval, this study) based on *n* available sites (see Fig. S1 for sample availability per time); b) relative lake

levels of lake Fürstenseer See based on the log-ratio transformed µ-XRF Calcium record, after Dietze et al. (2016); c) probability density function of ^{14}C ages of colluvial deposits, Mecklenburg Lake District, Germany (Küster, 2014); d) absolute number of dated colluvial deposits across northern Germany (Dreibrodt et al., 2010); e), g), and j) REVEALS-transformed (Theuerkauf et al., 2016), 1000-year LOESS-smoothed pollen taxa (sums) of lakes Belauer See (Dörfler et al., 2012), Krebssee (Jahns, 1999, 2000) and Gościąż (Ralska-Jasiewiczowa et al., 1998), respectively; i) depth-to-water table (DWT) of Tuchola mire, north-central Poland (Lamentowicz et al., 2008). Archaeological periods (from Table S3 and Fig. S2) are: MP, Mesolithic Period (EM/MM/LM, early/mid/late Mesolithic); EN/LN: early/late Neolithic Period; BA and IA, Bronze and Iron Ages (EB/LB, early/late Bronze Age); RM: Roman and Migration Period; and MA, Medieval Age. Red and blue framed boxes at top-right mark warm and cool periods during the last 3,000 years (IAC, Iron Age Cold Period, RWP, Roman Warm Period, and LIA, Little Ice Age) after Moffa-Sánchez and Hall (2017). Arrows mark divergence in CHAR composites from expected natural trend.

