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12,000-Years of fire regime drivers in the lowlands of Transylvania (Central-Eastern Europe): a data-model approach

A. Feurdean [a,b,*], J. Liakka [b], B. Vannière [c], E. Marinova [d], S.M. Hutchinson [e], V. Mosburgger [a], T. Hickler [a,b,f]

[a] Senckenberg Research Institute and Natural History Museum, Senckenberganlage 25, 60325 Frankfurt am Main, Germany
[b] Biodiversity and Climate Research Centre (BiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany
[c] CNRS, UMR 6249 Chrono-Environnement, Université de Franche-Comté, 16 route de Gray, 25030 Besançon Cedex, France
[d] Centre for Archaeological Sciences, University of Leuven, Celestijnenlaan 200E, Bus 2408, 3001 Leuven, Belgium
[e] School of Environment and Life Sciences, University of Salford, Salford M5 4WT, UK
[f] Goethe University, Department of Physical Geography, Altenhöferallee 1, 60438 Frankfurt am Main, Germany

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A B S T R A C T

The usefulness of sedimentary charcoal records to document centennial to millennial scale trends in aspects of fire regimes (frequency, severity) is widely acknowledged, yet the long-term variability in these regimes is poorly understood. Here, we use a high-resolution, multi-proxy analysis of a lacustrine sequence located in the lowlands of Transylvania (NW Romania), alongside global climate simulations in order to disentangle the drivers of fire regimes in this dry climatic region of Central-Eastern Europe. Periods of greater fire activity and frequency occurred between 10,700 and 7100 cal yr BP (mean Fire Interval = mFI 112 yr), and between 3300 and 700 cal yr BP (mFI 150 yr), whereas intervals of lower fire activity were recorded between 12,000 and 10,700 cal yr BP (mFI 217 yr), 7100 and 3300 cal yr BP (mFI 317 yr), and over last 700 years (no fire events detected). We found good correlations between simulated early summer (June, July) soil moisture content and near-surface air temperature with fire activity, particularly for the early to mid Holocene. A climate–fire relationship is further supported by local hydrological changes, i.e., lake level and runoff fluctuations. Fuel limitation, as a result of arid and strongly seasonal climatic conditions, led to low fire activity before 10,700 cal yr BP. However, fires were most frequent during climatically drier phases for the remaining, fuel-sufficient, part of the Holocene. Our results also suggest that the occurrence of more frequent fires in the early Holocene has kept woodlands open, promoted grassland abundance and sustained a more flammable ecosystem (mFI < 150 years) whereas the decline in fire risk under cooler and wetter climate conditions (mFI = 317 years) favoured woodland development. From 3300 cal yr BP, human impacts clearly were partly responsible for changes in fire activity, first increasing fire frequency and severity in periods with fire-favourable climatic conditions (halving the mFI from 300 years to about 150 years), then effectively suppressing fires over the last several centuries. Given the projected future temperature increase and moisture decline and the biomass accumulation due to the agricultural land abandonment in the region, natural fire frequency would be expected to return to <150 years.

1. Introduction

Current and future changes in spatial patterns in temperature and precipitation are projected to greatly influence the distribution and variability in fire regimes in Europe (EEA Report, 2012). However, fire regimes are complex and regulated by several factors ranging from climate, fuel (load, connectivity, and flammability) and ignition regimes (natural or anthropogenic) to landscape variables (van der Werf et al., 2006; Krawchuk et al., 2009; Whitlock et al., 2010; Spessa et al., 2010; Thonicke et al., 2010; Krawchuk and Moritz, 2011; Daniau et al., 2012; Molinari et al., 2013). These parameters are not entirely independent of each other; climate acts as a top-down driver (conditions need to be dry enough to enable ignition and to sustain burning) and vegetation cover as a bottom

* Corresponding author. Biodiversity and Climate Research Centre (BiK-F), Senckenberganlage 25, 60325 Frankfurt am Main, Germany. Tel.: +49 (0)6975 421870; fax: +49 69 7542 1800.
E-mail addresses: angelica.feurdean@senckenberg.de, angelica.feurdean@gmail.com (A. Feurdean).

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up driver (i.e., fuel must be sufficiently abundant and dry to sustain combustion), while humans can change fire ignition rates, fuel types and land cover. Disentangling the relative contribution of each of these drivers of fire regimes is therefore difficult and in many parts of the world this is complicated by long-standing anthropogenic impacts (Willis and Birks, 2006; Rius et al., 2012). The sedimentary charcoal records can provide information on centennial to millennial changes in fire regimes, notably fire frequency and to some extent fire severity, and, when associated with other proxies (of climate, vegetation and human impact), can be used to determine the drivers of long-term changes in these regimes and thereby enhance our understanding of their interaction (Vannière et al., 2008; Marlon et al., 2013).

Although the influence of anthropogenic burning on ecosystems and atmospheric gas composition is widely recognised, when and how strongly humans have altered the natural fire frequency and severity in different regions is still poorly understood (Vannière et al., 2010). This is because most of the available charcoal records do not have a high enough temporal resolution to adequately reconstruct fire frequency; tend to be limited to only a few geographical areas; their data sets are inadequate to allow environmental drivers to be disentangled from human impact or proxies for human impact are not adequately considered (Black et al., 2008; Colombaroli et al., 2008; Carcaillet et al., 2009; Kaltenrieder et al., 2010; Ali et al., 2012; Gałka et al., 2013).

The first synthesis of sedimentary charcoal records from the Carpathian region covering the last 15,000 years revealed a strongly divergent pattern in biomass burning between the lowlands and uplands during the Holocene (Feurdean et al., 2012). This is not surprising since the Carpathian region is characterised by strong variations in climate, topography and human impact; the key factors in the distribution of its biogeographical provinces and elevational vegetation zones. There is, however, currently no quantification of the changes in fire frequency (total number of fires within a time window), and magnitude (fire intensity or area burnt) in this region or more widely in Central-Eastern Europe. Extending fire research into a wider range of geographical regions and ecosystems with different human impact can be used as a substitute for measuring of how different vegetation types react to changes in fire activity throughout time and is therefore of relevance in predicting their sensitivity to future climate and land use change.

Here, we present a high-resolution 12,000 year palaeoecological record from Lake Stiucii in the lowlands of the Transylvanian Plain (NW Romania) which explores for the first time the variability in fire frequency and severity over the Holocene in Central-Eastern Europe. Specifically, we aim to: i) disentangle the drivers of long-term changes (climate, vegetation, humans) in fire regimes and understand their interaction; ii) determine which climate variables are the best predictor of the long-term changes in fire regimes, and iii) assess how fire regimes changed with different types of agro-pastoral activities. We have used a sediment macro-charcoal record to reconstruct trends in biomass burning and fire frequency at a local scale, and a pollen record and charred remains to determine variability in fuel load and composition. Climate conditions based on global simulations were used alongside local and regional climate reconstructions from proxy data to explore the influence of climate on the fire activity. Pollen indicators of anthropogenic impact at Lake Stiucii, alongside local archaeological and historical data, as well as modeled population density and cultivated area estimates (Klein Goldewijk et al., 2011) were used to evaluate the human impact on fire activity.

