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

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53   **Highlights**

54   • We report sedimentary charcoal composites for the Central European lowlands (CEL).

55   • Holocene fire activity shows convergence and divergence across three spatial scales.

56   • Divergence in low-flammability periods reflects cultural fire use in land management.

57   • Since 8,500 cal. BP, humans affected CEL-biogeochemical cycles beyond the local scale.

58

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Abstract

61 Fire is a natural component of global biogeochemical cycles and closely related to changes in human

62 land use. Whereas climate-fuel relationships seem to drive both global and subcontinental fire

63 regimes, human-induced fires are prominent mainly on a local scale. Furthermore, the basic

64 assumption that relates humans and fire regimes in terms of population densities, suggesting that few

65 human-induced fires should occur in periods and areas of low population density, is currently

66 debated. Here, we analyze human-fire relationships throughout the Holocene and discuss how and to

67 what extent human-driven fires affected the landscape transformation in the Central European

68 Lowlands (CEL). We present sedimentary charcoal composites on three spatial scales and compare

69 them with climate model output and land cover reconstructions from pollen records. Our findings

70 indicate that widespread natural fires only occurred during the early Holocene. Natural conditions

71 (climate and vegetation) limited the extent of wildfires beginning 8,500 cal. BP, and diverging

72 subregional charcoal composites suggest that Mesolithic hunter-gatherers maintained a culturally

73 diverse use of fire. Divergence in regional charcoal composites marks the spread of sedentary

74 cultures in the western and eastern CEL. The intensification of human land use during the last

75 millennium drove an increase in fire activity to early-Holocene levels across the CEL. Hence,

76 humans have significantly affected natural fire regimes beyond the local scale – even in periods of

77 low population densities – depending on diverse cultural land-use strategies. We find that humans

78 have strongly affected land-cover- and biogeochemical cycles since Mesolithic times.

79 **1. Introduction**

80 Major questions in the global debate on climate and environmental change are when, how and to

81 what extent humans have affected land cover and global carbon cycles beyond their natural

82 variability (Ruddiman et al., 2015; Strandberg et al., 2014; Waters et al., 2016). Fire is a key

4

83   component of many natural ecosystems and biogeochemical cycles worldwide (Jaffé et al., 2013;

84   Randerson et al., 2006) and closely linked to climate (Daniau et al., 2012). However, fire usage has

85   also been key in human evolution (Bowman et al., 2009; Roebroeks and Villa, 2011) and an

86   important tool in anthropogenic land cover change across the globe (Bowman et al., 2011), at least

87   until the time of active fire suppression and the notion of fire being a threat to society (Marlon et al.,

88   2008; Pyne, 2016). As fire risk and socioecological damage are currently increasing in many parts of

89   the world, human-fire relationships are highly debated (Balch et al., 2017; Syphard et al., 2017; Ward

90   et al., 2018). One of the assumptions accounting for humans as drivers of fire regimes is a close

91   relationship between human population densities and fire, where humans act first as ignition triggers.

92   Then, after reaching a certain threshold, humans act as fire suppressors by increasing landscape

93   fragmentation or by taking active suppressive measures (Guyette et al., 2002; Lasslop and Kloster,

94   2017; Ward et al., 2018). Given the low population densities throughout the early and mid-Holocene

95   (Kaplan et al., 2011; Klein Goldewijk et al., 2011), fire histories derived from sedimentary charcoal

96   (CHAR) compilations have been primarily associated with climatic factors (Daniau et al., 2012;

97   Marlon et al., 2013) and natural vegetation compositions (Blarquez et al., 2015). Only in the most

98   recent centuries, humans seem to have influenced natural fire regimes on global to regional scales

99   (Marlon et al., 2008; Pechony and Shindell, 2010).

100   However, local CHAR records and some regional CHAR compilations show divergent Holocene fire

101   regimes in adjacent European regions that cannot be explained solely by natural factors (climate,

102   vegetation) (Rius et al., 2011; Vannière et al., 2011). Instead, diverse local to regional fire regimes

103   (characterized by fire frequency, seasonality, intensity, and amount of biomass burned) could indicate

104   human fire use in diverse cultural subsistence traditions and land use practices at least since the last

105   7,000 to 3,000 years (Molinari et al., 2013; Rius et al., 2011; Vannière et al., 2016; Vannière et al.,

106   2011). However, to what extent early hunter-gatherer and farming societies altered natural fire

107 regimes and landscapes beyond the local scale remains poorly understood (Kaplan et al., 2016;

108 Marlon et al., 2013; Ruddiman, 2013; Vannière et al., 2016). The impacts of future climate change,

109 such as changing fire risk, will be highly variable at the regional scale and dependent on

110 preconditions that have shaped a landscape. Considering cultural dependencies in human-fire

111 relationships over multiple spatial scales relevant to political decision processes is important to (i)

112 unravel the long-term interactions between natural and human drivers on fire regimes and the

113 associated human impact on biogeochemical cycles (Arneth et al., 2017; van der Werf et al., 2013)

114 and (ii) enable informed discussions on future land management and nature conservation efforts

115 (Whitlock et al., 2018).

116 Here, we aim to provide (i) a long-term perspective of fire activity in the central European lowlands

117 that allows assessment of the preconditions of current and future fire risk, and (ii) an analysis of the

118 dependence of fire activity on natural and anthropogenic drivers. By comparing millennial-scale fire

119 trends at nested spatial scales to known Holocene climate, land cover, and archaeological histories,

120 we aim to determine and discuss when and how sociocultural characteristics such as foraging and

121 agricultural land management have altered the natural occurrence of fire and affected regional

122 biogeochemical cycles.

123 **2. Study area and assumption**

124 We analyze new sedimentary charcoal composites of the Central European Lowlands and the Baltic

125 States (CEL, Fig. 1), a temperate region with a well-studied Holocene land-cover and settlement

126 history (Marquer et al., 2017; Roberts et al., 2018; Trondman et al., 2015). Compared to other

127 regions of the world, the CEL are a low-flammability landscape; currently, spring and summer fire

128 events are rare and burned areas are small, usually < 5 ha (Archibald et al., 2013; FAO, 2007), except

129 for Poland, where slightly larger and more frequent fires have occurred during the last three decades

130 (San-Miguel-Ayanz et al., 2012). The low flammability of the CEL is due to active fire suppression

131 (Pyne, 2016), and several natural factors.
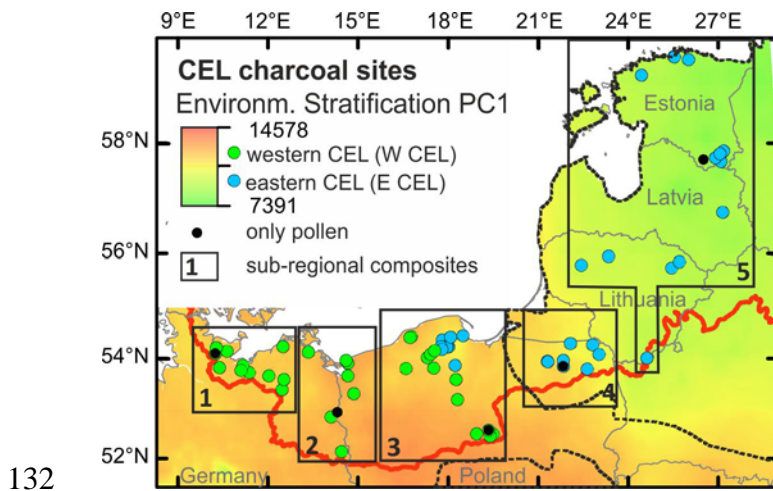
133 Fig. 1. Available sedimentary microcharcoal records in the Central European Lowlands (CEL). Sites are regionally

134 grouped (eastern vs. western CEL) following the modern environmental stratification of Europe after Metzger et al.