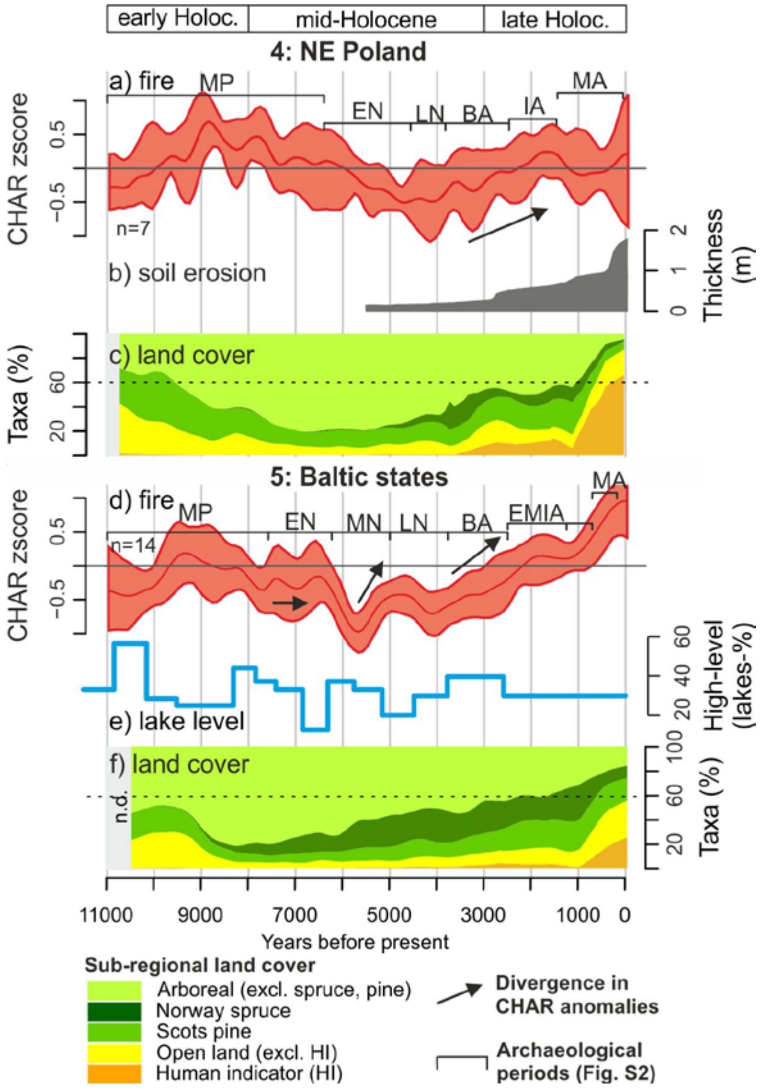

Fig. 4. Subregional Holocene fire activity, land cover, lake levels, and soil erosion reconstructions of the eastern CEL. a) and d) NE Poland and Baltic states CHAR composites, respectively (median and 95% confidence interval, this study), based on *n* available sites (see Fig. S1 for sample availability per time); b) cumulative thickness of colluvial deposits, Masurian Lake District, Poland (Smolska, 2011); c and f) REVEALS-transformed (Theuerkauf et al., 2016), 1000-year LOESS-smoothed pollen taxa (sums) of lakes Miłkowskie (Wacnik, 2009; Wacnik et al., 2012) and Ähijärv (Poska et al., 2017), respectively; and e) percentage of Estonian lakes with high water levels (Harrison and Saarse, 1992) with ^{14}C dates recalibrated using IntCal13 (Reimer et al., 2013). Archaeological periods (from Table S3 and Fig. S2) are: MP, Mesolithic Period; EN/LN, Early/Late Neolithic Period; BA and IA, Bronze and Iron Ages; and MA, Medieval Age). Arrows mark divergence in CHAR composites from expected natural trend.

3.3 Data for comparison

We compared CHAR composite anomalies with climate and land cover data as well as archeological knowledge from the literature to discuss natural and human drivers of fire activity in the CEL. The impact of past anthropogenic fire activity on regional biogeochemical cycles is discussed via comparison with soil erosion and water level changes.

3.3.1 Climate model output

During the Holocene, climatic conditions have responded to seasonal insolation (Laskar et al., 2004) and the loss of the last remnants of the large glacial ice sheets, inducing sea level rise. We used seasonal temperature and precipitation variations derived from a transient climate simulation of a global coupled atmosphere-ocean-model (CCSM3-Trace21k; Liu et al. (2009)) to assess millennial-scale climate variability. The modeled temperature evolution closely correlates with climate reconstructions from terrestrial pollen on millennial and centennial time scales (Marsicek et al., 2018). Summer (June to August) temperatures and precipitation represent the climate of the major fire season and were averaged over all grid cells that contain charcoal records of the subcontinental and regional groups (grid cell resolution: 3.75 x 3.75°). We extracted individual grid cells covering the areas of the subregional CHAR composites (N Germany to NE Poland, Fig. S1) and calculated the 99-year running mean of the three grid cells covering the Baltic States (centered at 22.5° E, 57.52° N; 26.25° E, 57.52° N, and 26.25° E, 53.81° N). Then, we calculated a 1000-year running mean ± 2σ relative to the Holocene averages (0 – 11,500 cal. BP), as with the CHAR composites. Fig. S3 shows that the climate model output (both averages and individual grid cell values) is not significantly different between adjacent subregions over millennial timescales. The mean subcontinental climate model output of the CEL is shown in Fig. 2.

3.3.2 Land cover reconstructions

We assessed natural vegetation and human deforestation using quantitative land cover reconstructions from Holocene pollen records (Fig. 1, Tables S1-S2). We used the longest, most representative, and best-resolved pollen records available for each subregion; these were chosen from lakes with basin areas >50 ha to allow application of the REVEALS model (Sugita, 2007). Hence, pollens from a source area of 100 km² and larger appropriately represent land cover at our subregional scale appropriately. We used the REVEALSinR function with pollen productivity estimates from the PPE.MV2015 data set and the default (LSM) dispersal model (Theuerkauf et al., 2016) to convert pollen% into land cover. We calculated the sums of arboreal taxa including *Corylus avellana*, but excluding the coniferous, flammable taxa *Picea abies* and *Pinus sylvestris* (discussed and shown separately in the text and Figs. 3, 4). The sum of open land includes all non-arboreal taxa, but excludes the sum of direct human indicators (HI: *Artemisia, Plantago major/media*, *Plantago lanceolata*, *Rumex acetosa/ acetosella*, and cereals according to Reitalu et al. (2013); Figs. 3, 4). We interpolated noncontinuous pollen records and *Picea abies* and *Pinus sylvestris* coverages by calculating the mean coverage in the same 100-year bins used for transformation of the CHAR records. Then, we fitted a LOESS to 1000-year windows for each taxon (sum) using the stats package in R and rescaled to one to fulfill the constant-sum constraint of the compositional pollen data (Figs. 3, 4).

3.3.3 Archeological periods

Cultural histories on millennial to centennial time scales are discussed using a compilation of representative archeological classifications per subregion based on archeological literature or, where archeological information was limited, land cover reconstructions from pollen. We provide here only a rough overview of the timing and duration of certain archeological periods (Table S3, Fig. S2). While a comprehensive review and data compilation that considers dating uncertainties and the spatial spread and interaction of past cultures would be helpful and relevant, it is beyond the scope of this work.