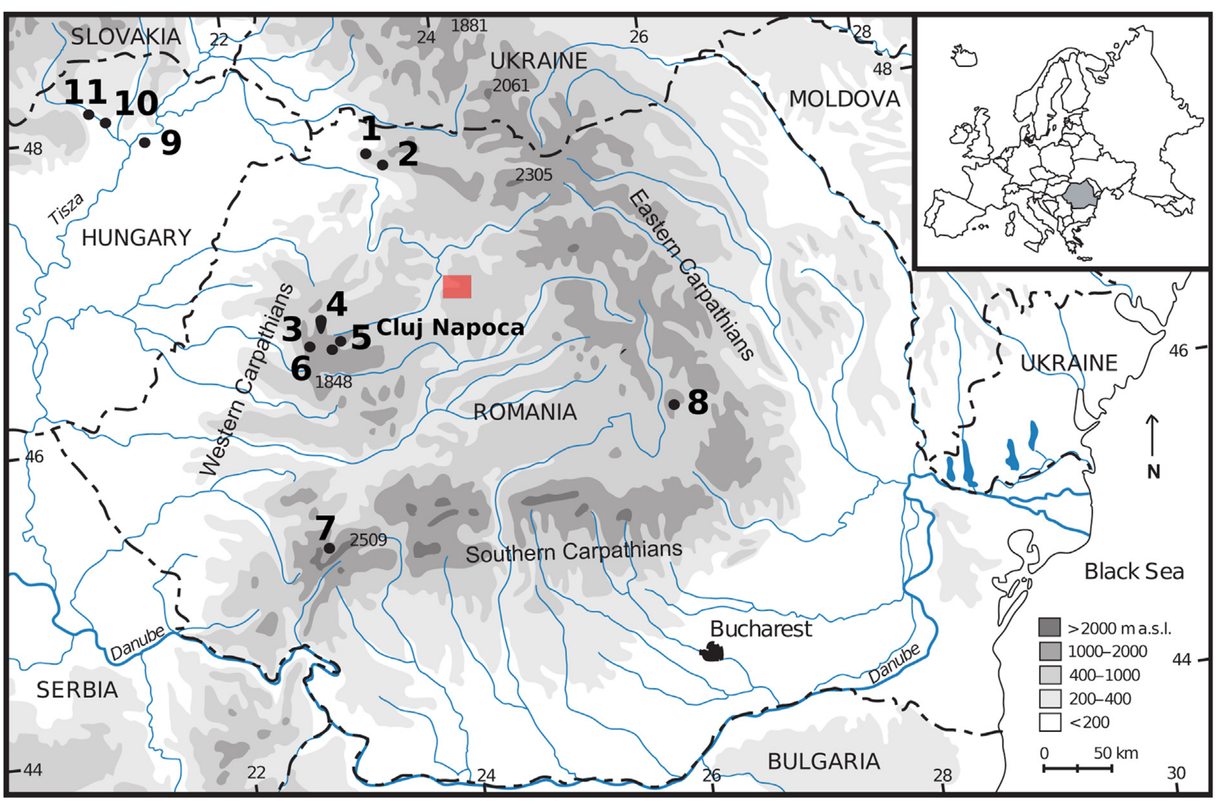


Fig. 1. Location of Lake Stiucii (square) in the lowland of Transylvania, NW Romania and in Europe. The location of other sites used in the synthesis paper of Feurdean et al. (2012) is highlighted: 1) Preluca Tiganului, 2) Steregoiu; 3) Padis Sondori, 4) Molhasul Mare, 5) Doda Pilii, 6) Calineasa, 7) Taul dintre Brazi, 8) Saint Ana, 9) Sarló-hát, 10) Nagymohos and 11) Kis Mohos.

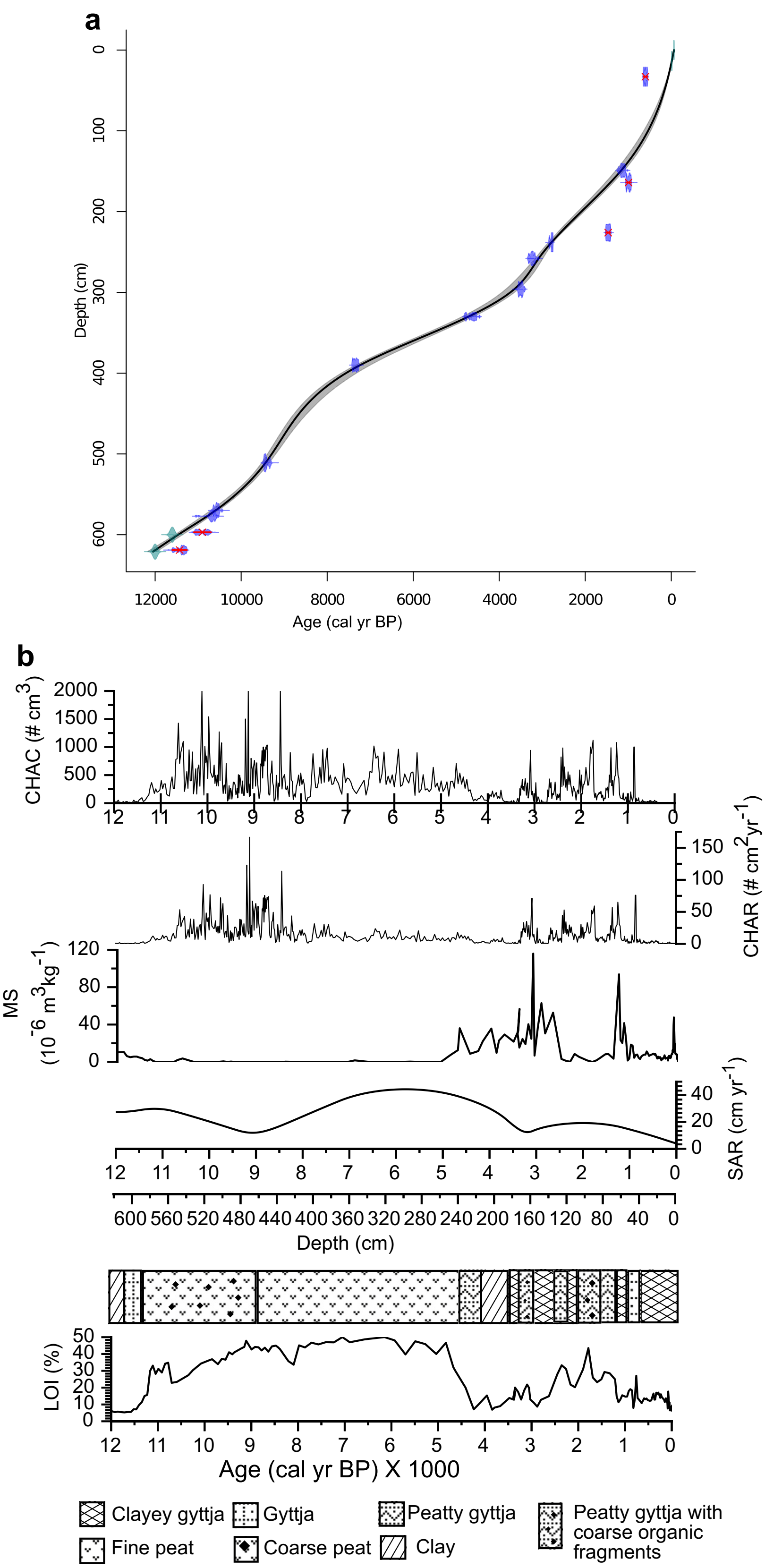


Fig. 2. (a). Age depth model at Lake Stiucii. Data points used for the construction of the age depth-model (blue); data points rejected from the age–depth model (red); pollen stratigraphical markers used to adjusted the age–depth (green). (b). Charcoal concentration (CHAC), charcoal accumulation rate (CHAR), magnetic susceptibility (MS), sediment accumulation rate (SAR), lithostratigraphy, and loss on ignition (LOI). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Study area

Lake Stiucii (239 m asl, N 46°58′ 044; E 23°54′ 106, 38 ha) is located in lowlands of NW Romania lying on the Transylvanian Plain (Fig. 1). It is a naturally formed lake of ca 38 ha with a watershed of about 131 ha including widespread wetland vegetation dominated by *Phragmites australis* (David, 2008). The lake and the surrounding wetland are part of a Natural Reserve and NATURA 2000 site protecting nesting birds (David, 2008). The climate is temperate continental in character with a mean annual temperature of ca 8–9 °C, the temperature of the coldest month (January) is ca −1 °C and of the warmest (July) is ca 18–20 °C (David, 2008; Buta, 2009). Annual precipitation varies between 500 and 650 mm, with the highest values occurring in spring and summer (May–July), and the lowest in late autumn–winter (October–March).

The potential natural vegetation in the region is mixed deciduous woodland/forest steppe (Bohn et al., 2004). However, anthropogenic impact has significantly altered the region's natural vegetation so that the present-day vegetation (within a 50 km radius of the lake) consists of approximately 16% forest, 17% pasture and meadows and 60–70% arable land and orchards (Environmental Protection Agency, 2006). The remnant woodland fragments occur on the hilltops and are primarily composed of deciduous tree species such as *Quercus robur*, *Quercus petraea*, *Fagus sylvatica*, *Carpinus betulus*, and plantations of *Robinia pseudoacaccia*, *Pinus sylvestris* and *Pinus nigra* (Pop, 2001; David, 2008).

Current fire activity in the area is not well documented, but given the study site's location in a rural, populated area, fire activity is likely to have been suppressed throughout the recent past. However, fire is often used to clear agricultural land (http://firms.modaps.eosdis.nasa.gov/firemap/), and, whether intentionally or accidentally ignited, fires are common on the wetland area.

Table 1
AMS ^{14}C and $^{210}Pb/^{137}Cs$ measurements at Lake Stiucii. Radiocarbon measurements treated as outliers in the age depth model are marked with asterisks.