135 (2005) with green-to-brown temperature-related PC1 scores representing the modern climatic-ecological gradient. Black

136 symbols represent pollen records used in land cover reconstructions. Black boxes frame subregional groups 1 – 5. The red

137 bold line marks the extent of the Fennoscandian ice sheet during the last glacial maximum (LGM), after Stroeven et al.

138 (2016). Black dashed lines enclose the current distribution of Norway spruce (*Picea abies*), after EUFORGEN (2018).

139 First, the generally humid climate of the CEL limits fires by reducing fire spread in wet fuel (Daniau

140 et al., 2012; Flannigan et al., 2009; Pausas and Ribeiro, 2013) and droughts are rare compared to

141 semi-arid, more fire-prone regions (Marlon et al., 2013). Lightning strikes (natural ignition triggers)

142 occur at comparably low frequencies, i.e., <5 flashes km^{-2} yr^{-1} (Christian et al., 2003) and 44 % of

143 the recorded fires in Poland between 1990 and 2006 were related to arson (FAO, 2007). Second,

144 natural fires require sufficient and connected flammable biomass (fuel), even during prolonged shifts

145 to dry conditions. Following a climatic gradient from more warm to more cool climate from the

146 western to the eastern CEL, respectively (Fig. 1), the natural dominance of temperate mixed

147 broadleaf trees decreases towards the eastern CEL and Norway spruce (*Picea abies*) becomes more

148 abundant in the temperate hemiboreal zone (Caudullo et al., 2016; Giesecke and Bennett, 2004).

149 Temperate mixed broadleaf forests of the western CEL rarely burn naturally, because of their high

150 leaf moisture and less-flammable tree compounds (Bowman et al., 2011; Rogers et al., 2015). In the

151 eastern CEL, the prevailing hemiboreal forests are mainly mixtures of broadleaf trees and Norway

152 spruce. The long-term fire ecology of Norway spruce is still under discussion: similar to other

153 conifers, the tree is easily flammable because of its resin-rich needles and canopy structure (Brown

154 and Giesecke, 2014; Caudullo et al., 2016; Feurdean et al., 2017), but it is generally regarded as a fire

155 avoider or even suppressor because it suffers in periods of frequent droughts and fires and its moist

156 understory limits fire (Caudullo et al., 2016; Ohlson et al., 2011; Rogers et al., 2015). In contrast,

157 Scots pine (*Pinus sylvestris*) is better adapted to dry soils and regenerates after a fires; its lighter

158 canopy results in rapid drying of its understory and, hence, increased flammability (Houston Durrant

159 et al., 2016; Rogers et al., 2015).

160 Given these natural background conditions in the CEL, we expect higher-than-average fire activity in

161 times of dry climate and widespread pine-dominated forests. In times of fully established temperate

162 broadleaf or spruce-dominated hemiboreal forests and wet climate, we expect lower-than-average fire

163 activity. Human alteration of natural fire regimes should result in diverging fire activity trends over

164 various spatial scales (Bowman et al., 2011; McWethy et al., 2013), as exemplified by (i) opposing

165 fire activity trends in adjacent regions, and/or (ii) fire activity trends that contrast the expected natural

166 flammability based on climate and vegetation trends.

167 **3. Material and methods**

168 **3.1 Sedimentary charcoal composites**

169 We compiled 61 (39 published and 22 unpublished) microscopic charcoal influx records (CHAR,

170 number of particles cm^{-2} yr^{-1}) from lake sediment and peatland cores (Table S1). As 80% of the

171   records derive from basins smaller than 90 ha, individual CHAR records represent fires with

172   potential source areas within 100 kilometers of the sampling site (Adolf et al., 2018; Marlon et al.,

173   2016) and thus integrate fire events of an extra-local area. We used only microscopic charcoal

174   records from pollen slides, as few continuous macroscopic charcoal records have been published

175   from this region (Feurdean et al., 2017; Marcisz et al., 2015; Pędziszewska and Latałowa, 2016).

176   Evaluation of individual age-depth models considering amount and quality of age control points and

177   type of calculation of age-depth models (see references in Table S2) showed a high diversity of age-

178   depth models. To improve consistency, we recalculated age-depth models for 33 sites using CLAM

179   in R (Blaauw, 2010) following the approach of Giesecke et al. (2014) and IntCal13 (Reimer et al.,

180   2013). For 9 Baltic sites, we recalculated age-depth models using OxCal 4.2.4 and IntCal13 (Reimer

181   et al., 2013) and for the remaining 19 sites, we used the original, high-quality age-depth models (i.e.,

182   based on more than 100 age control points, Table S2).

183   As the resolution and quantity of CHAR vary between sites, established statistical methods of data

184   transformation and compositing allow the detection of common fire trends (Marlon et al., 2016;

185   Power et al., 2008). All available charcoal flux records were transformed with the R paleofire

186   package (Blarquez et al., 2014) using the boxcox, minmax and z-score transformations and a

187   Holocene base period from – 50 to 11,500 years before 1950 AD (cal. BP) with the zero line

188   representing the Holocene mean of all transformed records. Prior to resampling sites, transformed

189   charcoal records were pre-binned in non-overlapping 100-year bins (i.e., at the approximate median

190   resolution across all records). CHAR composite anomalies were calculated for groups over different

191   spatial scales by fitting a robust locally-weighted scatterplot smoother (LOESS) to 1000-year

192   windows using the transformed charcoal records (Blarquez et al., 2014; Daniau et al., 2012).

