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Reconstructing past fire regimes: methods, applications, and relevance to fire management and conservation

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ABSTRACT

Biomass burning and resulting fire regimes are major drivers of vegetation changes and of ecosystem dynamics. Understanding past fire dynamics and their relationship to these factors is thus a key factor in preserving and managing present biodiversity and ecosystem functions. Unfortunately, our understanding of the disturbance dynamics of past fires is incomplete, and many open questions exist relevant to these concepts and the related methods. In this paper we describe the present status of the fire-regime concept, discuss the notion of the fire continuum and related proxies, and review the most important existing approaches for reconstructing fire history at centennial to millennial scales. We conclude with a short discussion of selected directions for future research that may lead to a better understanding of past fire-regime dynamics. In particular, we suggest that emphasis should be laid on (1) discriminating natural from anthropogenic fire-regime types, (2) improving combined analysis of fire and vegetation reconstructions to study long-term fire ecology, and (3) overcoming problems in defining temporal and spatial scales of reference, which would allow better use of past records to gain important insights for landscape, fire and forest management.

1. Introduction: towards an increasing awareness of fire as an ecological factor

The conditions that made fire possible on earth appeared approximately 350–400 million years ago in the Late Devonian period (Scott, 2000). Fire evolved on the earth under the direct influence of climate (e.g. drought, wind, fuel moisture content) and the build-up of burnable biomass at various temporal and spatial scales (Swetnam, 1993; Scott, 2000). Once fire was established, it affected atmospheric chemistry and the carbon cycle and became a key factor in changing the climate (Clark, 1997; Cofer et al., 1997). Between 500,000 and 50,000 BP humans progressively learned how to preserve, transport and light fire (James, 1989; Rolland, 2004). Domestication of fire brought about major changes to the fire regimes of the planet, such that no place on earth has completely escaped from the direct or indirect influence of anthropogenic burning practices. In many cases, anthropogenic practices such as slash and burn or logging alter the ecosystem such that it may be subject to high-intensity fires that in turn may produce progressively fire-adapted ecosystems (Caldararo, 2002). As a result, fire regimes depend not only on climatic and biological factors, but also greatly reflect the cultural background of how people managed ecosystems and fire. All these elements evolved continuously in time and space, creating fire histories (Pyne et al., 1996).

According to Bond et al. (2005), several of the world's major biomes are fire-dependent ecosystems, at least in regard to biomass production, tree cover or species composition. This makes biomass burning and resulting fire regimes a major evolutionary force that affects vegetation structure and generates disturbance-adapted ecosystems (Savage et al., 2000; Wooller et al., 2000; Caldararo, 2002).

Scientists and managers are increasingly becoming aware of the ecological role of fire and of the necessity to understand past dynamics and the relationship between fire and management practices in order to preserve and manage present biodiversity as

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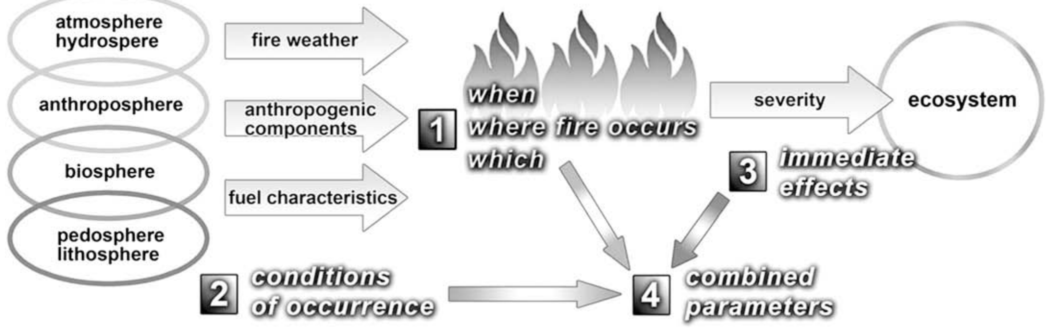