3.3.4 Records of soil erosion and water level changes

To discuss the impact of increased human fire usage and human land cover change on landscape transformation and regional biogeochemical cycles, we compare CHAR composite anomalies with records of land surface processes and hydrological processes in subregions with available reconstructions covering most of the Holocene. We derived soil erosion composites from compilations of colluvial deposits for N Germany and NE Poland, comprising a probability density function of ^{14}C dates from the sandur plains of northeastern Germany (Küster, 2014), a record of dated deposits across northern Germany, including the northeast (Dreibrodt et al., 2010), and a record of cumulative colluvial deposit thickness in northeastern Poland (Smolska, 2011).

Water level changes in northeastern Germany are based on the only available, continuous Holocene lake level reconstruction inferred from carbonate deposition in lake Fürstenseer See (Dietze et al., 2016), from which we reassembled the μXRF-Ca record considering 1000 age-depth models within the 2σ range of the ^{14}C dates (Fig. 3b shows the median and 95 % confidence interval). We derived water level changes in northern Poland from a testate amoebae-inferred depth-to-water table record of Tuchola mire (Lamentowicz et al., 2008). The changes in Baltic lake levels are based on a compilation of Estonian lake level records that were classified into high, intermediate, and low lake status by Harrison and Saarse (1992). We recalibrated their age-depth model using IntCal13 (Reimer et al., 2013) and present the percentage of high-level lakes in approximate 500-year bins (Fig. 4e).

4. Results

The CHAR composite anomalies show common trends and divergences at different spatial scales relative to the Holocene average of all records (Figs. 2 – 4). The subcontinental CHAR composite anomalies indicate three phases of CEL fire activity: (i) an early Holocene increase to above-average fire activity, (ii) a mid- to late Holocene decrease to and stabilization at below-average fire activity, and (iii) a late Holocene increase to above-average fire activity.

During the early Holocene (11,500 – 8,500 cal. BP), fire activity increased strongly to above-average levels in all CHAR composites, independent of spatial aggregation (Figs. 2 – 4). At the subcontinental and regional scales, this increase parallels increasing summer temperatures during maximum summer insolation and seasonality as shown by the analyzed climate model output (Fig. 2a-d). Summer precipitation was rather low throughout the CEL (Fig. 2b), and flammable vegetation, i.e., the sum of pine and open land (mainly grasses), reached their maximum coverage during the Holocene in both regions (Figs. 2e, f). Although the absolute timing of positive CHAR anomalies varies among subregions, increased fire activity was most pronounced in NW Poland/E Germany (Fig. 3f).

After c. 8,500 cal. BP, subcontinental and regional CHAR composites declined to below-average values by 7,000 cal. BP, following summer insolation and seasonality (Fig. 2a-d). The TraCE21k-climate model data suggest a strong increase in summer precipitation after 8,500 cal. BP across the CEL (Figs. 2b, S3). At 8,500 cal. BP, pine and open land coverages reduced to their Holocene minima, while broadleaf forests expanded (Figs. 2e, f; 3e, g, j; 4c, f), reducing the area of flammable vegetation. However, at the subregional scale, fire trends started to diverge significantly. NW Poland/E Germany (Fig. 3f) and NE Poland CHAR composites (Fig. 4a) show continuously declining trends since 9,000 cal. BP and until 6,500 and 4,500 cal. BP, respectively. The adjacent N Germany and N Poland composites indicate fire maxima between 8,500 and 6,500 cal. BP (Fig. 3a, h) and the Baltic CHAR composite values stabilize around the Holocene average between 7,500 and 6,500 cal. BP (Fig. 4d).

Although climate and forest composition did not change strongly, we note marked divergences between the regional CEL fire trends after 6,500 cal. BP that are not evident at the subcontinental scale (Fig. 2a). CHAR composites in the western CEL, especially N Germany, increased from c. 6,500 cal. BP, peaked at 5,800 cal. BP and declined afterwards (Figs. 2c; 3a, f, h). Human land use indicators, including cereals, appeared in pollen records and soil erosion increased (Fig. 3e, g, j). In contrast, CHAR composites in the eastern CEL, especially the Baltic States, show a minimum around 5,800 cal. BP and a slight increase in fire activity around 5,500 cal. BP (Figs. 2d; 4a, d). Furthermore, Norway spruce expanded across the Baltic region during that time (Fig. 4f), gradually replacing parts of the broadleaf forest.