193   Composite anomaly records are presented as medians and 95 % confidence intervals from 1000

194   bootstrap realizations (Figs. 2 – 4). Fig. S1 shows data availability for the 100-year bins.
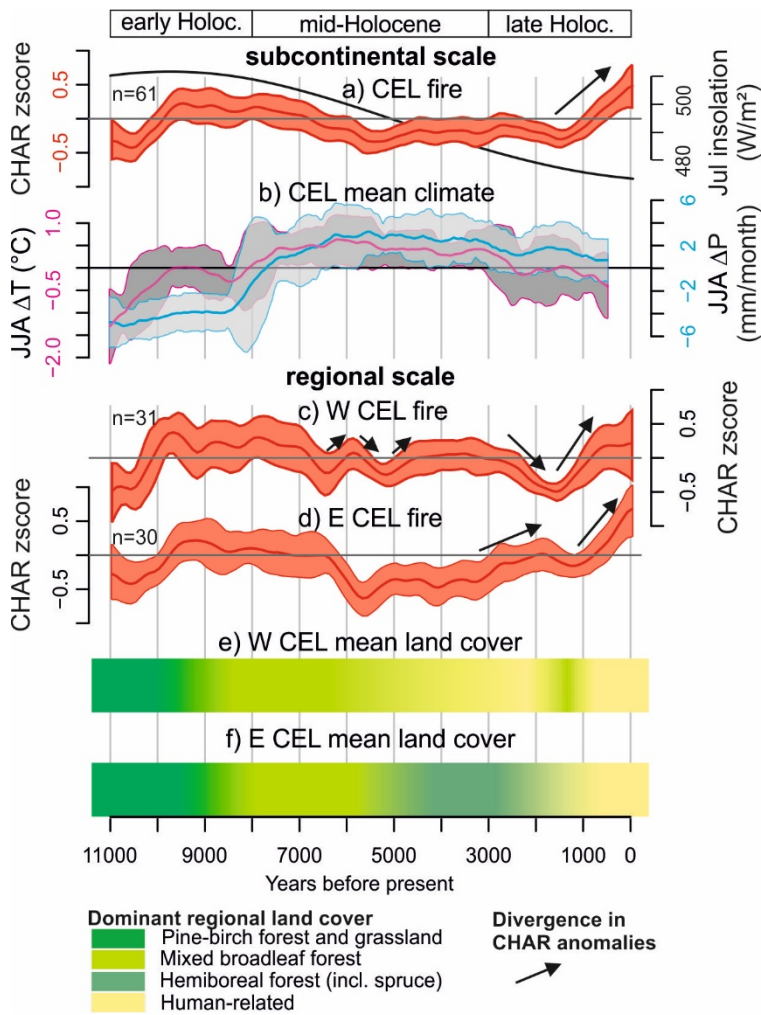
Fig. 2. Subcontinental and regional fire activity, climate, and vegetation trends during the Holocene in the Central European Lowlands and Baltic States (CEL). a) Subcontinental charcoal influx (CHAR) composite anomalies with the insolation curve for 55° N (Laskar et al., 2004); b) average CCSM3-TraCE21k (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).

207 CHAR composite anomalies relative to the Holocene average of all CEL sites represent fire activity,

208 fire occurrence, or biomass burnt (Harrison et al., 2018; Marlon et al., 2016), with smaller confidence

209 intervals reflecting greater agreement between records, especially when only few samples were

210 available in a certain time window (Fig. S1). We interpret CHAR composite anomalies as being

211 primarily derived from forest fires, with secondary sources being understory, grass, and crop residue

212 burning (Whitlock and Larsen, 2001).

213 **3.2 Spatial scale representation**

214 We aim to identify the spatial extent of human fire usage in the CEL during the Holocene at nested

215 subcontinental, regional, and subregional scales (Fig. 1), which have received little attention to date.

216 The subcontinental CHAR composite (covering ~1,300 x 500 km) integrates all records. The two

217 regional scale CHAR composites (~500 x 500 km) each represent half of the charcoal records as

218 separated according to modern climate and vegetation gradients. The latter is represented by the

219 natural spread of Norway spruce, whereas the climatic gradient is represented by the first principal

220 component (PC1) of the modern environmental stratification (EnS) of Europe (Fig. 1), which

221 represents temperature-related parameters of ecological relevance, such as altitude, slope, sunshine

222 duration, and monthly temperatures (Metzger et al., 2005). We calculated the average EnS PC1

223 values of 14 spatial buffers (1 – 50 km around each site) in QGIS and grouped sites into the eastern

224 and western CEL groups (E CEL and W CEL, respectively) according to the median of the data

225 distribution (Figs. 1, S1a). Some northern central Poland sites were included within the E CEL group

226 to account for the uneven spatial representation of records. Subcontinental and regional CHAR

227 composites are shown in Fig. 2.

228 Five subregional CHAR composites (~200 x 400 km) represent spatial clusters of charcoal records

229 from northern Germany, northwestern Poland/eastern Germany, north-central Poland and

11

230   northeastern Poland, and the Baltic States (Figs. 1, 3, 4). This grouping is based on the west-to-east

231   climatic-ecological gradients that affect fuel flammability and considers general knowledge of

232   cultural histories (Fig. S2, Table S3). For example, the Lithuanian sites were grouped together with

233   the Latvian and Estonian sites, because of the steep environmental gradient towards northeastern

234   Poland (Fig. 1) and the closer cultural similarities of present-day Lithuania and the other Baltic

235   States. Sample and site availabilities per 100-year bin are shown in Fig. S1 for all CHAR composite

236   anomaly records at the subcontinental scale (n = 61; Fig. S1b), regional scale (W CEL, n = 31; E

237   CEL, n = 30; Fig. S1b) and subregional scales (N Germany, n = 12; NW Poland/E Germany, n=8; N

238   Poland, n = 20; NE Poland, n = 7; Baltics, n = 14; Fig. S1c), suggesting that further records are

239   needed to approve or disprove the trends discussed below, especially those during the early Holocene

240   in northeastern Poland.