Fig. 1. Components of the fire-regime concept. The first group [1] assembles the core components (fire regime *sensu strictu*) describing which fire (type, intensity, fire behavior, etc.), when (frequency, seasonality, synchronicity, etc.) and where (size, shape of fires, etc.) it occurs. The other three groups [2, 3 and 4] represent clusters of complementary, additional or combined parameters (fire regime *sensu latu*): [2] conditions controlling fire occurrence (fire weather, wind regime, ignition sources, fuel characteristics, flammability, etc.); [3] immediate fire effects (severity, mortality, costs and damages, etc.); [4] derived or composite parameters resulting from the combination of two or more basic variables and conceived to represent some complex characteristics of fire occurrence (trends, variations, classifications systems, etc.).

well as ecosystem function (Swetnam et al., 1999; Bengtsson et al., 2000; Bergeron et al., 2002). In the last few decades an increasing number of studies on the role of fire as a fundamental ecological factor on both long and short time scales have been performed, and scientific and cross-disciplinary meetings on past fire reconstruction and its implications for ecology and ecosystem management have been organized (e.g. Crutzen and Goldammer, 1993; Clark et al., 1997; Scott et al., 2000b; Heyerdahl and Card, 2000).

There is now a growing awareness among scientists and managers that a broad and rigorous use of palaeoenvironmental proxies will allow a better understanding of both the long-term climate–fire–vegetation interactions at different spatial and temporal scales and the role of anthropogenic activities in present and ancient fire histories (e.g. Heyerdahl and Card, 2000; Whitlock and Larsen, 2001). Unfortunately, the general understanding of past fires disturbance dynamics is still incomplete, and many open questions exist at both conceptual and methodological levels (Clark, 1990). In addition, new problems related to changing environmental conditions, such as the role of invasive species, air pollution, climate change and infrequent but severe disturbances such as windthrows, may make it difficult or impossible to apply the knowledge acquired from studies of past dynamics to future fire management (Overpeck et al., 1990; Flannigan et al., 2000, 2005; Whitlock et al., 2003b; Pierce et al., 2004).

In this paper we review the most important approaches for reconstructing the long-term fire history and fire ecology and discuss open questions for future research on past fire regimes, fire history and long-term fire ecology.

2. Reconstructing past fire regimes and fire ecology

2.1. Defining fire regimes

The concept of fire regime originated in the early 1960s out of the need for fire ecologists and managers to bring together into a unified concept all the ecologically relevant characteristics and dimensions of fire occurrence within a defined area or in a specific ecosystem over a certain period (Gill, 1977; Christensen et al., 1981; Heinselman, 1981). The idea of fire disturbance as a basic natural force shaping ecosystems was rapidly and widely accepted in the United States and was implemented in the wildlife management strategies of the national parks (Leopold et al., 1963). In Europe the discussion of the ecological role of fire has been less acute since the majority of the forests are not of a pristine nature or have been significantly co-shaped by long-term land-use systems (Bengtsson et al., 2000), with some major exceptions being boreal forests (Bradshaw and Hannon, 1992; Zackrisson et al., 1996; Niklasson and Granström, 2000) and French fire research in the frame of colonial forestry and geography (Neff, 1995).

The concept of fire regime has now developed into a generalized and structured description of the role of fire in ecosystems and may therefore be defined as a sequence of fires that occur in a defined space-time window (Falk and Swetnam, 2003). Describing fire regimes consists of defining a broad collection of fire characteristics that may be organized, assembled and used in very different ways according to the needs of the users. Fire regime may thus refer to different times and time windows (past, present, future; single event, years, decades, centuries, millennia), different spatial units (a single ecosystem, single vegetation type, specific geographical areas, etc.), different origins of fire (natural, anthropogenic), and may consider not only the fire characteristics (fire intensity, fire type, fire behavior), but also conditions that determine fire occurrence (fuel type, fire weather, etc.) and immediate fire impact (fire severity, etc.). Besides the fire-regime definition *sensu strictu*, describing which fire occurs when and where (frequency, size, seasonality, intensity and type), there are also a significant number of other attributes and derived variables that may be combined to build ad hoc fire-regime definitions *sensu latu* (Fig. 1). Such a modular and flexible definition of fire regime is needed to bring some structure to a very heterogeneous body of fire attributes and to reconcile the physical nature of fire with the biological context within which it occurs (Pyne, 1984; Goldammer et al., 2001).