During the late Holocene (after 4,000 cal. BP), fire activity increased continuously until present day throughout the eastern CEL, especially in the Baltic subregion (Figs. 2d, 4d). Regional and subregional composites in the western CEL showed several periods of positive and negative CHAR anomalies. The climate model output suggests that cooler and wetter conditions were established across the entire CEL (Fig. 2b). Flammable, but fire-avoiding and suppressing spruce spread and reached its maximum coverage between 3,500 and 2,000 cal. BP in the eastern CEL, and human indicator pollen records increased during that time (Figs. 2f; 4c, f). Between 2,500 and 1,000 cal. BP, regional and subregional composites (especially in the western CEL) show pronounced negative CHAR anomalies of various timings and durations (Figs. 2c, d; 3a, f, h) that follow a trend towards cooler and wetter summers (Fig. 2b). During that time, human indicator taxa in pollen records decreased (Fig. 3e, g, j).

During the last millennium, fire activity increased markedly until present day, reaching burning levels similar to those during the early Holocene, although recent natural conditions were less favorable for fire (Fig. 2). Human-indicator pollen records show that farming intensified in all subregions (Figs. 3e, g, j; 4c, f) and soil erosion increased (Fig. 3c, 4b). However, we observe a significant divergence in subregional CHAR composites. Whereas fire activity in N Poland and the Baltic States increased until present day (Figs. 4a, d), N Germany CHAR anomalies peak around 800 cal. BP and decline afterwards (Fig. 3a).

5. Discussion

5.1 Natural burning conditions

Fire has been an important component of the CEL landscape in the past (Figs. 2 – 4). Absolute values of N Germany CHAR composite anomalies (Fig. 3a) were lower than those of the Baltic CHAR composite anomalies (Fig. 4d), especially during the last millennium. Thus, the natural climatic and vegetation gradient across the CEL influences biomass flammability: northern Germany is more oceanic and has less pine coverage (Figs. 3, 4) than the more continental areas towards the east, which have more coniferous forest cover, are more affected by summer droughts (Lindner et al., 2010) and, hence, are more fire-prone (Marcisz et al., 2017). However, we focus on the interpretation of trends in CHAR composite anomalies, because absolute anomalies can only be linked to relative and not quantitative differences in fire regime properties.

Subcontinental fire activity trends followed major changes in climate/vegetation across the CEL since the last glacial period, similar to southern Scandinavia (Olsson et al., 2010) and northeastern Europe (Marlon et al., 2013). Previous (sub)continental CHAR composite anomalies of Europe and central Europe have shown increasing fire activity throughout the Holocene (Marlon et al., 2013; Molinari et al., 2013; Power et al., 2008). However, we find alternating periods of high and low fire activity, similar to southern European CHAR compilations (Vannière et al., 2011). The CEL fire activity trends are sometimes divergent between adjacent areas at various spatial scales (Figs. 2 – 4) and could be related to both, natural (i.e., climatic and fuel-related) and human drivers.

During the early Holocene, fire activity paralleled increasing summer temperatures (Figs. 2 – 4, S3) similar to fire trends at the global scale (Daniau et al., 2012; Marlon et al., 2013; Power et al., 2008). Frequent droughts related to dominating continental air masses have been reported from regional hydrological reconstructions mainly based on geochemical and paleoecological proxies (Dietze et al., 2016; Harrison et al., 1993; Lauterbach et al., 2011; Väliranta et al., 2015). Hence, the climate and natural land cover (dominated by extensive pine forests and grasslands) favored natural fires.

The natural flammability of the CEL landscape reduced after a shift towards wetter summers around 8,500 cal. BP (Fig. 2b), probably related to the increasing influence of north Atlantic air masses across the CEL, similar to the present-day air mass dominance (Lauterbach et al., 2011; Rust et al., 2018). However, proxy data does not consistently show increased summer wetness after 8,500 cal. BP (Dietze et al., 2016; Gałka et al., 2014; Latałowa et al., 2013) (Figs. 3b, i; 4e), which we attribute at different sensitivity and temporal resolution of the proxies. Furthermore, with the establishment of mixed broadleaf forests across the CEL, less-flammable fuel was available, with pine forests dominating only in very wet or very dry sites. The slight increase in Baltic CHAR anomalies after 5,500 cal. BP is synchronous with lake level reductions that suggest drier conditions (Harrison and Saarse, 1992). Climatic conditions became even less favorable for fire during the last 4,000 years, when climate model output and proxy reconstructions suggest that cooler and wetter conditions established across the entire CEL (Figs. 2 – 4) (Dietze et al., 2016; Wanner et al., 2008). However, fire activity did not decrease accordingly: CHAR composites diverged from the expected natural trend at the subregional scale since 8,500 cal BP (Figs. 3, 4), at the regional scale since 6,500 cal BP, and at the subcontinental scale since 1,000 cal BP (Fig. 2).