Lab. No.	Core	Depth (cm)	Mat dated	C^{14}	$\delta^{13}C$
$^{210}Pb/^{137}Cs$					
^{210}Pb	Gravity	0		2012 ± 0	
^{210}Pb	Gravity	1		2010 ± 2	
^{210}Pb	Gravity	3		2005 ± 2	
^{210}Pb	Gravity	4.5		1998 ± 2	
^{210}Pb	Gravity	5.5		1994 ± 2	
^{210}Pb	Gravity	6.5		1988 ± 3	
^{210}Pb	Gravity	7.5		1984 ± 3	
^{210}Pb	Gravity	9.5		1977 ± 3	
^{210}Pb	Gravity	11.5		1969 ± 4	
^{210}Pb	Gravity	12.5		1964 ± 4	
^{210}Pb	Gravity	13.5		1963 ± 4	
^{210}Pb	Gravity	14.5		1963 ± 4	
^{210}Pb	Gravity	15.5		1961 ± 4	
^{14}C					
*UBA-21062	Gravity	33	Gyttja	611 ± 23	−35.6
UBA-20364	4.2	110	*Phragmites*	1197 ± 23	−24.2
UBA-19030	2.1	149	*Phragmites*	1210 ± 33	−34.2
*UBA-19031	2.2	164	*Phragmites*	1076 ± 35	−35.7
*UBA-19033	2.3	226	*Phragmites*	1574 ± 22	−29.8
UBA-19035	2.2	238	*Phragmites*	2675 ± 25	−22.6
UBA-20365	2.3	258	*Phragmites*	3018 ± 31	−25.8
UBA-18402	2.3	296	*Phragmites*	3269 ± 36	−25.6
UBA-19034	2.4	330	Peat	4105 ± 25	−28.7
UBA-19035	2.5	390	Peat	6404 ± 42	−25.2
UBA-19037	2.6	511	*Phragmites*	8387 ± 41	−30.5
UBA-19036	2.6	570	Peat	9349 ± 38	−29.0
UBA-20362	4.8	577	*Phragmites*	9445 ± 50	−26.1
UBA-20361	4.8	597	Plant macros	9547 ± 54	−27.3
UBA-20363	4.8	619	*Phragmites*	9962 ± 39	−27.0

3. Materials and methods

3.1. Proxy data: sampling and analyses

Sediment cores were extracted with a Livingstone piston corer (1 m long, 5 cm diameter) from the deepest part (6.5 m) of the lake in summer 2011 (530 cm; CP2) and winter 2012 (675 m CP4). In addition, the loose sediment at the surface (37 cm) was retrieved with a gravity corer and sliced at 1 cm intervals in the field. A lithostratigraphic description was made according to changes in texture, colour, grain size, and organic carbon content (LOI). For LOI, samples were dried at 105 °C over night, combusted for 5 h at 550 °C and expressed as percentage loss of the dry weight. The sediment cores were screened using magnetic susceptibility measurements (Bartington Instruments Ltd MS2 meter and C loop) (Walden et al., 1999). The composite sedimentary core record totalling 724 cm was constructed using the gravity core and the overlapping central Livingstone cores after carefully eliminating the overlapping or disturbed sections using information derived from magnetic susceptibly, texture, colour and organic carbon content. Here, we report on the first 626 cm of the record comprising the past 12,000 cal yr BP (Fig. 2a,b).

3.1.1. Chronology

The chronology was established based on fifteen AMS ^{14}C measurements performed at the Belfast Radiocarbon Laboratory, Northern Ireland, and on ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am measurements (Table 1) by gamma assay in the Bloomsbury Environmental Isotope Facility (BEIF) at University College London (Appleby, 1986). The radiocarbon (^{14}C AMS) age estimates were converted into calendar years BP via Clam software (Blaauw, 2010) using the INTCAL09 data set of Reimer et al. (2009). An age–depth curve was derived based on a smoothing spline model (with 0.3 smooth; 10,000 iterations). Calendar age point estimates for depths were based on weighted average age–depth curves and also by taking into account the error range of the calibrated ages (Fig. 2a). Several 'too young' radiocarbon ages were rejected as they provided models with a large number of age–depth reversals and contamination with overlying material during coring was suspected (Fig. 2a). Pollen stratigraphic markers i.e., the decline in *Artemisia* and Chenopodiaceae were used to slightly adjust the Younger Drays/Holocene transition as this appeared to be about 300 years younger based on the radiocarbon age. The age depth model for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am was calculated using Constant Rate of Supply model (CRS) (Appleby, 2001). The CRS age–depth model was joined to the radiocarbon chronology by assuming a constant sedimentation rate between the two types of dated points (Fig. 2a).

3.1.2. Macro-charcoal and pollen

626 contiguous 1 cm^2 sub-samples were retrieved by volumetric displacement at 1 cm intervals and gently wet-sieved through a 160-μm mesh. The total number of macro-charcoal particles in each sample was counted under a binocular microscope. Samples at selected depths ($n = 21$) were screened for charred macro-remains for further identification of the burnt material and to distinguish between charcoal originating from arboreal or herbaceous vegetation. A sample volume of 30 cm^3 was placed in ca 50 cm^3 distilled water for a few hours and screened without sieving for charcoal fragments larger than 0.2 cm. Observations were made in 3 anatomical surfaces/planes (transversal, radial and tangential) when possible to ensure correct identification. To facilitate identification, reference collections of the Center for Archaeological Sciences, KULeuven and corresponding literature were used (Schweingruber et al., 1990; Gale and Cutler, 2000).

Pollen analysis was performed on 87 samples at intervals of 2–10 cm along the core after the standard procedures of Bennett and Willis (2001). The total pollen counts (excluding spores and aquatics) at each level varies between 197 and 746 (343 mean). Terrestrial pollen types counted were converted into percentages of their total sum. Pollen was used to derive a regional estimate of vegetation development, which, given the size of the basin, should represent an area of max 50 km radius around the lake (Sugita et al., 2007; Feurdean et al., in prep.). The pollen record was statistically divided into pollen zones using optimal splitting based on the information content technique (Bennett, 2007).

3.2. Statistical analyses of fire regime

The macro-charcoal record was used to identify fire peaks (C_{peak}), i.e., high frequency variation in charcoal representing fire events that are conspicuous against the background component ($C_{background}$), namely the low frequency changes in charcoal associated with regional fire activity and secondary charcoal deposition (Gavin et al., 2006; Higuera et al., 2009). The macro-charcoal sedimentary record was first interpolated to a median sampling resolution i.e., 20 yr and transformed into macro-charcoal accumulation rates (CHAR, particles cm^{-2} yr^{-1}). Because deposition time varies within the record (<20 yr/cm between 12,000 and 8000 cal yr BP and 3500 and 0 cal yr BP, and *c.* 40 yr/cm between 8000 and 3500 cal yr BP; Fig. 2) re-sampling at a lower resolution of ca 40 yr would lead to fire events being omitted, whereas re-sampling at a higher resolution (ca 20 yr) would not significantly alter the fire events outcome (Higuera, 2009). Fire peaks were obtained by subtracting $C_{interpolated}$ from $C_{background}$. The sampling window selected to smooth the data was chosen by looking at threshold values, which showed that the number of fire peaks would not change using smoothing values above 400 years. A Gaussian mixture model was used to distinguish noise-related variations from local fire peaks. The magnitude of fire peaks was used as an approximate (qualitative) indication of fire intensity or the area burnt (Higuera et al., 2009). Fire episode frequencies were smoothed using a 1000 year window, where the Fire Return Interval (FRI) is the time between two adjacent fire events and the fire frequency (FF) is the total number of fires within a 1000 year window (Fig. 3). The mean Fire Interval (mFI) sums the FRI over a statistically delimited period (see below).

We used change point analysis (CPA), to detect whether there were significant change points in time within the fire record associated with major shifts in fire frequency and/or area burnt (Pezzatti et al., 2013). CPA has a robust mathematical approach to detecting the most probable change points in the period under investigation and thus discriminating between the normal variability within a fire regime and any significant shift in a fire regime. It therefore provides confidence levels and intervals for the changes detected (Taylor, 2010). We then chose to apply a Weibull model to examine the distribution of FF and FI within each fire period identified by CPA. Goodness of fit of each Weibull model was then tested using the Kolmologovo–Smirnov (KS test). MFI and FF analyses were performed with the CharAnalysis 0.9 program (Higuera, 2009).

In order to identify deviations in the long-term trends in fire activity (positive and negative anomalies), the charcoal record was normalised and standardised following the protocol of Power et al. (2010); also detailed by Feurdean et al. (2012). A base period of the whole record was chosen to normalise the record.

3.3. Climate

3.3.1. Model and experimental design

To characterise the evolution of climate conditions during the Holocene, we employed the NCAR CAM3.1 global atmospheric model (Collins et al., 2004) coupled to the CLM3.0 land model (Oleson et al., 2004) and a slab-ocean model. Details of the model design are provided in the Supplementary Material S1.