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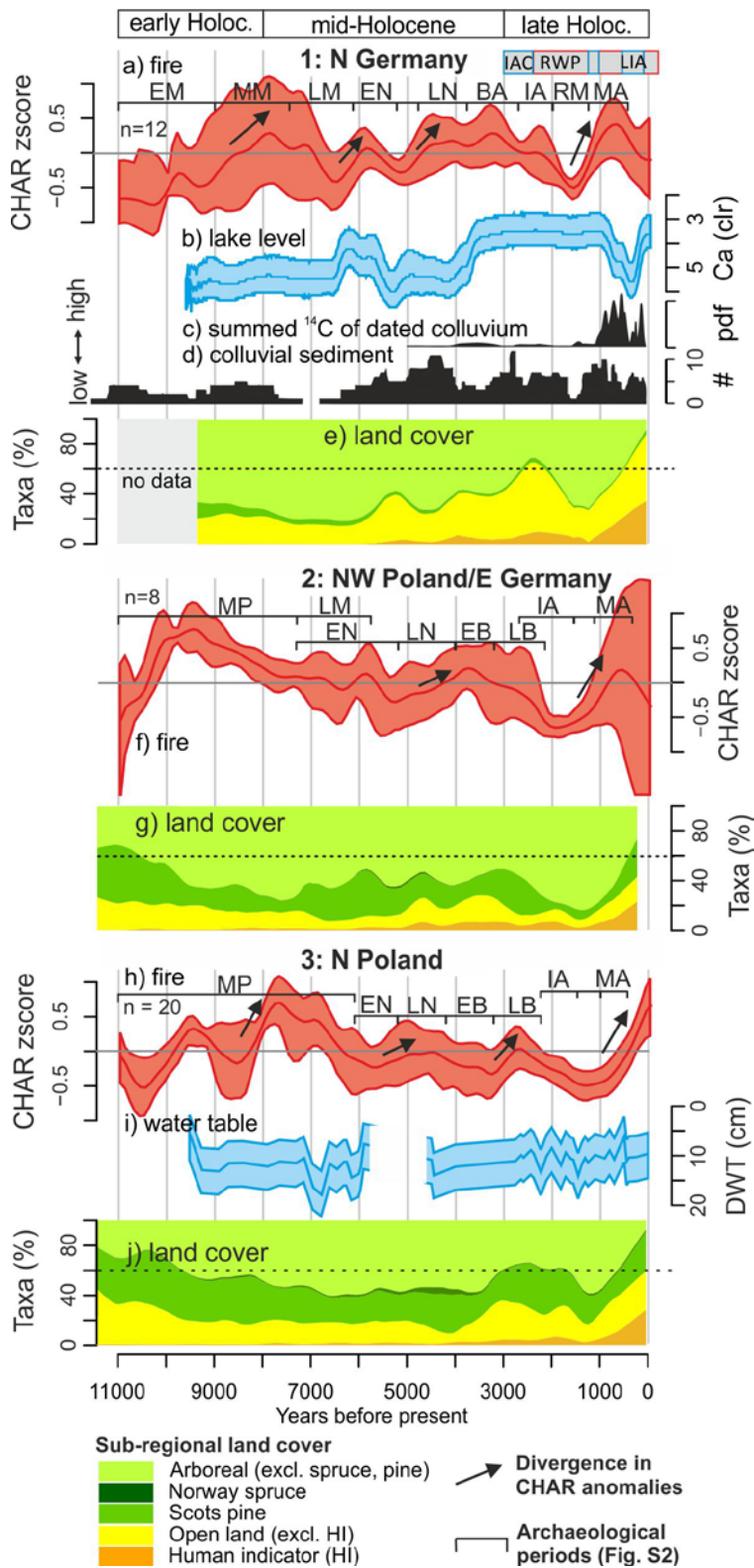
Fig. 3. Subregional Holocene fire activity, lake levels, soil erosion, and land cover reconstructions of the western CEL. a),

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

245 levels of lake Fürstenseer See based on the log-ratio transformed μ-XRF Calcium record, after Dietze et al. (2016); c)

246 probability density function of ^{14}C ages of colluvial deposits, Mecklenburg Lake District, Germany (Küster, 2014); d)

247 absolute number of dated colluvial deposits across northern Germany (Dreibrodt et al., 2010); e), g), and j) REVEALS-

248 transformed (Theuerkauf et al., 2016), 1000-year LOESS-smoothed pollen taxa (sums) of lakes Belauer See (Dörfler et

249 al., 2012), Krebssee (Jahns, 1999, 2000) and Gościąż (Ralska-Jasiewiczowa et al., 1998), respectively; i) depth-to-water

250 table (DWT) of Tuchola mire, north-central Poland (Lamentowicz et al., 2008). Archaeological periods (from Table S3

251 and Fig. S2) are: MP, Mesolithic Period (EM/MM/LM, early/mid/late Mesolithic); EN/LN: early/late Neolithic Period;

252 BA and IA, Bronze and Iron Ages (EB/LB, early/late Bronze Age); RM: Roman and Migration Period; and MA,

253 Medieval Age. Red and blue framed boxes at top-right mark warm and cool periods during the last 3,000 years (IAC, Iron

254 Age Cold Period, RWP, Roman Warm Period, and LIA, Little Ice Age) after Moffa-Sánchez and Hall (2017). Arrows

255 mark divergence in CHAR composites from expected natural trend.

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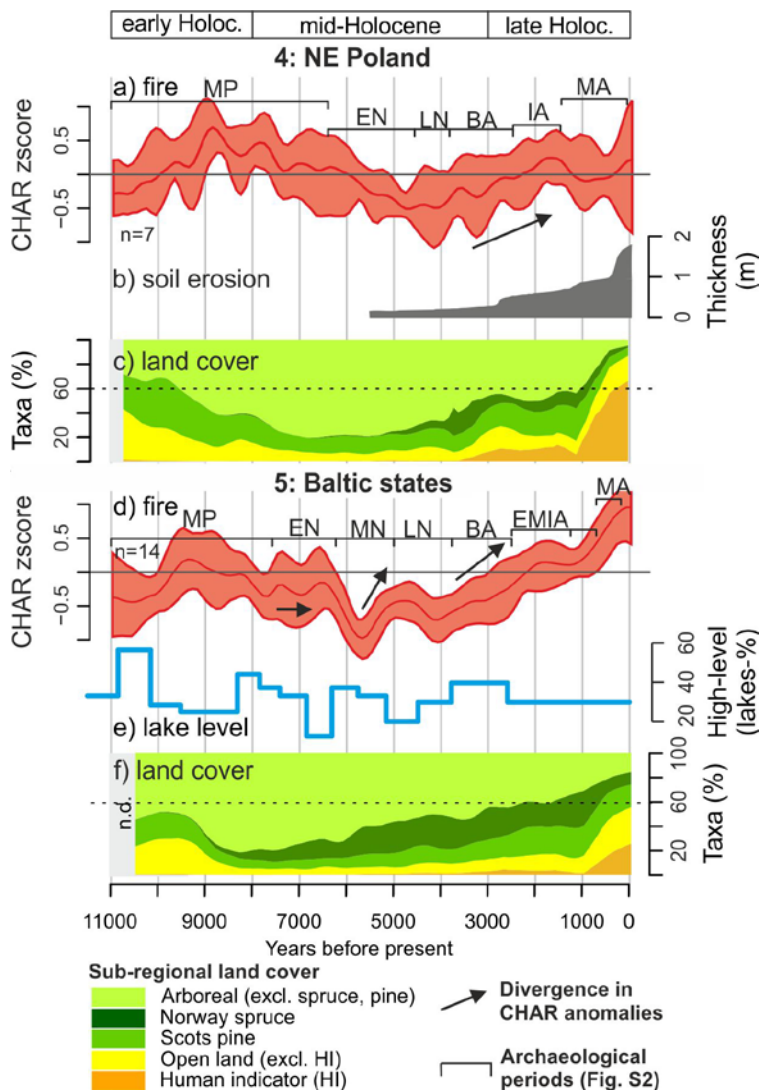
Fig. 4. Subregional Holocene fire activity, land cover, lake levels, and soil erosion reconstructions of the eastern CEL. a) and d) NE Poland and Baltic states CHAR composites, respectively (median and 95% confidence interval, this study), based on *n* available sites (see Fig. S1 for sample availability 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

281 the areas of the subregional CHAR composites (N Germany to NE Poland, Fig. S1) and calculated

282 the 99-year running mean of the three grid cells covering the Baltic States (centered at 22.5° E,

283 57.52° N; 26.25° E, 57.52° N, and 26.25° E, 53.81° N). Then, we calculated a 1000-year running

284 mean ± 2σ relative to the Holocene averages (0 – 11,500 cal. BP), as with the CHAR composites.