We propose that the divergence of CHAR composite anomalies from the expected natural trends and between adjacent subregions indicates human alteration of natural fire regimes. We assume spatially homogeneous climatic trends across the CEL because modern short-term climatic events show strong spatial coherence (Merz et al., 2018; Rust et al., 2018) and long-term (i.e., millennial-scale) climate models and available land-cover data do not suggest a spatial heterogeneity of natural trends between adjacent regions. This assumption is limited by some constraints: first, available climate proxy data is heterogeneous concerning archive type, temporal coverage, and the type and spatiotemporal extent of the proxy-climate relationship (Mauri et al., 2015; Salonen et al., 2012; Väliranta et al., 2015); second, we lack comparable and independent syntheses of climate-proxy and land cover data on similar spatiotemporal scales (Marquer et al., 2017; Trondman et al., 2015); and third, the analyzed climate model output only provides larger-scale trends based on the first-order effects of CO_2 and orbital forcing (Rehfeld and Laepple, 2016; Zhang et al., 2017) and does not consider regional climate-land cover feedbacks (Qian et al., 2015).

During periods of low natural flammability but increased fire activity after 8,500 cal. BP, we assume that humans set fires for multiple purposes by taking advantage of dry fuel during short-term droughts that occur in both wetter and drier climates. As proof of concept, we discuss two examples of human-fire relationships that affected fire activity even in periods and areas of low population densities.

5.2 Fire use by hunter-gatherers

Superimposed on the naturally occurring fire trends, we suggest that maxima in the subregional CHAR composites between 8,500 and 6,000 cal. BP indicate forest fires started by Mesolithic and early Neolithic Baltic hunter-gatherers. So far, there is little direct evidence that Mesolithic groups drove fire activity on larger spatial scales, as archaeological sites document only localized fire use (Bishop et al., 2015) and the open-land signal in vegetation reconstructions is barely distinguishable from natural disturbances (Bishop et al., 2015) such as wind throw and forest grazing by large herbivorous mammals (e.g., Birks (2005). However, the presence of local Mesolithic groups and social interactions between them are well known across the CEL (Latałowa, 1992; Wacnik et al., 2011; Zvelebil, 2006, 2008). Increasing knowledge of Mesolithic (and early Neolithic) cultures around the Baltic Sea indicates that their subsistence mainly relied on marine or freshwater fishing, but always included forest-based resources (Meadows et al., 2016; Rimantienė, 1992; Zvelebil, 2008) that required maintaining open space in forests (Bishop et al., 2015). Fire is regarded as an important tool, for example, to selectively support food production, especially hazel (*Corylus avellana*) (Holst, 2010; Wacnik et al., 2011; Zvelebil, 2008), or to keep clearings open to attract game (Bishop et al., 2015).

The degree of intentional forest disturbance and use of forest resources probably varied in space and time (Meadows et al., 2016; Poska and Saarse, 2002; Wacnik et al., 2011; Zvelebil, 2008) and in relation to access to other resources from, e.g., rivers, the sea, or early contacts with sedentary cultures (Krause-Kyora et al., 2013; Silva and Vander Linden, 2017). For example, new analytical approaches in archaeology suggest that Mesolithic forest-based diets were reduced in favor of water-based diets in the Baltic hinterland (Meadows et al., 2016). Accordingly, Baltic CHAR anomalies (Fig. 4d) suggest that fire usage of the mid-Neolithic Narva hunter-gatherers (Table S3, Fig. S2) might have reduced their fire usage around 5,800 cal. BP, when the Baltic CHAR composite declines to a minimum.

We argue that diverse extents of woodland alteration by hunter-gatherers can explain the offset from the expected natural fire trends on the subregional scale, which represents roughly the territories that Mesolithic hunter-gatherers occupied (Zvelebil, 2006). Hence, we support earlier interpretations that Mesolithic communities could have significantly affected landscapes by burning forest to construct their niche (Bishop et al., 2015; Latałowa, 1992; Poska and Saarse, 2002; Wacnik et al., 2011). We propose that fire activity was linked not only to human population densities, but also to cultural subsistence strategies that were based on diverse usage of terrestrial resources.

5.3 Fire as an agrarian land management tool

Divergent regional CHAR composite anomalies after 6,500 cal. BP mirror divergent rates in Neolithisation and agricultural land use, as previously suggested by discrete charcoal data (Robin and Nelle, 2014). CHAR composites allow determination of the spatial spread of human fire usage in prehistoric and historic agrarian land management, which was previously described using archaeological compilations (Feeser and Dörfler, 2015; Poska et al., 2004; Silva and Vander Linden, 2017) and quantitative land cover reconstructions (Marquer et al., 2017; Trondman et al., 2015).