3.4. Climate from proxy data

We used independent climate proxies from the study site to determine whether the climate-based simulations of the fire season were reasonable. These included indicators of lake level fluctuations derived from Lake Stiucii plus published literature providing regional scale quantitative and qualitative climate reconstructions. The lake level changes at Lake Stiucii were derived from changes in sediment composition, organic content and

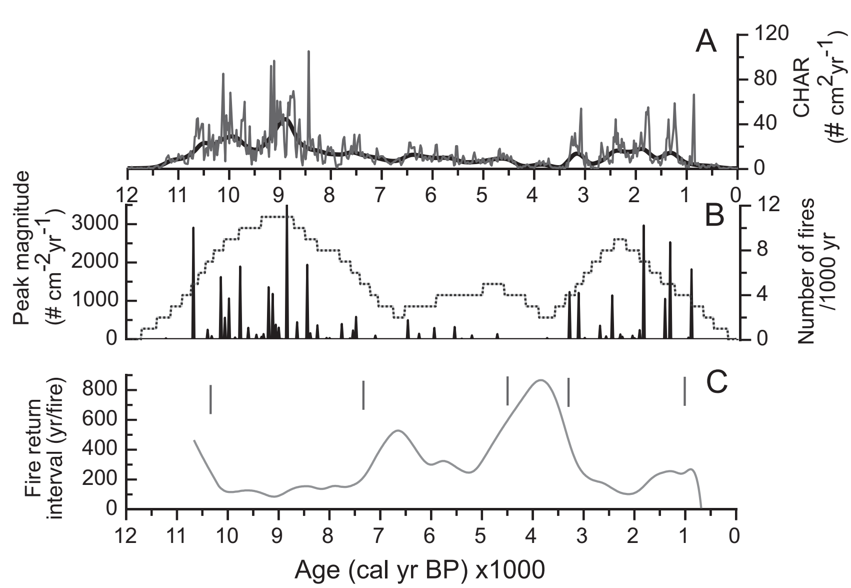


Fig. 3. A) Interpolated macroscopic charcoal accumulation rate (CHAR; grey curve) and background CHAR (black curve); B) inferred number of fires/1000 years (grey dashed curve) and peak magnitude (vertical lines), and C) inferred fire return interval/1000 years. Vertical grey lines denote statistically significant zones.

mineral magnetic susceptibility. These were complemented by information from the sedimentary geochemical and grain size records. The sediment sequence composed of peat with high organic content (this study) and low values of elements such as K, Ti, Rb, and Zr, alongside weaker magnetic susceptibility and a finer median grain size was associated with a wetland phase, whereas deposition of various types of gyttjas and clays with higher magnetic susceptibility and low organic content (this study), and a corresponding increased in K, Ti, Rb, Zr and generally coarser grain size (Veres et al., in prep; Hutchinson et al., in prep.) were taken as indicators for high lake levels.

3.5. *Anthropogenic impact estimates from land use changes and population growth*

To assess the potential impact of population growth and land-use changes on vegetation and fuel demands, estimates on the demographic growth, cropland, and pasture dynamics over the last 12,000 years were taken from the HYDE 3.1 population database of Klein Goldewijk et al. (2011). Data extracted cover a geographical area ranging between 49°00′ and 45°00′N and 22°00′ and 26°00′E.

4. Results

4.1. *Sediment stratigraphy and charcoal source area*

The lithology of the core indicates three major shifts in sediment composition (Fig. 2b) over the past 12,000 years such as: i) an early lacustrine phase between 12,000 and 11,450 cal yr BP (621–600 cm, clayed gyttja and gyttja); ii) a wetland context between 11,450 and 4700 cal yr BP (600–483 cm, coarse *Phragmites* peat and 483–333 cm, fine *Phragmites* peat); and iii) a second lake phase over the last 4700 cal yr BP (333–0 cm, peaty gyttja, gyttja and clay facies). Apart from the interval between 6500 and 4500 cal yr BP, where a low deposition time (i.e., 40 yr cm^{-1}) resulted in a low charcoal accumulation rate (CHAR) as opposed to high charcoal concentrations (CHAC), there is no significant difference between the CHAR and CHAC throughout the Lake Stiucii record (Figs. 2B and 3).

Based on experimental and simulation studies of charcoal dispersal and accumulation, the relevant source area for macro-charcoal particles (>100–200 μm) is up to 1–3 km around fire sites (Lynch et al., 2004; Higuera et al., 2007, 2011). Apart from atmospheric fallout, increases in charcoal may also reflect significant sediment in-wash events related to periods of high rainfall (Carcaillet et al., 2007). At Lake Stiucii there is no significant change in the CHAR at the transition between the lake and wetland phases of the basin. This implies that changes in the basin type did not affect the charcoal source area, by either restricting it to aerial fallout when the basin was wetland, or as a lake, significantly enlarging it via fluvial inputs and the introduction of secondary charcoal through erosion. There are, however, two peaks in magnetic susceptibility at 3000 and 1200 cal yr BP, respectively, coincident with spikes in CHAR, which suggest that the charcoal input into the basin might have been enhanced by runoff (Fig. 2b).

4.2. *Simulated Holocene climate change at the proxy site*

Preliminary analysis of the simulated climate at the proxy site indicates that the summers (June–September) had the lowest precipitation rates and the driest soils, i.e., conditions most favourable for fire ignition and spread (Fig. 4). Due to the different characteristics of the orbital configurations in early (June–July) and late (August–September) summer, the simulated climate changes

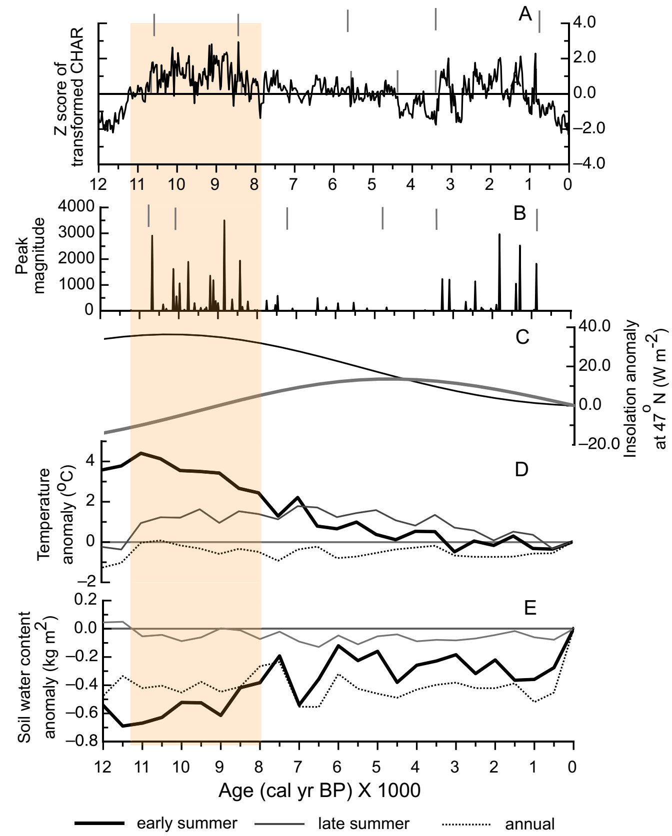


Fig. 4. A) Z-score of charcoal accumulation rate; B) inferred peak magnitude (a proxy for fire magnitude or area burnt); statistically significant changes in CHAR and peak magnitude are indicated by the vertical grey line; C) early (black) and late (grey) summer insolation (Berger and Loutre, 1991); modelled early and late summer as well as annual temperature (D) and soil water content (E). Orange rectangular highlights the warmest and driest modelled time interval of the Holocene and the associated high fire activity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are significantly different between these two parts of the summer (Fig. 4). For example, the annual mean and the late summer climate conditions remained fairly constant throughout the Holocene (except for the 0 ka time step, which shows higher precipitation rates and soil moisture). In contrast, according to the model, the most prominent climate changes occurred for early summers and in the early Holocene; the increased early-summer insolation in the early Holocene gave rise to a ~4 °C higher temperature than at the pre-industrial time step (Fig. 4). Furthermore, the increased early-summer insolation led to a reduction in precipitation and soil moisture content.

The simulated early-summer precipitation rate averaged over the 12–9 ka period is about two thirds (~18 mm/month) of the average precipitation rate between 9 ka and 0 ka (~27 mm/month). Precipitation and soil moisture content are highly correlated ($r = 0.97$, $p < 0.0001$) as are temperature and precipitation ($r = -0.77$; $p < 0.0001$). Because of the high correlation between precipitation and soil moisture we can restrict our discussion of the climate–fire relationship to soil moisture and air temperature. We have chosen soil moisture as it is used as a proxy for total fuel moisture and is an important driver of fire dynamics in models such as GlobFirm (Thonicke et al., 2001) and as a proxy for live grass fuel moisture in SPITFIRE (Thonicke et al., 2010; Pfeiffer and Kaplan, 2012). Based on the model's results, we anticipate that a key issue in understanding the effects of climate on fire regimes during the Holocene will be associated with early-summer changes in temperature and soil moisture.