285 Fig. S3 shows that the climate model output (both averages and individual grid cell values) is not

286 significantly different between adjacent subregions over millennial timescales. The mean

287 subcontinental climate model output of the CEL is shown in Fig. 2.

288 3.3.2 Land cover reconstructions

289 We assessed natural vegetation and human deforestation using quantitative land cover

290 reconstructions from Holocene pollen records (Fig. 1, Tables S1-S2). We used the longest, most

291 representative, and best-resolved pollen records available for each subregion; these were chosen from

292 lakes with basin areas >50 ha to allow application of the REVEALS model (Sugita, 2007). Hence,

293 pollens from a source area of 100 km² and larger appropriately represent land cover at our

294 subregional scale appropriately. We used the REVEALSinR function with pollen productivity

295 estimates from the PPE.MV2015 data set and the default (LSM) dispersal model (Theuerkauf et al.,

296 2016) to convert pollen% into land cover. We calculated the sums of arboreal taxa including *Corylus*

297 *avellana*, but excluding the coniferous, flammable taxa *Picea abies* and *Pinus sylvestris* (discussed

298 and shown separately in the text and Figs. 3, 4). The sum of open land includes all non-arboreal taxa,

299 but excludes the sum of direct human indicators (HI: *Artemisia, Plantago major/media, Plantago*

300 *lanceolata, Rumex acetosa/ acetosella,* and cereals according to Reitalu et al. (2013); Figs. 3, 4). We

301 interpolated noncontinuous pollen records and *Picea abies* and *Pinus sylvestris* coverages by

302 calculating the mean coverage in the same 100-year bins used for transformation of the CHAR

303 records. Then, we fitted a LOESS to 1000-year windows for each taxon (sum) using the stats package

304   in R and rescaled to one to fulfill the constant-sum constraint of the compositional pollen data (Figs.

305   3, 4).

306   3.3.3 Archeological periods

307   Cultural histories on millennial to centennial time scales are discussed using a compilation of

308   representative archeological classifications per subregion based on archeological literature or, where

309   archeological information was limited, land cover reconstructions from pollen. We provide here only

310   a rough overview of the timing and duration of certain archeological periods (Table S3, Fig. S2).

311   While a comprehensive review and data compilation that considers dating uncertainties and the

312   spatial spread and interaction of past cultures would be helpful and relevant, it is beyond the scope of

313   this work.

314   3.3.4 Records of soil erosion and water level changes

315   To discuss the impact of increased human fire usage and human land cover change on landscape

316   transformation and regional biogeochemical cycles, we compare CHAR composite anomalies with

317   records of land surface processes and hydrological processes in subregions with available

318   reconstructions covering most of the Holocene. We derived soil erosion composites from

319   compilations of colluvial deposits for N Germany and NE Poland, comprising a probability density

320   function of ^{14}C dates from the sandur plains of northeastern Germany (Küster, 2014), a record of

321   dated deposits across northern Germany, including the northeast (Dreibrodt et al., 2010), and a record

322   of cumulative colluvial deposit thickness in northeastern Poland (Smolska, 2011).

323   Water level changes in northeastern Germany are based on the only available, continuous Holocene

324   lake level reconstruction inferred from carbonate deposition in lake Fürstenseer See (Dietze et al.,

325   2016), from which we reassembled the μXRF-Ca record considering 1000 age-depth models within

326 the 2σ range of the ^{14}C dates (Fig. 3b shows the median and 95 % confidence interval). We derived

327 water level changes in northern Poland from a testate amoebae-inferred depth-to-water table record

328 of Tuchola mire (Lamentowicz et al., 2008). The changes in Baltic lake levels are based on a

329 compilation of Estonian lake level records that were classified into high, intermediate, and low lake

330 status by Harrison and Saarse (1992). We recalibrated their age-depth model using IntCal13 (Reimer

331 et al., 2013) and present the percentage of high-level lakes in approximate 500-year bins (Fig. 4e).

332 **4. Results**

333 The CHAR composite anomalies show common trends and divergences at different spatial scales

334 relative to the Holocene average of all records (Figs. 2 – 4). The subcontinental CHAR composite

335 anomalies indicate three phases of CEL fire activity: (i) an early Holocene increase to above-average

336 fire activity, (ii) a mid- to late Holocene decrease to and stabilization at below-average fire activity,

337 and (iii) a late Holocene increase to above-average fire activity.

338 During the early Holocene (11,500 – 8,500 cal. BP), fire activity increased strongly to above-average

339 levels in all CHAR composites, independent of spatial aggregation (Figs. 2 – 4). At the

340 subcontinental and regional scales, this increase parallels increasing summer temperatures during

341 maximum summer insolation and seasonality as shown by the analyzed climate model output (Fig.

342 2a-d). Summer precipitation was rather low throughout the CEL (Fig. 2b), and flammable vegetation,

343 i.e., the sum of pine and open land (mainly grasses), reached their maximum coverage during the

344 Holocene in both regions (Figs. 2e, f). Although the absolute timing of positive CHAR anomalies

345 varies among subregions, increased fire activity was most pronounced in NW Poland/E Germany

346 (Fig. 3f).

347 After c. 8,500 cal. BP, subcontinental and regional CHAR composites declined to below-average

348 values by 7,000 cal. BP, following summer insolation and seasonality (Fig. 2a-d). The TraCE21k-

349 climate model data suggest a strong increase in summer precipitation after 8,500 cal. BP across the

350 CEL (Figs. 2b, S3). At 8,500 cal. BP, pine and open land coverages reduced to their Holocene

351 minima, while broadleaf forests expanded (Figs. 2e, f; 3e, g, j; 4c, f), reducing the area of flammable

352 vegetation. However, at the subregional scale, fire trends started to diverge significantly. NW

353 Poland/E Germany (Fig. 3f) and NE Poland CHAR composites (Fig. 4a) show continuously

354 declining trends since 9,000 cal. BP and until 6,500 and 4,500 cal. BP, respectively. The adjacent N

355 Germany and N Poland composites indicate fire maxima between 8,500 and 6,500 cal. BP (Fig. 3a,

356 h) and the Baltic CHAR composite values stabilize around the Holocene average between 7,500 and

357 6,500 cal. BP (Fig. 4d).

358 Although climate and forest composition did not change strongly, we note marked divergences

359 between the regional CEL fire trends after 6,500 cal. BP that are not evident at the subcontinental

360 scale (Fig. 2a). CHAR composites in the western CEL, especially N Germany, increased from c.

361 6,500 cal. BP, peaked at 5,800 cal. BP and declined afterwards (Figs. 2c; 3a, f, h). Human land use

362 indicators, including cereals, appeared in pollen records and soil erosion increased (Fig. 3e, g, j). In

363 contrast, CHAR composites in the eastern CEL, especially the Baltic States, show a minimum around

364 5,800 cal. BP and a slight increase in fire activity around 5,500 cal. BP (Figs. 2d; 4a, d). Furthermore,

365 Norway spruce expanded across the Baltic region during that time (Fig. 4f), gradually replacing parts

366 of the broadleaf forest.