During the transition from foraging to sedentary cultures that adopted pastoralism and agriculture, western CEL CHAR composites, especially N Germany and NW Poland/E Germany, show increasing and declining anomalies that coincide with a known societal cycle of increasing and declining population development between 6,500 and 5,000 cal BP (Feeser and Dörfler, 2015; Latałowa, 1992) (Figs. 2 – 4), as inferred from archeological remains (Warden et al., 2017). During that time, the temperature in the Baltic Sea area increased towards the mid-Holocene thermal optimum and subsequently decreased after 5,500 cal BP, suggesting a response of cultural development to climate change on millennial time scales (Warden et al., 2017). However, despite continued decreases in overall population densities and Baltic Sea temperatures between 5,000 and 3,000 cal. BP (Warden et al., 2017), fire use increased on regional and subregional scales after the transition from the Funnel Beaker towards the Corded Ware culture around 4,800 cal. BP.

Yet, the role of fire in Neolithic land management is strongly debated in the western CEL (Feeser et al., 2012), because of lacking evidence for slash-and-burn practices that were common in other regions (Bowman et al., 2011; Vannière et al., 2016). Although fire probably helped to alter woodland structures during the initial period of adoption of animal husbandry (Feeser and Dörfler, 2014; Feeser and Dörfler, 2015), further regional land management strategies without fire usage evolved for deforestation and agricultural maintenance (Feeser et al., 2012; Latałowa, 1992). Hence, fire usage seems to depend more on the variable cultural practices than on population densities (see archeological phases in Figs. 3, S2).

In the eastern CEL, fire activity increased after 5,500 cal. BP but only reached or exceeded the Holocene average after 3,000 cal. BP (Figs. 2, 4). Lake levels in the Baltic States decreased between 5,200 and 4,000 cal. BP, suggesting a drier climate possibly related to increasing Baltic Sea temperatures (Warden et al., 2017). Eastern CEL fire activity might therefore be influenced by a climatic shift. Although the first traces of cereals and pastoralism appear in the region during that time (Madeja et al., 2010; Poska et al., 2004; Trondman et al., 2015) as a result of the appearance of, e.g., the Funnel Beaker and Corded Ware cultures (Table S3), archeological and land cover data suggest that Baltic cultures still relied primarily on forest- and water-based resources (Meadows et al., 2016; Poska et al., 2004; Rimantienė, 1992; Wacnik, 2009). Only after the onset of the Bronze Age (4,000 cal. BP) do human indicator pollen and soil erosion records show increasing agricultural land use (Gałka et al., 2013; Poska et al., 2004; Reitalu et al., 2013; Smolska, 2011) (Fig. 4). Hence, increasing CHAR composite anomalies parallel the major onset and spread of farming in the eastern CEL more than 2,000 years later than in the western CEL (Figs. 2 – 4).

Whereas eastern CEL CHAR composites continuously increased towards present day, western CEL CHAR composites follow known archaeological phases of altered land management and technological transitions, such as those occurring during the Bronze and Iron Ages (Fig. 3). Most prominently, negative fire anomalies of varying timings and durations in adjacent regions between 2,500 and 1,000 cal. BP follow a millennial-scale climatic cooling (Helama et al., 2017; Wanner et al., 2008) (Fig. 2). Additionally, the expansion of beech (*Fagus sylvatica*) and hornbeam (*Carpinus betulus*) in Germany and northern Poland further reduced fire-prone pine forest cover (Marquer et al., 2017; Pędziszewska and Latałowa, 2016). Although societal responses to climatic changes are complex and difficult to decipher at millennial time scales (Haldon, 2016), the reduction in fire activities during that time suggests an altered use of fire in land management. In many areas, reduced human land use *per se* during the Migration Period can explain the minimum CHAR composite anomalies (Figs. 3, S2). Although debated, large-scale human reorganization during this period was probably related to less-favorable climatic conditions of the Dark Age cold period (Helama et al., 2017; Kaplan et al., 2009; Zhang et al., 2011) and led to the reforestation of large areas, mainly with broadleaf taxa (Marquer et al., 2017) (Figs. 2 – 4).

The strong increase of fire activity in all CHAR composites during the last millennium (Figs. 2 – 4) parallels population growth after the Migration Period (Helama et al., 2017). This increase clearly overrides the millennial-scale cool and wet climatic trends (Fig. 2), similar as suggested for recent times over shorter time scales (Syphard et al., 2017). Farming extended into previously unsuitable sites and intensified in all subregions, as reflected in pollen and soil erosion records (Dreibrodt et al., 2010; Kaplan et al., 2009; Marquer et al., 2017) (Fig. 3). Fire activity driven by human land cover change reached early Holocene levels, even at the subcontinental scale (Fig. 2).