4.3. Fire–climate relationship over the past 12,000 cal yr BP

CHAR, FF and peak magnitude at Lake Stiucii has varied greatly over the past 12,000 years (Table 2; Fig. 3). There are six statistically significant temporal shifts in the fire frequency: zone one (12,000–10,100 cal yr BP) with a 270 year mFI and a maximum FF of 4 fires/1000 years; zone two (10,100–7100 cal yr BP) with a 112 year mFI and a maximum FF of 9 fires/1000 years; zone three (7100–4700 cal yr BP) with a 317 year mFI and a maximum FF of 3 fires/1000 years; zone four (4700–3300 cal yr BP) with a no fire events; zone five (3300–700 cal yr BP) with a 150 year mFI and a maximum FF of 6.5 fires/1000 years; and zone six (the last 700 cal yr BP) with no fire events. The Weibull b parameter shows that the fire regime in zone two and five show a similar fire return interval distribution (Table 2).

The dry and warm early-summer simulated conditions between 11,500 and 8300 cal yr BP corresponded to a period of high fire activity, whereas the prevalence of cooler and wetter summer conditions during the middle Holocene (8300–3300 cal yr BP) with low fire activity (Fig. 4). The simulated climate conditions remained cool and wet between 3300 and 500 cal yr BP while fire activity become enhanced. The increased summer moisture over the last 500 years coincided with a low fire activity (Fig. 4).

4.4. Fire–vegetation relationship

Zonation of the Lake Stiucii pollen record revealed five statistically significant zones occurring at around 9400, 6900, 3700, 300, and 70 cal yr BP whereas the major shifts in fire frequency occurred at about 10,100, 7100, 4700, 3300, and 700 cal yr BP (Fig. 5). The vegetation was composed of a mixture of grass (Poaceae), steppe (*Artemisia*, Chenopodiaceae) and boreal taxa (*Pinus*, *Betula*, *Salix*) at the end of the YD and the onset of the Holocene (12,000–11,500 cal yr BP); periods characterised by low fire activity (Fig. 5). Subsequently (11,500–9000 cal yr BP) woodland predominantly composed of *Pinus* with *Picea abies* and various proportions of deciduous tree taxa (*Ulmus* predominant) expanded, while fire activity increased. *Pinus* declined markedly first at around 10,500 cal yr BP then at around 9000 cal yr BP, which is associated with the expansion of *P. abies* and *Corylus avellana*, while fire activity remains high. Mixed *P. abies*–*C. avellana* woodlands persisted until 4300 cal yr BP, which also included abundant *Quercus* and *C. betulus* from about 7100 cal yr BP, and was associated with a decline in grassland cover and in fire activity (Fig. 5). A reduction in tree pollen percentages in parallel with the expansion of open herbaceous communities, also including anthropogenic pollen indicators, occurred at around 3700 cal yr BP, which parallels a marked increase in fire activity (Figs. 5 and 7).

Analysis of charred plant remains showed that monocotyledons (Poaceae and *Phragmites*) and, at some intervals dicotyledon herbs, dominated throughout the sequence, although these appeared in higher quantity before 10,000 and over the last 3700 cal yr BP (Fig. 6). Tree charcoal remains were only visible during the YD and between 5000 and 1000 cal yr BP during the lake phases of the development of the basin. They appear to peak during erosive events as indicated by the magnetic susceptibility profile (Figs. 2 and 6). However, it is highly probable that the paucity of charred and sub-fossil trees macro-remains may reflect taphonomic processes at this site i.e., a rather large basin size and that the *Phragmites* reed beds have acted as a filter trapping these fragments at the margins of the basin (Figs. 5 and 6).

5. Discussion

Results from the charcoal record at Lake Stiucii in the lowlands of Transylvania show that fire frequency has varied significantly over the last 12,000 years. Below we explore the three hypotheses of the dominant controls of the fire activity: climate, vegetation and human impact.

5.1. Climate hypothesis: are the long-term fire activity changes driven by centennial to millennial changes in climate conditions?

Changes in southern and central European summer climate are largely associated with the latitudinal expansion of the Azores high pressure over the Atlantic. Because higher insolation values lead to a northward displacement of this zone, drier zones tend to shift further north leading to a warmer and drier-than-today early Holocene climate. Results from our charcoal record and the simulated climate conditions suggest that trends in fire activity in the region were highly associated with changes in the early summer (June, July) climate conditions. The decline of early summer insolation and therefore in temperature seasonality and the increase in soil moisture content from the early Holocene and onwards led to progressively cooler and wetter summers, which correspond to a decline in fire frequency until 3500 years (Fig. 4). Although the increase in fire activity between 3500 and 1000 cal yr BP can not be explained by the simulated climate conditions, it is in good agreement with the proxy-derived climate conditions (see below). A strong link between precipitation and temperature related parameters in the early Holocene has recently been modelled for Europe (Molinari et al., 2013), whereas worldwide past trends in biomass burning are best predicted by increasing temperatures and intermediate levels of moisture (Daniau et al., 2012).

Table 2
Fire regime statistics for each statistically significant zone at Lake Stiucii as defined by change point analysis. Parentheses enclose 95% confidence intervals estimated by 1000 bootstrapped samples. No FRI is the total number of fire return intervals in each zone.

Time period	No FRI	Mean FRI	Weibul b		Vegetation types	Charred remains
700–0	0	0	0	0	Wooded steppe (*Quercus*, *Carpinus*, *Fagus*)	Poaceae, *Phragmites*
3300–700	6		150 (96–204)	167 (108–229	Open deciduous woodland	Poaceae, *Phragmites* wood
4700–3300	0		0	0		Open deciduous woodland (*Quercus*, *Carpinus*, *Fagus*) Poaceae, *Phragmites*, wood
7100–4700	6	6	317 (203–470)	360 (224–529)	Less open deciduous woodland	
10,100–7100	25	23	112 (91–137)	127 (104–155)	Open woodland (*Corylus*, *Picea-Quercus*)	Poaceae, *Phragmites*
12,000–10,100 (YD)	0.31	4	270 (130–450)	303 (146–500)	Steppe-woodland (*Pinus*, *Ulmus*, *Quercus*)	Poaceae, *Phragmites*, wood

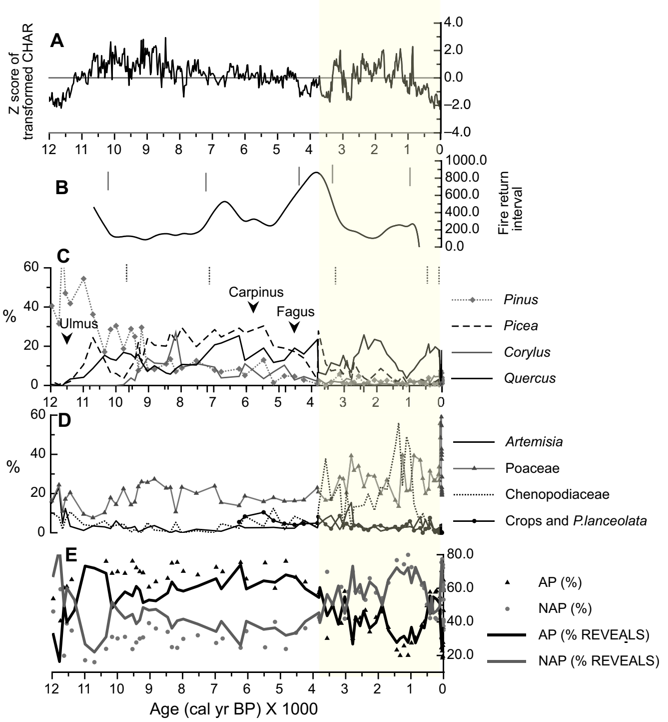


Fig. 5. A) Z-score of charcoal accumulation rate; B) fire return interval; C) selected tree pollen taxa (the arrows mark the arrival of *Ulmus*, *Carpinus betulus* and *Fagus sylvatica*); D) selected herbaceous pollen taxa; E) summary percentages of arboreal pollen types (AP, a proxy for woodland cover) and non arboreal pollen types (NAP, a proxy for open landscape), as well as estimated regional woodland versus grassland cover based on the REVEALS model that corrects for biases in taxon-specific pollen productivity and dispersal and basin type (Feurdean et al., sub). The yellow square highlights the onset of stronger human impact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