2.2. Fire continuum and proxy archives

Data used to reconstruct fire history can derive from the geosphere (e.g. magnetism, geo-chemistry), from the biosphere (e.g. palynology and palaeoecology, including charcoal analysis and dendrochronology) or from the anthroposphere (archaeological relicts, written documents, photographic records) (Pyne et al., 1996). Unfortunately information on long-term fire dynamics is only available from proxies in natural archives and is often fragmentary and difficult to interpret. Palaeoenvironmental proxies are usually natural materials (e.g. pollen grains, minerals, microfossils), sedimentary structures (e.g. signatures of thermokarsts, debris-flows or landslides) or specific parameters of these materials and structures (e.g. reflectance, thermoluminescence, distribution of charred macrofossils) preserved in soils, sedimentary deposits or sedimentary rocks that have been affected or indirectly influenced by paleoenvironmental variables. Different proxies are differently tied to the target variable, and represent by definition a more or less rough approximation of the reality. This is particularly true for paleoecological proxies that are always influenced by a multitude of palaeoenvironmental variables. Getting an accurate picture of all

Table 1
Properties of the combustion continuum components.

	combustion continuum			
uncharred biomass	slightly charred biomass	charcoal	soot and graphitic black carbon	graphite
	combustion residues		condensates	
properties, characteristics or parameters	**typical value, range of values, and/or trend (shaded area)**			
size	mm and larger	cm to micron	micron to submicron	
formation temperature	<300 °C	200-600 °C	>500 °C	
recognizability of plant structures	wood structure	altered wood structure	graphite-like structure	
dominant shape		angular appearance	globular or spherical habit	
difficulties in defining the origin of the particles	plant species	plant family or even genus	combustion process	
chemical stability (inertia, reactivity)				
stability against thermal oxidation				
O/C ratio	0.6-0.4	0.4-0.2	<0.2	
H/C ratio	1.2-0.8	0.8-0.4	<0.4	
N concentration			?	
aromaticity of chemical structure, fraction of Aryl C				
bulk density	0.3-0.8 g/cm^3	0.1-0.6 g/cm^3	0.7-1.1 g/cm^3	
total surface area by nitrogen adsorption (BET method)	?	7-326 m^2/g	0.9-100 m^2/g	
total pore volume by mercury porosimetry	0.5 cm^3/g	0.7-4 cm^3/g	1.1 cm^3/g	
electrical resistivity	10^{16}-10^{2} Ω∗cm	10^{8}-10^{-1} Ω∗cm	10^{1}-10^{-3} Ω∗cm	
reflectance				
transport in suspension				
typical sedimentary distance from the source				
supposable residence time in intermediate sedimentary pools				

The wedge-shaped shading indicates growing or decreasing values of the variables (adapted from Hedges et al., 2000; Masiello, 2004; Hammes et al., 2007 and others).

processes affecting production, transport, settling, and filtering represents a real challenge (Giraud, 2006).

Many studies exploit the carbon-rich materials produced by fires (e.g. charcoal and soot), which can be described as part of a "combustion products continuum" (Table 1, see Supplementary Material for related bibliography) that reflects the multiplicity of combustion products which are often difficult to unambiguously recognize or distinguish in the environment (Goldberg, 1985; Schmidt and Noack, 2000; Hedges et al., 2000; Masiello, 2004). From a methodological point of view, every element of the combustion products continuum in every sedimentary situation may be used for reconstructing past fire regimes. Similarly, every individual or combined methodological approach has its own specific set of advantages and inconveniences in terms of information reliability, time span of reference, and temporal/spatial resolution of fires (Fig. 2).