The pattern in N German CHAR composites, which diverges from other subregional composites, follows the generally assumed relationship between fire and population densities: increasing population first lead to increased fire activity, and eventually to landscape fragmentation that indirectly limited the spread of fires (Marlon et al., 2008; Pechony and Shindell, 2010). The landscape in northern Germany seems to have become fragmented by around 1200 AD: land cover reconstructions from pollen data and models suggest that more than 60 % of the land was deforested in northern Germany by that time, compared to less than 40 % in the Baltic states (intermediate estimates based on Kaplan et al. (2009), Kaplan et al. (2017), Marquer et al. (2017) and Figs. 3, 4). All other analyzed subregions did not reach this extent of open land (Figs. 3, 4) and, within uncertainty, most still show an upward trend in fire activity (Figs. 3, 4). This trend might not only relate to land openness and associated landscape fragmentation, but also to forest composition and biomass flammability, as coniferous taxa cover a greater extent in the continental eastern CEL than in the western CEL (Figs. 1, 3, 4; Marcisz et al. (2017). We note that the Lake Miłkowskie pollen record (Fig. 4c) shows representative land openness trends in NE Poland, but locally reconstructed openness was exceptionally high already since ca. 800 cal. BP, whereas other areas remained strongly forested (Wacnik et al., 2016).

Our relative CHAR composite anomalies do not allow us to infer absolute changes in past fire regime properties in terms of fire frequency, area, or the amount and type of biomass burned (Marlon et al., 2016). Uncertainties in our reconstructions are still large due to limited data availabilities during certain periods, especially at the subregional scale (Fig. S1), indicating the need for more and highly resolved Holocene fire records that allow better characterization of past fire regimes (Feurdean et al., 2017; Vannière et al., 2016). Hence, the impact of human-driven fires and associated human land management on biogeochemical cycles can only be discussed in general terms.

5.4 The roles of fire and human land cover change in Holocene landscape transformation and biogeochemical cycles

Our results suggest that humans have increased fire activity beyond the local scale in the CEL throughout the Holocene. Accordingly, humans could have significantly affected biogeochemical cycles in this landscape of low natural flammability. Since the divergence of CHAR composites from the expected natural trends at the transition from the early to mid-Holocene, the increased occurrence of fire in a landscape of low natural flammability probably increased carbon release and altered albedo and vegetation composition and, hence, regional climate-carbon cycle feedbacks (Harrison et al., 2018; Schimel and Baker, 2002).

In addition to the indirect feedback with regional climate (Strandberg et al., 2014), human fire usage in land management probably affected biogeochemical cycles also via other landscape components in the CEL such as soil erosion and water budgets (Latałowa, 1992). Indeed, observations have shown increased erosion on the catchment scale (<100 km^2) following fires (Allen, 2007; Bodí et al., 2014; Leys et al., 2016), with charcoal remains being a classical diagnostic property of central European hillslope, i.e., colluvial, sediments (Robin and Nelle, 2014). Hoffmann et al. (2013) quantified significant carbon burial and storage in floodplain and hillslope sediments due to Holocene human-induced soil erosion. Our lake- and peatland-derived CHAR composite anomalies mirror soil erosion trends in N Germany and NE Poland (Dreibrodt et al., 2010; Dreibrodt and Wiethold, 2015; Smolska, 2011) after Neolithisation (6,500 and 4,000 cal. BP, Fig. 3) and, hence, provide an independent record of human-induced and biogeochemically-relevant soil erosion and land cover change.

Water level changes are generally interpreted in terms of precipitation-evaporation ratios (Harrison et al., 1993; Shuman et al., 2010). In northern Germany, we observe that significant lake level changes (considering age uncertainties from Dietze et al. (2016) parallel the CHAR composite anomalies during the Neolithic period (Fig. 3a, b). Thus, human fire usage in land management may have resulted in regionally increased groundwater recharge and higher water levels, as shown by Woodward et al. (2014) on the global scale. Further intense lake level fluctuations related to human water management (Dietze et al., 2016) occurred at the time of maximum land openness and fire activity during the last millennium (Fig. 3).

Hence, human land cover change could have significantly affected regional hydrological and sediment budgets, especially since the Neolithic time (Dietze et al., 2016; Latałowa, 1992; Ruddiman et al., 2015). Integration and compilation of land, ecosystem, and paleoclimate records over different spatial and temporal scales are needed to better understand and quantify the interactions between climate and human drivers of past landscape transformation (Marquer et al., 2017) and the role of cultural fire use.