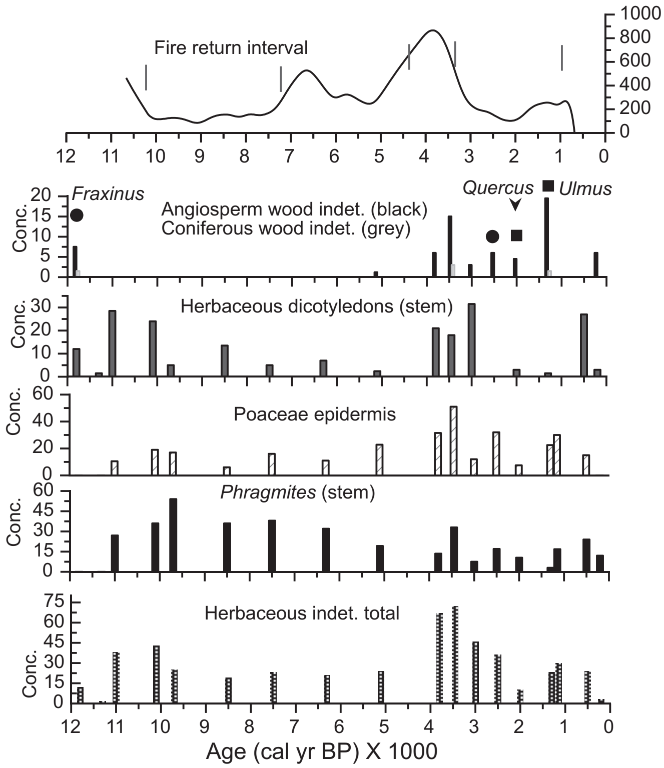


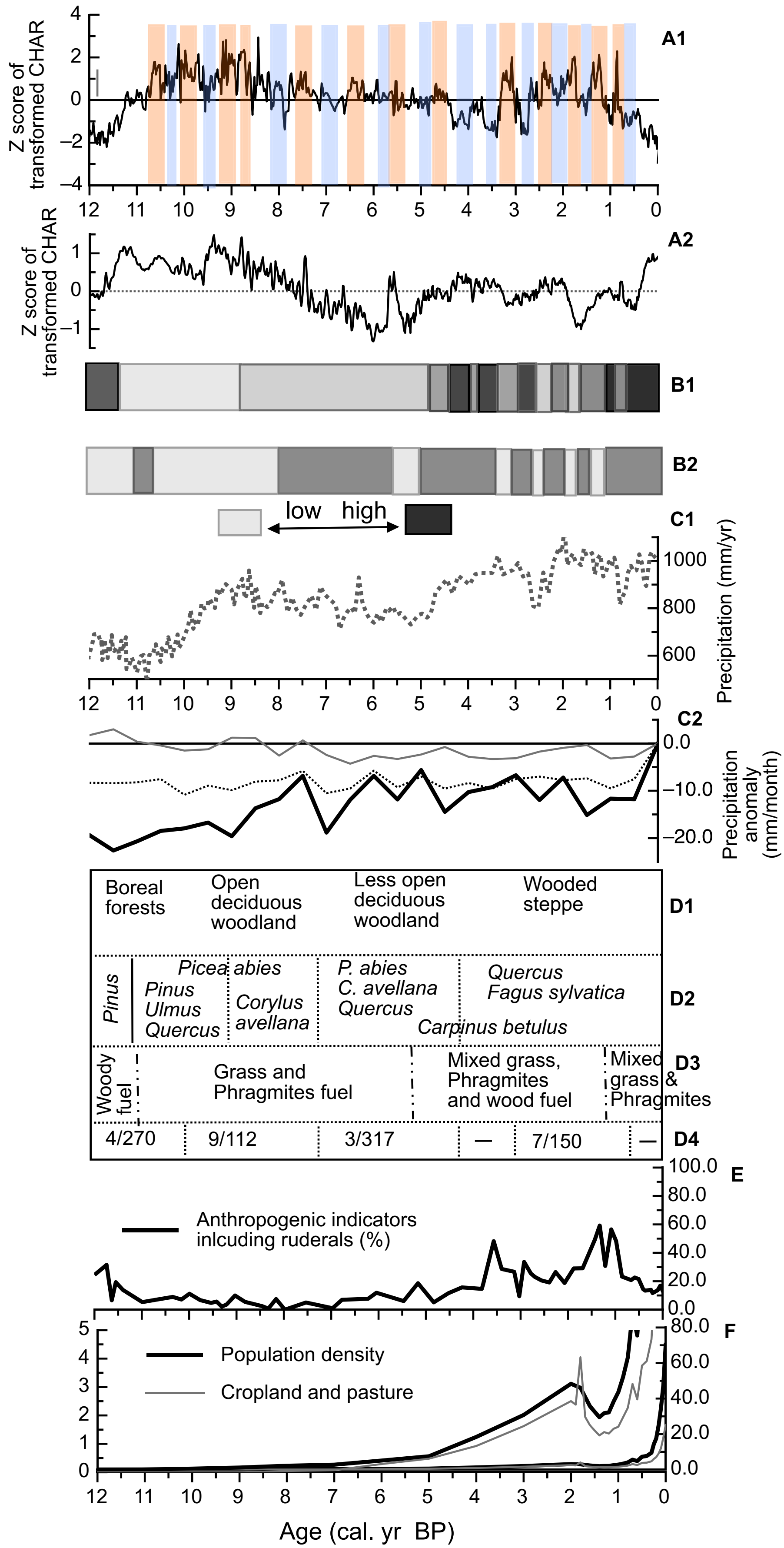
Fig. 6. Fire return interval and charred plant macrofossil remains (>3 mm) of wood and herbaceous plants (bars). The symbols indicate the occurrence of identified charred wood remains of *Quercus*, *Fraxinus* and *Ulmus*. Poaceae may also include *Phragmites* steam. Herbaceous indet. total includes monocotyledons (Poaceae and Cyperaceae), and herbaceous dicotyledons. Conc. represents the total number of remains found in 30 ml sample volume.

5.1.1. Warmer and drier conditions (12,000–8300 cal yr BP) and high fire activity (10,700–7100 cal yr BP)

Following the period of low fire activity at the end of YD, charcoal influx rose to a slightly positive anomaly from about 11,400 cal yr BP, whereas fire frequency increased from 300 year mFI at 10,700 cal yr BP to 112 year mFI between 10,100 and 7100 cal yr BP (Figs. 3 and 4). The whole period corresponds to one of maximum early summer insolation over the past 11,500 years, which apparently led to higher temperatures (of about 4 °C) and lower soil moisture and precipitation values (about half) than at present. Local climate proxies from Lake Stiucii (litholostratigraphy, magnetic susceptibility and loss on ignition) show that this interval of maximum fire activity in the early Holocene corresponded to a transition from a shallow lake to a long-lasting *Phragmites* wetland phase between 11,450 and 6000 cal yr BP (Figs. 2 and 7). Greater-than-today summer temperatures (1–1.5 °C higher) have been reconstructed for the region during the early Holocene (Feurdean et al., 2008a; Renssen et al., 2009), as well as a decrease in peat surface moisture and lake levels (Feurdean and Bennike, 2004; Feurdean, 2005; Magyari et al., 2009; Perşoiu, 2010; Fig. 5). The early Holocene warm and dry climate conditions at our proxy site better resemble those of southern Europe (35–40° N), than more central European locations (Renssen et al., 2009; Connor et al., 2013). Furthermore, fire activity was also enhanced in the Mediterranean region at this time (Vannière et al., 2011; Connor et al., 2013). An increase in fire frequency is evident from about 10,000 cal yr BP in the Pyrenees (Rius et al., 2011) and about 9500 cal yr BP in Italy (Vannière et al., 2008; Kaltenrieder et al., 2010).