There is, however, still a lack of agreement in terms of how to define fire-derived materials, the best choice of extraction procedures, and the recognition of the processes involved in their formation and sedimentation. Similarly, organizing the different proxies in a systematic way according to predefined categories is not always unambiguously possible. Fire proxies such as intact or altered products of plant combustion (fossil charcoals, charcoal remains, pyrochemical particles), partially combusted biological materials (fire scars, charred bones, charred plant macrofossils), or incombustible materials exhibiting heating evidences (fire cracked rocks, heating reactions in minerals, fire-induced surface weathering of stones) are usually considered direct indications of palaeofires (Tables 2 and 3 and Supplementary Material for related bibliography). Indirect fire proxies include sedimentary evidence of variations in ecosystem processes and phenomena deriving from deferred reactions to fire events or to changes in fire regime, such as

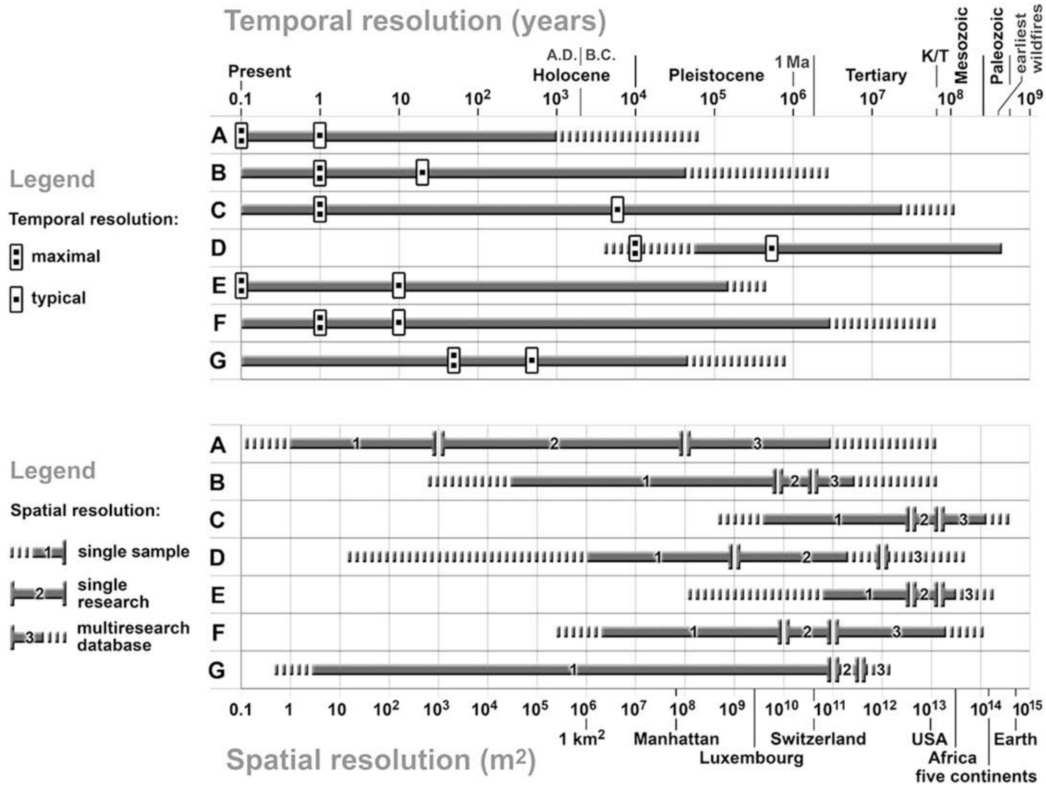

Fig. 2. Temporal and spatial resolution achievable with different approaches to fire history. A: dendrochronology and fire scars analysis; B: charcoal in lake sediments and peat bogs; C: charcoal and black carbon in marine sediments; D: fossil charcoal (fusain, fusinite) in sedimentary rocks; E: chemical markers and black carbon in ice cores; F: pollen-based fire history reconstruction; G: charcoal and black carbon analysis in soils. Solid bars indicate the most common range whereas dashed bars show the farthest extensions of the range. Modified from Delcourt and Delcourt (1991) and Swetnam et al. (1999).