6. Conclusions and implications

We provide a new reconstruction of Holocene fire activity in the low-flammability landscape of the Central European Lowlands. When natural conditions (climate and land cover) limited widespread fire occurrence, millennial-scale fire activity seems well explained by the cultural use of fire suggesting that humans have affected natural terrestrial systems at varying intensities over several millennia, and providing new insights into past human-environment interactions.

We have identified convergences and divergences (i) among nested subregional to subcontinental CHAR composites and (ii) from the expected natural flammability across spatial scales. This approach provides a step forward in determining early human-fire-land use relationships (Fig. 5) when high-resolution macrocharcoal records are lacking, i.e., beyond the assumption of direct fire-population density relationships and independent of classical pollen-derived human impact indicators. This approach adds to previous studies in other areas of the globe where natural conditions did not support the frequent occurrence of fire (McWethy et al., 2013).

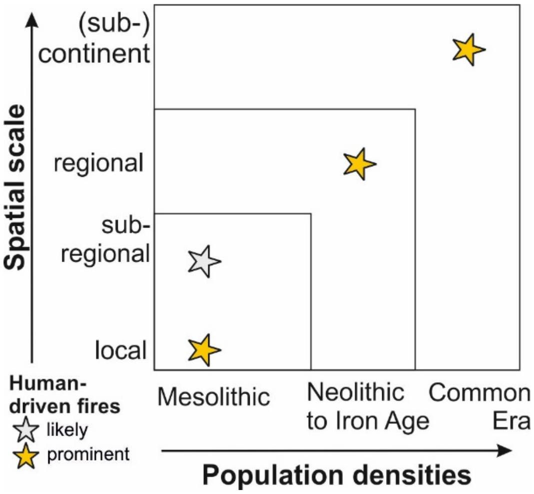

Fig. 5. Scale dependency of millennial fire trends in low-flammability landscapes, based on CEL CHAR composites. Early human fire usage can be detected with composites aggregating sedimentary charcoal records at small spatial scales. Whereas the impact of Mesolithic hunter-gatherers is archaeologically well known at the local scale, CHAR composites allow detection of Mesolithic impacts at the subregional scale under less suitable natural burning conditions, despite low population densities (Kaplan et al., 2009; Klein Goldewijk et al., 2011).

Our reconstructions have two major implications. First, past human-fire relationships were multifaceted. Hunter-gatherer subsistence strategies in the CEL seem to have altered natural fire regimes beyond the local scale despite low population densities, supporting previous hypotheses (Kaplan et al., 2016; White, 2013). In agrarian societies, millennial CHAR composite anomalies seem closely associated with cultural land use strategies, which is difficult, but possible to parameterize in fire models (Lasslop and Kloster, 2017; Pfeiffer et al., 2013).

Second, our millennial scale paleofire perspective provides long-term background information on the interplay of natural and human drivers of land-cover change, a prerequisite to inform future land management and nature conservation efforts (Whitlock et al., 2018). At the spatial scales relevant to political decisions in the CEL, the last millennium seems key to understanding the preconditions that determine future fire risks. Although during the last century only minor fire events have occurred in the CEL compared to other areas of the world, forest cover is expected to increase in the future and fuel will accumulate in widespread human-planted pine and spruce monocultures (Caudullo et al., 2016; Houston Durrant et al., 2016). Future climate change scenarios predict drier and warmer summers, and the frequency of natural ignition by lightning might increase (Douville and Plazzotta, 2017; Lhotka et al., 2018; Romps et al., 2014). These factors increase fire hazard and fire risk (Hardy, 2005), leading to a much more flammable landscape—a situation comparable to the early Holocene. Our study supports previous suggestions that natural and/or human-driven substitution of flammable coniferous for broadleaf forests could outpace the increasing fire danger in the continental and hemiboreal CEL (Feurdean et al., 2017).

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Data Availability

Charcoal data of this study will be available via the Global Charcoal Database, hosted by the Laboratoire Chrono-environnement (UMR 6249 du CNRS) at the University of Bourgogne / Franche-Comté (Besançon, France): https://paleofire.org/index.php.

Author Contributions

ED, MT, MS and BV designed the study. MT, ML, IF, SJ, PK, ML, LG, KM, MKK, TG, MO, AP, MS, NS, JS, MS, SV, AW, DW, and MW provided charcoal data, AW, AP, and JW provided pollen data. ED and MT performed the data analyses of charcoal and pollen data. JV analyzed Baltic age-depth models. KR analyzed CCSM3-TraCE21k model output. All authors participated in the data interpretation. ED wrote the paper with contributions from all authors.

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