5.1.2. Cooler and wetter conditions (8300–3300 cal yr BP) and low fire activity (7100–3300 cal yr BP)

Fire activity had already declined from 8300 cal yr BP, and there is also a statistically significant change in fire frequency from 112 year mFI to 317 year mFI at 7100 cal yr BP and the lowest fire activity in the record (no major fire events) between 4700 and 3300 cal yr BP (Fig. 4). The onset of decreased fire activity is associated with a decline in simulated early summer temperatures (ca 2 °C) and an increase in soil moisture levels (Fig. 4) and precipitation (Fig. 7). The local proxy data at Lake Stiucii, i.e., the replacement of coarse peat by fine peat and the appearance of floating aquatic plants (Feurdean et al., in prep.) possibly indicates a slight increase in the wetland water depth between 9000 and 6000 cal yr BP (Fig. 4). Furthermore, runoff increased at about 6000 cal yr BP and lake level rose markedly at 4700 cal yr BP (Fig. 2b). The highest relative water levels and most marked runoff are visible between 4300 and 2800 cal yr BP and over the last 1200 years parallel two fire-free intervals (Figs. 2, 4 and 7). Although with some variations, regional proxy records (peat wetness, lake levels, fluvial activity), indicate a moisture increase and/or temperature decline approximately between 8000 and 5800 cal yr BP, and 4800 and 3500 cal yr BP in Romania (Onac et al., 2002; Feurdean, 2005; Feurdean et al., 2007, 2008b; Magyari et al., 2009; Perşoiu, 2010, 2011). Our estimates of mid-Holocene low fire frequency (mFI = 317 year) between 8300 and 5000 cal yr BP are in contrast to the intermediate fire frequency reported in central Italy (mFI = 160 year, Vannière et al., 2008), and the Pyrenees (mFI = 200 year, Rius et al., 2011). Low biomass burning has previously been documented in the Carpathian region between 8000


A1
Z score of transformed CHAR
A2
B1
B2
low high
C1
Precipitation (mm/yr)
C2
Precipitation anomaly (mm/month)
Boreal forests
Open deciduous woodland
Less open deciduous woodland
Wooded steppe
D1
Pinus
Picea abies
Pinus
Ulmus
Quercus
Corylus avellana
P. abies
C. avellana
Quercus
Quercus
Fagus sylvatica
Carpinus betulus
D2
Woody fuel
Grass and Phragmites fuel
Mixed grass, Phragmites and wood fuel
Mixed grass & Phragmites
D3
4/270
9/112
3/317
—
7/150
—
D4
E
Anthropogenic indicators inlcuding ruderals (%)
F
Population density
Cropland and pasture
Age (cal. yr BP)

and 5500 cal yr BP (Feurdean et al., 2012), and implies that these regions were climatically disconnected at this time. Nevertheless, our reconstructed high lake level and fire-free period between 4700 and 3300 cal yr BP matches the broader regional tendency of high lake level stands throughout the mid latitudes (lat. 45°N) in Europe (Magny et al., 2012), an extension of coastal lakes and mires on Danube (Egger, 1997) and a marked decline fire frequency noted around this latitude (Vannière et al., 2008; Rius et al., 2011).

5.1.3. Contrasting simulated and proxy derived climate condition (3300–700 cal yr BP) and high fire activity

A higher fire frequency of 150 year mFI was re-established between 3300 and 700 cal yr BP and a fire-free interval followed over the last 700 years (Fig. 4). The proxy data from Lake Stiucii indicate that there is a close relationship between fire activity and lake water levels. Specifically, a good match exists between the lake level inferred dry conditions and episodic increases in fire frequency occurring around 3300, 2400, 1800, and 1500 cal yr BP (Fig. 4). As in the case of fire activity, lake level changes are most sensitive to summer conditions (Magny et al., 2007; Vannière et al., 2008). In contrast, the palaeoclimate simulations showed a slight drop in soil moisture and precipitation between 3200 and 1000 cal yr BP, which fails to explain the fire activity increase and the lake level falls (Figs. 4 and 7). Interestingly, there is a significant increase in the simulated summer soil moisture over last 500 years, which matches very well the fire frequency reduction and the high lake levels. A similar decline in fire frequency from about 3000 years was reconstructed for central Italy (Vannière et al., 2008), whilst an increase was visible for northeastern Italy (Kaltenrieder et al., 2010) and the Pyrenees (Rius et al., 2012).

5.1.4. Response of fire activity to short-lived climate events

Fire activity appears to be sensitive to the short-lived climate events that occurred locally and regionally during the Holocene. Episodic increases in fire activity were recorded approximately 10,700, 9200, 8700, 7600, 6400, 5500, 3300, 2400, 1800 and 1350 cal yr BP and matched well a number of the local hydrological changes (i.e., lower lake levels and decreased runoff during drier basin condition at Lake Stiucii, Fig. 7). These intervals of high fire activity were concurrent with well-recognised warm/dry periods across Europe (Andresen et al., 2005), conditions that increased the probability of frequent or large fires. In contrast, short-lived declines in biomass burning are recorded around 10,300, 9300; 8200, 7000, 5900, 5200, 4200, 3500, 2800, 1500, 600–200 yr BP (Fig. 3) and appear to be associated with a number of well known short-term cool/moist events (Mayewski et al., 2004; Tămaş et al., 2005; Wanner et al., 2008; Feurdean et al., 2008a; Perşoiu, 2011). A strong link between the short-term climate changes occurring around 5500–5000, 1200–900 (Medieval Warm Period) and 800–400 cal yr BP (Little Ice Age) and changes in fire activity has been previously documented in the Carpathians (Feurdean et al., 2009, 2012), as well as in southern European lake sequences (Vannière et al., 2011), the northern hemisphere and globally (Marlon et al., 2008, 2013).

5.2. Vegetation hypothesis: did vegetation mediate the direct impact of climate?

It has been documented that vegetation quantity and characteristics (composition, structure, flammability) can either amplify or reduce the effect of climate on fire frequency, burnt area, and intensity (Gavin et al., 2006; Higuera et al., 2009; Whitlock et al., 2010; Krawchuk and Moritz, 2011). Three main conclusions regarding the fire vegetation relationship can be drawn from the Lake Stiucii lowland pollen and charred macro-remain.

First, the combined pollen and macro-charcoal record indicates that the low fuel availability related to the persistence of dry climate conditions acted as limiting factor for biomass burning during the YD (>12,000 cal yr BP) and extended into the early Holocene (~10,700 cal yr BP (Fig. 5). A delayed increase in fire activity until about 10,700 cal yr BP in the Transylvanian lowlands appears to have persisted until there was a more consistent rise in the soil moisture content and biomass i.e., arboreal cover (Fig. 5). This contradicts previous finding in the region based on micro-charcoal data suggesting that there was already sufficient fuel to sustain high biomass burning in the early Holocene (Feurdean et al., 2012), although some other areas such as the lowlands of Hungary also displayed a later increase in biomass burning (Willis, 2007). Low biomass burning is characteristic of glacial conditions (cold and dry) or modern xeric, steppe, and grassland environments, where burning is more frequent during wetter phases that promote vegetation growth and fuel accumulation (Power et al., 2008; Turner et al., 2008; Gill-Romera et al., 2010; Krawchuk and Moritz, 2011; Feurdean et al., 2012; Marlon et al., 2013). It has also been documented that, although vegetation burning in temperate regions appears more frequent in warm/dry climates, the fire events are often preceded by wetter conditions as this favours biomass build-up (Zumbrunnen et al., 2009).

Second, there is a link between the arboreal versus grassland cover and fire activity. Generally, the mFI was longer whilst woodlands were dominant (7100–4000 cal yr BP, mFI = 317 years), whereas the mFI was shorter (<150 years) during the prevalence of more open woodlands with abundant grasslands (10,700–7100 and 4000–0 cal BP (Fig. 5). This is more evident in the woody cover estimates based on the REVEALS model (Fig. 7) that corrects for biases in taxon-specific pollen productivities and dispersal and basin type (Feurdean et al., in prep.). Dry forests with grasslands provide both abundant fine grass fuel in addition to coarse wood, a fuel mix favourable for ignition and high flammability (Whitlock et al., 2010; Krawchuk and Moritz, 2011; Hoffmann et al., 2012). The threshold for a shift from highly flammable, dry forest to less flammable, dense forest has been found to be governed by the ability of tree cover to reach a sufficient density to exclude the highly flammable grasses (Hoffmann et al., 2012). This shift occurs under cooler and more humid climate conditions. Results from our study suggest that the occurrence of more frequent fires in the dry climate of the early Holocene has kept the landscape open, promoted grassland abundance and sustained a more flammable ecosystem. Conversely, the decline in fire risk under cooler and wetter climate conditions (8000 cal yr BP), favoured the tree cover

Fig. 7. Synthesis of environmental evidence: A1) Z-score of charcoal accumulation rate at Lake Stiucii (blue bars highlight short-term wet periods and red bars highlight short-term warm dry periods derived from Lake Stiucii proxy record). A2) Z-score of charcoal accumulation rate in the Carpathian region (Feurdean et al., 2012); B1) Lake Stiucii lake level and wetland wetness fluctuations; B2) synthesis of climate developments in the region based on published literature on peat surface moisture, pollen-based quantitative climate and fluvial activity; C1) pollen-based precipitation reconstruction from Preluca Tiganului, NW Romania based on weigh averaging polynomial least square (Feurdean et al., 2008b, unpublished); C2) modelled early (black) and late summer (grey) as well as annual (dotted) precipitation (this study); D) schematic representation of D1) woodland dynamics; D2) dynamics of the main tree pollen types); D3) Type of fuels burnt based on the analysis of charred plant remains); D4) number of fires/1000 years and the fire return interval/1000 years; E) summary percentages of anthropogenic indicators; F) regional population (inhabitant number/km^2), and cropland and pasture estimates (km^2/grid cell) from the HYDE 3.1 database (Klein Goldewijk et al., 2011). Note the change in scale before and after 1000 years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

increase at the expense of grasses, further accentuating the decline in fire frequency brought by wetter climate conditions.