variation in pollen and spore assemblages, fire-induced massive mortality of animal communities or increased erosion rates (Tables 2 and 4 and Supplementary Material for related bibliography). Other proxies reflect changes in broader environmental conditions due to fire, such as atmospheric oxygen concentrations or the palaeoclimate (Tables 2 and 5 and Supplementary Material for related bibliography).

In recent times, many methods using fire markers have been developed. Some fire markers may be considered second degree (secondary) proxies that trace the presence/absence or measure the amount of related primary fire proxies, such as charcoal or black carbon concentration (see also Table 6 and Supplementary Material for related bibliography). The use of secondary fire proxies is very frequent, although they offer a different, probably lower, level of diagnostic value than do primary proxies. With respect to measurements of the pyrogenic fraction of sediments, a wide array of methods exist, and one may obtain vastly different results depending on the extraction and detection method employed (Schmidt et al., 2001; Andreae and Gelencsér, 2006; Hammes et al., 2007). This makes the results of the innumerable fire history studies based on measurements of black carbon content of soils and sediments difficult to compare, not only because of the peculiarity of each environment but also because of the differences in the analytical procedures applied.

Proxy materials may also be subjected to a wide array of physical and biological processes that may alter or destroy their embedded information differently depending on the environment. The fidelity of the reconstruction of the desired environmental variables is highly dependent on having an accurate understanding and model of the proxy–fire relationship and the transport and filtering processes involved and on the method or combination of methods used for the analysis and interpretation (Swetnam et al., 1999; Birks and Birks, 2006).

Tables 3–6 represent a first attempt to provide an overview of existing proxies and methods for reconstructing past fire regimes, along with a few potential proxies, highlighting the complexity and complementarity of the different approaches. This compilation does not emphasize the stage of development, the effectiveness or the breadth of each approach. In the following discussion, we review in detail some of the most common approaches used for reconstructing past fire regimes and discuss their contributions and limitations to our understanding of the role of past fires.

2.3. Dendrochronology

The use of dendrochronology for reconstructing past fire events depends on the capacity of tree species to grow annual rings and to overgrow fire injuries (Swetnam et al., 1999). Although some authors consider tree scars too generic features to be unambiguously related to fire (Caldararo, 2002), there is now a general consensus to consider tree rings and especially leeward fire scarring (Gutsell and Johnson, 1996) as a useful direct proxy for reconstructing past fire events (Tables 2 and 3). Where robust tree ring chronologies exist, fire scars of single trees can be dated with annual precision by synchronizing their ring sequences with the reference chronology (cross-dating, Madany et al., 1982). If the position of the scar within the ring is visible, even the season and in certain cases the month of the event can be estimated (Baisan and Swetnam, 1990). By compiling fire scar records from numerous specimens collected throughout forest stands, it is then possible to reconstruct fire events with extremely high time resolution over periods of several centuries and to synchronize these records across multiple spatial scales (Swetnam et al., 1999; Morgan et al., 2001) (Fig. 3).

Fire scars are usually best recognised on full cross-sections. According to Dieterich and Swetnam (1984) single cross-sections may fail to record all fire events because of the patchy behavior of

Table 2
Explanation of the abbreviations used in Tables 3–5.