367 During the late Holocene (after 4,000 cal. BP), fire activity increased continuously until present day

368 throughout the eastern CEL, especially in the Baltic subregion (Figs. 2d, 4d). Regional and

369 subregional composites in the western CEL showed several periods of positive and negative CHAR

370 anomalies. The climate model output suggests that cooler and wetter conditions were established

371 across the entire CEL (Fig. 2b). Flammable, but fire-avoiding and suppressing spruce spread and

372 reached its maximum coverage between 3,500 and 2,000 cal. BP in the eastern CEL, and human

373   indicator pollen records increased during that time (Figs. 2f; 4c, f). Between 2,500 and 1,000 cal. BP,

374   regional and subregional composites (especially in the western CEL) show pronounced negative

375   CHAR anomalies of various timings and durations (Figs. 2c, d; 3a, f, h) that follow a trend towards

376   cooler and wetter summers (Fig. 2b). During that time, human indicator taxa in pollen records

377   decreased (Fig. 3e, g, j).

378   During the last millennium, fire activity increased markedly until present day, reaching burning

379   levels similar to those during the early Holocene, although recent natural conditions were less

380   favorable for fire (Fig. 2). Human-indicator pollen records show that farming intensified in all

381   subregions (Figs. 3e, g, j; 4c, f) and soil erosion increased (Fig. 3c, 4b). However, we observe a

382   significant divergence in subregional CHAR composites. Whereas fire activity in N Poland and the

383   Baltic States increased until present day (Figs. 4a, d), N Germany CHAR anomalies peak around 800

384   cal. BP and decline afterwards (Fig. 3a).

385   **5. Discussion**

386   **5.1 Natural burning conditions**

387   Fire has been an important component of the CEL landscape in the past (Figs. 2 – 4). Absolute values

388   of N Germany CHAR composite anomalies (Fig. 3a) were lower than those of the Baltic CHAR

389   composite anomalies (Fig. 4d), especially during the last millennium. Thus, the natural climatic and

390   vegetation gradient across the CEL influences biomass flammability: northern Germany is more

391   oceanic and has less pine coverage (Figs. 3, 4) than the more continental areas towards the east,

392   which have more coniferous forest cover, are more affected by summer droughts (Lindner et al.,

393   2010) and, hence, are more fire-prone (Marcisz et al., 2017). However, we focus on the interpretation

394   of trends in CHAR composite anomalies, because absolute anomalies can only be linked to relative

395   and not quantitative differences in fire regime properties.

396   Subcontinental fire activity trends followed major changes in climate/vegetation across the CEL

397   since the last glacial period, similar to southern Scandinavia (Olsson et al., 2010) and northeastern

398   Europe (Marlon et al., 2013). Previous (sub)continental CHAR composite anomalies of Europe and

399   central Europe have shown increasing fire activity throughout the Holocene (Marlon et al., 2013;

400   Molinari et al., 2013; Power et al., 2008). However, we find alternating periods of high and low fire

401   activity, similar to southern European CHAR compilations (Vannière et al., 2011). The CEL fire

402   activity trends are sometimes divergent between adjacent areas at various spatial scales (Figs. 2 – 4)

403   and could be related to both, natural (i.e., climatic and fuel-related) and human drivers.

404   During the early Holocene, fire activity paralleled increasing summer temperatures (Figs. 2 – 4, S3)

405   similar to fire trends at the global scale (Daniau et al., 2012; Marlon et al., 2013; Power et al., 2008).

406   Frequent droughts related to dominating continental air masses have been reported from regional

407   hydrological reconstructions mainly based on geochemical and paleoecological proxies (Dietze et al.,

408   2016; Harrison et al., 1993; Lauterbach et al., 2011; Väliranta et al., 2015). Hence, the climate and

409   natural land cover (dominated by extensive pine forests and grasslands) favored natural fires.

410   The natural flammability of the CEL landscape reduced after a shift towards wetter summers around

411   8,500 cal. BP (Fig. 2b), probably related to the increasing influence of north Atlantic air masses

412   across the CEL, similar to the present-day air mass dominance (Lauterbach et al., 2011; Rust et al.,

413   2018). However, proxy data does not consistently show increased summer wetness after 8,500 cal.

414   BP (Dietze et al., 2016; Gałka et al., 2014; Latałowa et al., 2013) (Figs. 3b, i; 4e), which we attribute

415   at different sensitivity and temporal resolution of the proxies. Furthermore, with the establishment of

416   mixed broadleaf forests across the CEL, less-flammable fuel was available, with pine forests

417   dominating only in very wet or very dry sites. The slight increase in Baltic CHAR anomalies after

418   5,500 cal. BP is synchronous with lake level reductions that suggest drier conditions (Harrison and

419   Saarse, 1992). Climatic conditions became even less favorable for fire during the last 4,000 years,

420   when climate model output and proxy reconstructions suggest that cooler and wetter conditions

421   established across the entire CEL (Figs. 2 – 4) (Dietze et al., 2016; Wanner et al., 2008). However,

422   fire activity did not decrease accordingly: CHAR composites diverged from the expected natural

423   trend at the subregional scale since 8,500 cal BP (Figs. 3, 4), at the regional scale since 6,500 cal BP,

424   and at the subcontinental scale since 1,000 cal BP (Fig. 2).

425   We propose that the divergence of CHAR composite anomalies from the expected natural trends and

426   between adjacent subregions indicates human alteration of natural fire regimes. We assume spatially

427   homogeneous climatic trends across the CEL because modern short-term climatic events show strong

428   spatial coherence (Merz et al., 2018; Rust et al., 2018) and long-term (i.e., millennial-scale) climate

429   models and available land-cover data do not suggest a spatial heterogeneity of natural trends between

430   adjacent regions. This assumption is limited by some constraints: first, available climate proxy data is

431   heterogeneous concerning archive type, temporal coverage, and the type and spatiotemporal extent of

432   the proxy-climate relationship (Mauri et al., 2015; Salonen et al., 2012; Väliranta et al., 2015);

433   second, we lack comparable and independent syntheses of climate-proxy and land cover data on

434   similar spatiotemporal scales (Marquer et al., 2017; Trondman et al., 2015); and third, the analyzed

435   climate model output only provides larger-scale trends based on the first-order effects of CO_2 and

436   orbital forcing (Rehfeld and Laepple, 2016; Zhang et al., 2017) and does not consider regional

437   climate-land cover feedbacks (Qian et al., 2015).

438   During periods of low natural flammability but increased fire activity after 8,500 cal. BP, we assume

439   that humans set fires for multiple purposes by taking advantage of dry fuel during short-term

440   droughts that occur in both wetter and drier climates. As proof of concept, we discuss two examples

441   of human-fire relationships that affected fire activity even in periods and areas of low population

442   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)

466   might have reduced their fire usage around 5,800 cal. BP, when the Baltic CHAR composite declines

467   to a minimum.