Third, there is little evidence of statistically significant changes in the individual tree species composition and abundance synchronous with major shifts in fire activity over the past 12,000 cal yr BP. However, our pollen record is not as highly resolved as the macro-charcoal record to allow a precise determination of whether changes in fire frequency were a direct result of a change in species composition.

5.3. Human fire legacy

Although the influence of anthropogenic burning is widely recognised, it remains uncertain to what extent humans have altered natural background levels of fires in the environment, especially when fire frequency will also have fluctuated with climate change (Bowman et al., 2011).

Numerous archaeological sites dating from the mid to late Neolithic (7500–6000 cal yr BP) are reported from the study area, reflecting Lake Stiucii's position close to a major river corridor, the Somesul Mare (Crisan et al., 1992; Repertoriul Arheologic National, 2013). However, our pollen record shows only a minor increase in grasses and ruderals such as Poaceae, Asteraceae, Tubuliflorae and Liguliflorae, which could indicate small-scale agro-pastoral activity in the early Neolithic (ca 8000 cal yr BP) during periods of severe and frequent fires (Fig. 5). Humans may have taken the advantage of these intense wildfires to extend their agro-pastoral activities, rather than being major drivers of fire dynamics. Biomass burning and fire frequency was low between 6000 and 3000 cal yr BP, the Copper to Early Iron Age. On the other hand, the level of anthropogenic impact increased slightly during this period, which is consistent with the estimated modest population growth for the region (Fig. 5), suggesting the occurrence of only small scale fires or that fires might not have been extensively used in the direct vicinity of the lake watershed.

Fire frequency increased markedly at about 3300 cal yr BP (mFI = 150 years) and there are clear shifts in charcoal peak magnitude over the past 3300 years (Fig. 3). Several lines of evidence from our charcoal and pollen records, as well from archaeological, historical and population data, suggest that human activity has strongly altered the fire regime during this period. It is therefore also probable that settlements, fields or pastures developed around the lake to have modified the fire return interval. However, episodic increases in fire activity also overlap climatically dry phases, and suggest synergic effects of humans and climate on fire activity over the past 3300 years.

The shift in the fire regime from low biomass burning and no major fire events prior to 3500 cal yr BP to frequent fires between 3300 and 2000 cal yr BP occurred just slightly before the marked decline of the extent of woodland cover (in particular of *C. betulus*, *F. sylvatica* and *Quercus*) and the expansion of anthropogenic indicators (ruderal, pasture indicators and cultivars) (Fig. 6). Increased incidence of crown fires in *Quercus*, *Fraxinus* and *Ulmus* forest between 3700 and 1200 cal yr BP (Fig. 6) is also documented by the analysis of charred plant remains. The identified burnt woody species at Lake Stiucii were largely similar in composition to the charred assemblages found at archaeological sites in eastern Hungary (Moskal-del Hoyo, 2013). A significant forest decline (Tanţău et al., 2006), reflecting clearance, fire and grazing was also observed in S Transylvania Balkans approximately ~4000 cal y BP (Tonkov and Marinova, 2005; Marinova and Atanassova, 2006; Marinova et al., 2012; Connor et al., 2013).

Fire episodes became more frequent and less severe/smaller towards the end of this interval (2400–2000 cal yr BP), associated with a marked increase in cultivars and pastoral indicators (Fig. 6). Abundant *Phragmites* charred remains indicate that burning of the land for agro-pastoral activities might have incidentally extended into the *Phragmites* reeds or that the reeds were intentionally burnt (Fig. 5). This change is also consistent with an increase in the number of settlements (Crisan et al., 1992) and salt deposit exploitation in the study area (Hardin and Kavruk, 2010). Larger-scale agro-pastoral activities (Feurdean et al., 2013), as well as the estimated population growth and expansion of cultivated areas (Kaplan et al., 2011; Klein Goldewijk et al., 2011) have been documented for the Carpathian region. This pattern of a concurrent rise in the proportion of cultivated and grazed areas and fire, together with a decline in the proportion of the forest cover from about 3300 cal yr BP, may indicate a shift from the sporadic and/or opportunistic use of burning to a more systematic use of fire for agro-pastoral activities. In central and western Europe, such a change in the fire regime was observed during the Iron Age to Roman Age (Tinner et al., 2005; Vannière et al., 2008; Carcaillet et al., 2009; Rius et al., 2012; Connor et al., 2013). This period was then followed by an interval (2000–700 cal yr BP) of less frequent but severe fires (Fig. 3). Although this period is characterised by low arboreal pollen, the abundant charred wood of both coniferous and deciduous trees (*Quercus* and *Ulmus*) suggest the prevalence of crown fires. A low-density woody cover would be expected to produce small, frequent fires as the effect of anthropogenic burning on temperate ecosystems was found to be stronger where fuel biomass is abundant and contiguous (McWethy et al., 2013). We therefore presume as the most likely scenario, that this increase in woodland burning could be attributed to humans and that these fire were likely prevalent in woodlands occurring close to the lake.

Finally, low biomass burning characterised the past 700 years, i.e., the Middle Ages and modern times (Fig. 5). Although this period coincided with cool and wet climate conditions including the Little Ice Age (600–200 cal yr BP) and the relative high lake level, we suggest that its fire activity might also be attributed to active fire suppression due to population pressure and settlement expansion and indirectly via low vegetation connectivity due to the wood removal. Historical documents reveal that most of the settlement in the lowlands of Transylvania, including villages in the proximity of the study site, emerged during the early Middle Ages around 800 years ago (Crisan et al., 1992; Repertoriul Arheologic National, 2013). Our charred remains analysis indicate that all such material over the past 1000 years originate from Poaceae, other herbs, and *Phragmites*. Thus fires were probably mainly used to manage pastoral and agricultural fields, a form of land management visible until present. Our reconstructed low biomass burning is in stark contrast to the pattern shown in the Carpathian Mountains, where fire continued to be used as a tool to open up the forests (Feurdean et al., 2012). However, this is in agreement with findings in the lowlands of Hungary, where fire activity declined to a low level during the last millennium (Feurdean et al., 2012). However, it should be noted that recent, large-scale abandonment of agricultural land (post 1990 AD) throughout the region has lead to a progressive biomass build up and provides fuel for burning.

6. Concluding remarks

Results from our charcoal record and estimated changes in climate, vegetation and human impact from the lowlands of Transylvania provide information about the drivers of fire regimes in the lowlands of Central-Eastern Europe; to date a poorly studied region. The fire return intervals (FRI) varied between 89 years and 866 years throughout the Holocene with a mean estimate of about 323 years. The highest mFI occurred between 10,100 and

7100 cal yr BP (112 years) and indicates the presence of a fire-prone ecosystem that was comparable to that of the Mediterranean region. There was a switch to a less fire-prone condition after 7100 cal yr BP (with a mFI of 317 year), similarly to that of central-western Europe.

We found a clear link between the long-term trend in fire activity and simulated climate changes driven by the variations in orbital forcing, that was particularly strong over the early and middle Holocene. The relationship between fire activity and the reconstructed local hydrological changes (i.e., lake levels fluctuations and runoff) appears to be strong and is maintained throughout the Holocene.

Except for the YD and the early Holocene (12,000–10,700 cal yr BP), where low fire activity most probably reflects fuel limitation due to arid and highly seasonal climatic conditions, fires were most frequent during climatically drier phases for the majority of the non fuel limited Holocene. Results from our study suggest that the occurrence of more frequent fires in the dry climate of the early Holocene has kept the landscape open, promoted grassland abundance and sustained a more flammable ecosystem, whereas the decline in fire risk under cooler and wetter climate conditions and favoured woodland development.

Humans were responsible for modification in fire frequency, and probably also the severity over the past 3300 cal yr BP; had halved the mFI to about 150 years between 3300 and 700 cal yr BP, and have efficiently suppressed fires over the last several centuries. Given the projected future temperature increase and moisture decline and biomass accumulation as a result of land abandonment in the region, fire frequency would be expected to rise to values similar to those of the early Holocene. However, due to the synergic influence of natural and anthropogenic factors on fire activity, fire is likely to continue to be suppressed.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2013.09.014.

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