Abbreviation	Analysed material
Spatial domain of analysis	
unb	Unburied organisms
soi	Soils, regolith, buried soils, paleosols
arc	Archaeological sites
tuf	Tufa, travertine, speleothem, stalagmite
col	Colluvial deposits
pea	Peat deposits, mire sediments, small hollow sediments
aeo	Aeolian sediments
ter	Other or undifferentiated terrestrial sediments
var	Varved (laminated) lake, limnic sediments
unv	Unvarved (unlaminated) lake, limnic sediments
flu	Fluvial sediments, alluvial fan, alluvium, debris flows
mar	Marine sediments, coastal lagoons, tidal zone
roc	Sedimentary rocks
mix	Mixed approach
ice	Ice deposits, ice sheets, glaciers
sno	Snow, snow pits
etc	When more than five spatial domains of analysis

Abbreviation	Period	Years
Temporal domain of analysis		
VI	Historical period	0–2000 yr
V	Postglacial	2000–15,000 yr
IV	Quaternary	15,000 yr–2 Myr
III	Tertiary	2–65 Myr
II	Secondary (Mesozoic)	65–250 Myr
I	Primary (Paleozoic)	250–540 Myr

Abbreviation	Level of use
Level of use	
h	High: most used, most reliable, most typical or well-known fire proxy
m	Medium: rather used, quite typical or partly widespread fire proxy
l	Low: exceptional, hardly reliable, underestimated or neglected proxy

Abbreviation	Details	Category
Type of information on fire		
GloBioBu	Information on global biomass burning	Indirect information on fire occurrences
IndiConFi	Indirect confirm. of fires or changes in fire regime	
RecoFiEv	Recognition of fire events	When fire occurs
DataFiEv	Datation of fire events, time since last fire	
Frequenc	Frequency, return interval	
Seasonal	Seasonality	
SpatiDistr	Fire size, spatial distribution of fires	Where fire occurs
Intensity	Intensity, temperature range, duration of heating	Which fire occurs
FireType	Fire type, fire behavior, burned vegetation layer	
FireClima	Climatic conditions, fire weather	Conditions by which fire occurs
FireCause	Fire causes, ignition sources	
FuelType	Fuel type	
Severity	Severity, mortality	Consequences of fire
Ecology	Fire ecology, ecological impact of fire	
FiProCom	Identification of fire-prone communities	

forest fires. Gutsell and Johnson (1996) demonstrated that the airflow around the bole of very small tree does not form any leeward vortices, which may result in no fire scars. The most complete records of fire occurrence may be obtained by sampling numerous trees in close proximity to each other (Bergeron, 2000). Because of the limitations of taking complete cross-sections from living trees, alternative methods that provide satisfactory evidence of fire scars involve extracting partial cross-sections (wedges) or carefully sampling increment cores (Arno and Sneck, 1977; Sheppard et al., 1988). However, these methods are much more likely to miss fire damage than would cross-sections, especially if trees only sustained small and overhealed scars caused by low to medium fire-intensity (Lageard et al., 2000). In addition, cores are not the best method for dating multiple scars within a single tree, since it is rarely possible to sample more then one scar with a single core (Sheppard et al., 1988). Some authors try to avoid missing fire records by targeting individual trees showing multiple scars and long records of fire (Arno and Sneck, 1977) or by assessing Composite Fire Intervals (CFI, filtered or not) (Dieterich, 1980; Grissino-Mayer, 1995) calculated separately according to the fire-size category (Baker and Ehle, 2001, 2003). Problems with this approach may arise from the scale-dependence of most measures of the fire regime (Falk and Swetnam, 2003). Kou and Baker (2006) showed how factors such as sample area, frequency of small fires, scarring ratio, total number of sample trees, and number of scar samples may affect the precision of the calculated Composite Fire Interval. On the other hand, Swetnam and Baisan (2003) demonstrated that, at least for widespread or regional fires, applying a minimum filter on a set of few sample trees tends to stabilize the obtained fire frequencies. Another open question is the accuracy of methods using origin-to-scar (OS) intervals, i.e. the interval between the year of origin of the tree and the occurrence of the first fire scar. Contrary to Baker and Ehle (2003), Van Horne and Fulé (2006) do not consider the pit of a tree as a surrogate for fire occurrence. Table 7 summarizes the different palaeofire-regime descriptors and models that dendrochronologists recently developed around the basic concept of the fire return interval.