468   We argue that diverse extents of woodland alteration by hunter-gatherers can explain the offset from

469   the expected natural fire trends on the subregional scale, which represents roughly the territories that

470   Mesolithic hunter-gatherers occupied (Zvelebil, 2006). Hence, we support earlier interpretations that

471   Mesolithic communities could have significantly affected landscapes by burning forest to construct

472   their niche (Bishop et al., 2015; Latałowa, 1992; Poska and Saarse, 2002; Wacnik et al., 2011). We

473   propose that fire activity was linked not only to human population densities, but also to cultural

474   subsistence strategies that were based on diverse usage of terrestrial resources.

475   **5.3 Fire as an agrarian land management tool**

476   Divergent regional CHAR composite anomalies after 6,500 cal. BP mirror divergent rates in

477   Neolithisation and agricultural land use, as previously suggested by discrete charcoal data (Robin and

478   Nelle, 2014). CHAR composites allow determination of the spatial spread of human fire usage in

479   prehistoric and historic agrarian land management, which was previously described using

480   archaeological compilations (Feeser and Dörfler, 2015; Poska et al., 2004; Silva and Vander Linden,

481   2017) and quantitative land cover reconstructions (Marquer et al., 2017; Trondman et al., 2015).

482   During the transition from foraging to sedentary cultures that adopted pastoralism and agriculture,

483   western CEL CHAR composites, especially N Germany and NW Poland/E Germany, show

484   increasing and declining anomalies that coincide with a known societal cycle of increasing and

485   declining population development between 6,500 and 5,000 cal BP (Feeser and Dörfler, 2015;

486   Latałowa, 1992) (Figs. 2 – 4), as inferred from archeological remains (Warden et al., 2017). During

487   that time, the temperature in the Baltic Sea area increased towards the mid-Holocene thermal

488   optimum and subsequently decreased after 5,500 cal BP, suggesting a response of cultural

489   development to climate change on millennial time scales (Warden et al., 2017). However, despite

490   continued decreases in overall population densities and Baltic Sea temperatures between 5,000 and

491   3,000 cal. BP (Warden et al., 2017), fire use increased on regional and subregional scales after the

492   transition from the Funnel Beaker towards the Corded Ware culture around 4,800 cal. BP.

493   Yet, the role of fire in Neolithic land management is strongly debated in the western CEL (Feeser et

494   al., 2012), because of lacking evidence for slash-and-burn practices that were common in other

495   regions (Bowman et al., 2011; Vannière et al., 2016). Although fire probably helped to alter

496   woodland structures during the initial period of adoption of animal husbandry (Feeser and Dörfler,

497   2014; Feeser and Dörfler, 2015), further regional land management strategies without fire usage

498   evolved for deforestation and agricultural maintenance (Feeser et al., 2012; Latałowa, 1992). Hence,

499   fire usage seems to depend more on the variable cultural practices than on population densities (see

500   archeological phases in Figs. 3, S2).

501   In the eastern CEL, fire activity increased after 5,500 cal. BP but only reached or exceeded the

502   Holocene average after 3,000 cal. BP (Figs. 2, 4). Lake levels in the Baltic States decreased between

503   5,200 and 4,000 cal. BP, suggesting a drier climate possibly related to increasing Baltic Sea

504   temperatures (Warden et al., 2017). Eastern CEL fire activity might therefore be influenced by a

505   climatic shift. Although the first traces of cereals and pastoralism appear in the region during that

506   time (Madeja et al., 2010; Poska et al., 2004; Trondman et al., 2015) as a result of the appearance of,

507   e.g., the Funnel Beaker and Corded Ware cultures (Table S3), archeological and land cover data

508   suggest that Baltic cultures still relied primarily on forest- and water-based resources (Meadows et

509   al., 2016; Poska et al., 2004; Rimantienė, 1992; Wacnik, 2009). Only after the onset of the Bronze

510   Age (4,000 cal. BP) do human indicator pollen and soil erosion records show increasing agricultural

511   land use (Gałka et al., 2013; Poska et al., 2004; Reitalu et al., 2013; Smolska, 2011) (Fig. 4). Hence,

512   increasing CHAR composite anomalies parallel the major onset and spread of farming in the eastern

513   CEL more than 2,000 years later than in the western CEL (Figs. 2 – 4).

514   Whereas eastern CEL CHAR composites continuously increased towards present day, western CEL

515   CHAR composites follow known archaeological phases of altered land management and

516   technological transitions, such as those occurring during the Bronze and Iron Ages (Fig. 3). Most

517   prominently, negative fire anomalies of varying timings and durations in adjacent regions between

518   2,500 and 1,000 cal. BP follow a millennial-scale climatic cooling (Helama et al., 2017; Wanner et

519   al., 2008) (Fig. 2). Additionally, the expansion of beech (*Fagus sylvatica*) and hornbeam (*Carpinus*

520   *betulus*) in Germany and northern Poland further reduced fire-prone pine forest cover (Marquer et al.,

521   2017; Pędziszewska and Latałowa, 2016). Although societal responses to climatic changes are

522   complex and difficult to decipher at millennial time scales (Haldon, 2016), the reduction in fire

523   activities during that time suggests an altered use of fire in land management. In many areas, reduced

524   human land use *per se* during the Migration Period can explain the minimum CHAR composite

525   anomalies (Figs. 3, S2). Although debated, large-scale human reorganization during this period was

526   probably related to less-favorable climatic conditions of the Dark Age cold period (Helama et al.,

527   2017; Kaplan et al., 2009; Zhang et al., 2011) and led to the reforestation of large areas, mainly with

528   broadleaf taxa (Marquer et al., 2017) (Figs. 2 – 4).

529   The strong increase of fire activity in all CHAR composites during the last millennium (Figs. 2 – 4)

530   parallels population growth after the Migration Period (Helama et al., 2017). This increase clearly

531   overrides the millennial-scale cool and wet climatic trends (Fig. 2), similar as suggested for recent

532   times over shorter time scales (Syphard et al., 2017). Farming extended into previously unsuitable

533   sites and intensified in all subregions, as reflected in pollen and soil erosion records (Dreibrodt et al.,

534   2010; Kaplan et al., 2009; Marquer et al., 2017) (Fig. 3). Fire activity driven by human land cover

535   change reached early Holocene levels, even at the subcontinental scale (Fig. 2).

536   The pattern in N German CHAR composites, which diverges from other subregional composites,

537   follows the generally assumed relationship between fire and population densities: increasing

538   population first lead to increased fire activity, and eventually to landscape fragmentation that

539   indirectly limited the spread of fires (Marlon et al., 2008; Pechony and Shindell, 2010). The

540   landscape in northern Germany seems to have become fragmented by around 1200 AD: land cover

541   reconstructions from pollen data and models suggest that more than 60 % of the land was deforested

542   in northern Germany by that time, compared to less than 40 % in the Baltic states (intermediate

543   estimates based on Kaplan et al. (2009), Kaplan et al. (2017), Marquer et al. (2017) and Figs. 3, 4).