Among the major limitations to the fire scar approach is the fact that the methodology is confined to areas where trees are long-lived, remain alive and sound after being scarred or have timber resistant to decay after tree mortality. Dendrochronology can also rarely provide information on fire history in areas where the time since last fire exceeds the age of trees (Van Horne and Fulé, 2006). In regions where stand-replacing fires occur, only the youngest burn can be reconstructed by assessing the spatial distribution of age classes of post-fire forest stand renewal across the landscape (Niklasson and Granström, 2000). As a general consequence, the accuracy of fire history reconstruction fades with time (Swetnam and Brown, 1992). Exceptions to this include the use of subfossil woody material from peat bogs, mires, buried moss or buried soils that display fire scars in the cross section (Dechamps, 1984; Chambers et al., 1997). Unfortunately this approach has rarely been used, in spite of some very encouraging results (e.g. Arseneault and Sirois, 2004). Lageard et al. (2000) suggest alternative dendrochronological methods such as the use of increases in ring width as a complementary indicator of a fire event. According to the authors, positive growth-reactions can probably be related to nutrient release in the form of ash and to the burning away of competitors in the herb- and shrub-layers. Other authors, however, report growth reductions after fire (Brugger et al., 2007).

2.4. Charcoal analysis in lake sediments and peat bogs

Particulate charcoal is produced by the incomplete combustion of organic matter and therefore provides direct evidence of burning (Tables 2 and 3). Dispersal after fire and deposition in lake sediments or peat bogs allow the information to be preserved as a fossil charcoal assemblage that can be sampled and analysed for reconstructing fire history (Fig. 4). Since the pioneering work of Iversen (1941), analyses of fossil microscopic charcoal from terrestrial and lacustrine sediments have been widely used and represent a very powerful approach for reconstructing fire histories over time spans that fire scars cannot provide (Clark, 1988b; Whitlock et al., 2003a).

Table 3
Scientific approaches to fire history and past fire regimes using fire proxies related to combustion products, immediate signs of combustion, or direct heating effects.