544   All other analyzed subregions did not reach this extent of open land (Figs. 3, 4) and, within

545   uncertainty, most still show an upward trend in fire activity (Figs. 3, 4). This trend might not only

546   relate to land openness and associated landscape fragmentation, but also to forest composition and

547   biomass flammability, as coniferous taxa cover a greater extent in the continental eastern CEL than in

548   the western CEL (Figs. 1, 3, 4; Marcisz et al. (2017). We note that the Lake Miłkowskie pollen

549   record (Fig. 4c) shows representative land openness trends in NE Poland, but locally reconstructed

550   openness was exceptionally high already since ca. 800 cal. BP, whereas other areas remained

551   strongly forested (Wacnik et al., 2016).

552   Our relative CHAR composite anomalies do not allow us to infer absolute changes in past fire regime

553   properties in terms of fire frequency, area, or the amount and type of biomass burned (Marlon et al.,

554   2016). Uncertainties in our reconstructions are still large due to limited data availabilities during

555   certain periods, especially at the subregional scale (Fig. S1), indicating the need for more and highly

556   resolved Holocene fire records that allow better characterization of past fire regimes (Feurdean et al.,

557   2017; Vannière et al., 2016). Hence, the impact of human-driven fires and associated human land

558   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 km²) 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

28

582 during the Neolithic period (Fig. 3a, b). Thus, human fire usage in land management may have

583 resulted in regionally increased groundwater recharge and higher water levels, as shown by

584 Woodward et al. (2014) on the global scale. Further intense lake level fluctuations related to human

585 water management (Dietze et al., 2016) occurred at the time of maximum land openness and fire

586 activity during the last millennium (Fig. 3).

587 Hence, human land cover change could have significantly affected regional hydrological and

588 sediment budgets, especially since the Neolithic time (Dietze et al., 2016; Latałowa, 1992; Ruddiman

589 et al., 2015). Integration and compilation of land, ecosystem, and paleoclimate records over different

590 spatial and temporal scales are needed to better understand and quantify the interactions between

591 climate and human drivers of past landscape transformation (Marquer et al., 2017) and the role of

592 cultural fire use.

593 **6. Conclusions and implications**

594 We provide a new reconstruction of Holocene fire activity in the low-flammability landscape of the

595 Central European Lowlands. When natural conditions (climate and land cover) limited widespread

596 fire occurrence, millennial-scale fire activity seems well explained by the cultural use of fire

597 suggesting that humans have affected natural terrestrial systems at varying intensities over several

598 millennia, and providing new insights into past human-environment interactions.

599 We have identified convergences and divergences (i) among nested subregional to subcontinental

600 CHAR composites and (ii) from the expected natural flammability across spatial scales. This

601 approach provides a step forward in determining early human-fire-land use relationships (Fig. 5)

602 when high-resolution macrocharcoal records are lacking, i.e., beyond the assumption of direct fire-

603 population density relationships and independent of classical pollen-derived human impact

604   indicators. This approach adds to previous studies in other areas of the globe where natural

605   conditions did not support the frequent occurrence of fire (McWethy et al., 2013).
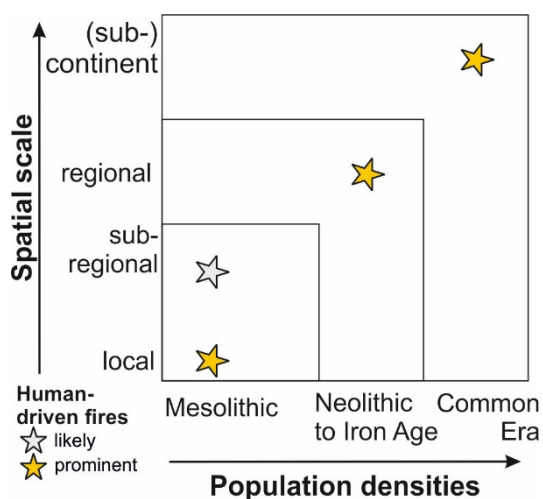
606

607   Fig. 5. Scale dependency of millennial fire trends in low-flammability landscapes, based on CEL CHAR composites.

608   Early human fire usage can be detected with composites aggregating sedimentary charcoal records at small spatial scales.

609   Whereas the impact of Mesolithic hunter-gatherers is archaeologically well known at the local scale, CHAR composites

610   allow detection of Mesolithic impacts at the subregional scale under less suitable natural burning conditions, despite low

611   population densities (Kaplan et al., 2009; Klein Goldewijk et al., 2011).

612   Our reconstructions have two major implications. First, past human-fire relationships were

613   multifaceted. Hunter-gatherer subsistence strategies in the CEL seem to have altered natural fire

614   regimes beyond the local scale despite low population densities, supporting previous hypotheses

615   (Kaplan et al., 2016; White, 2013). In agrarian societies, millennial CHAR composite anomalies

616   seem closely associated with cultural land use strategies, which is difficult, but possible to

617   parameterize in fire models (Lasslop and Kloster, 2017; Pfeiffer et al., 2013).

618   Second, our millennial scale paleofire perspective provides long-term background information on the

619   interplay of natural and human drivers of land-cover change, a prerequisite to inform future land

620   management and nature conservation efforts (Whitlock et al., 2018). At the spatial scales relevant to

621   political decisions in the CEL, the last millennium seems key to understanding the preconditions that

622 determine future fire risks. Although during the last century only minor fire events have occurred in

623 the CEL compared to other areas of the world, forest cover is expected to increase in the future and

624 fuel will accumulate in widespread human-planted pine and spruce monocultures (Caudullo et al.,

625 2016; Houston Durrant et al., 2016). Future climate change scenarios predict drier and warmer

626 summers, and the frequency of natural ignition by lightning might increase (Douville and Plazzotta,

627 2017; Lhotka et al., 2018; Romps et al., 2014). These factors increase fire hazard and fire risk

628 (Hardy, 2005), leading to a much more flammable landscape—a situation comparable to the early

629 Holocene. Our study supports previous suggestions that natural and/or human-driven substitution of

630 flammable coniferous for broadleaf forests could outpace the increasing fire danger in the continental

631 and hemiboreal CEL (Feurdean et al., 2017).

655   **Data Availability**

656   Charcoal data of this study will be available via the Global Charcoal Database, hosted by the

657   Laboratoire Chrono-environnement (UMR 6249 du CNRS) at the University of Bourgogne /

658   Franche-Comté (Besançon, France): https://paleofire.org/index.php.

659   **Author Contributions**

660   ED, MT, MS and BV designed the study. MT, ML, IF, SJ, PK, ML, LG, KM, MKK, TG, MO, AP,

661   MS, NS, JS, MS, SV, AW, DW, and MW provided charcoal data, AW, AP, and JW provided pollen

662   data. ED and MT performed the data analyses of charcoal and pollen data. JV analyzed Baltic age-

663   depth models. KR analyzed CCSM3-TraCE21k model output. All authors participated in the data

664   interpretation. ED wrote the paper with contributions from all authors.

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