kingdom	scientific field	specific approach, proxy, fire indicator, biomarker, marker	domain of analysis: spatial	temporal: I	II	III	IV	V	VI	use	GloBioBu	IndiConFi	RecoFiEv	DataFiEv	Frequenc	Seasonal	SpatiDistr	Intensity	FireType	FireClima	FireCause	FuelType	Severity	Ecology	FiProCom
plant and fungi	dendrochronology, wood anatomy	in unaltered and unburied ligneous material (fire-scars analysis)	unb						■	h		■	■	■	■	■	■	■	■	■	▪	■	■	▪	■
		in unaltered and unburied ligneous material (stand-age analysis and stand-origin maps)	unb						■	h		■	■	■	■		■	■	■		▪	▪	■	▪	■
		in buried ligneous material	pea					■	■	l		■	■	■	■	■		■	■			■			
		in subfossil fire-scarred trees	pea-soi-aeo					■	■	l		■	■	■	■	■									
		in fossil charred or uncharred woods, traumatic tissue and rings with growth interruption	roc-flu	■	■	■	■			l						■				■					
	anthracology, charcoal analysis	in varved (laminated) lacustrine sediments	var			▪	▪	■	■	h		■	■	■	■	■				■	▪	■			
		in non-varved lacustrine sediments	unv			▪	▪	■	■	h		■	■	■	■					■	▪	■			
		in small forest hollow sediments	peat					■	■	l		■	■	■	■					■	▪	■			
		in peat	pea					■	■	l		■	■	■	■		■			■	▪	■			
		in soils (pedoanthracology), paleosoils and loess-paleosol sequences	soi-aeo-flu				■	■	■	m		■	■	■	▪		■	■	▪	■	▪	■	▪		
		in fluvial sediments, alluvial fan and debris flows	flu				▪	■	■	l		■	▪	▪	▪		▪	■	■	■	▪	■	■	■	
		charcoal texture, morphology and morphotypes, length-to-width ratio	soi-flu-var-unv						■	l			■	■				■				■			
		charcoal size distribution analysis, charcoal mean surface area per sample	unv-mar				■	■	■	m							■	■							
		graminoid / non-graminoid microcharcoal, grass / total charcoal	soi-pea-var-unv				■	■	■	l		■						▪	■	▪	▪	■	■		■
	black carbon analysis in sediments	black carbon, fly-ash, spherical carbonaceous particles (SCPs) in ice	ice				▪	■	■	l	■	■	▪	▪		■									
		black carbon, soot in snow, snowpack and snow pits	sno						■	l			■	■		■									
		elemental carbon in loess-paleosol sequences	soi-aeo				■	■	■	l	■	■	▪	▪	▪			▪							
		black carbon in soils and buried soils	soi				▪	■	■	l		■	▪				■	▪			▪				
		black carbon, oxidation resistant elemental carbon (OREC), soot in marine sediments	mar			■	■	■	■	m	■	■	▪	▪	▪		▪								
		black carbon, thermal resistant carbon (TRC), elemental carbon in lake or swamp sediments	unv-pea				■	■	■	l		■	■	■	▪		▪								
		soot, elemental and black carbon in sedimentary rocks	roc		■	■				l	■	■	▪	▪				▪							
	palaeobotany of charred plant fossils	study of charred fungi remains and funginites	soi-arc-ter-roc		■	■	■	■	■	l		▪						▪	■			▪	▪		
		study of charred grass cuticles (area, fluxes, types, etc.)	unv-flu-mar-riv			■	■	■	■	l	■	■	▪	▪	▪			▪	■			■	▪		
		study of different charcoalified plant organs (stems, fruits, flowers, seeds, leaves,etc.)	tuf-flu-pea-roc-etc		■	▪	▪	■	■	l		■					■	■	■			■	■	■	■
		taxonomy of charred plant meso or macrofossils (recognition of plant taxa and communities)	flu-pea-roc-mar-etc		■	■	▪	■	■	m		■			▪	▪	▪	■	■	■		■	▪	■	■
		inclusion of particulate carbon in burned phytoliths, refractive index of siliceous phytoliths	soi-unv-arc-ter				■	■	■	m		■	■	■	▪	■	▪	■							
	coal petrology	analysis of coal, fusain fragments, inertinite, fossil charcoal	roc-flu-mar-ter-etc	■	■	■				h		■	■				■		■			■		■	
		comparison of the distribution of charred and uncharred plant fossils within the facies context	roc-flu-ter	■	■	▪	▪	▪		l		▪					▪	▪	■			■	▪	▪	■
		qualitative petrography, semifusinites / fusinites quantification, fusinite reflectance	roc-mar	■	■	▪				h								■							
	pyrochemical analysis	electrical conductivity method (ECM), ability of the ice to conduct current	ice				▪	■	■	l	■														
		chemical markers (levoglucosan, PAHs, BPCAs, light carboxylic acids, isotopes, etc.)	unv-mar-roc-ice-etc	■	■	■	■	■	■	h	■	■	■	■			■	■	■	■	■	■			▪
animal	vertebrate taphonomy	burnt fossil bones, direct fire-induced massive mortalities, study of burned skeletal deposits	roc-flu-unv-arc-ter	■	■	■	■	▪	▪	l				■			■	■	■				■	■	
mineral	thermochronometry, thermochronology	helium in apatite and zircon (Ur-Th/He), thermochronometric signals in detrital minerals	roc-soi	▪	■	■	■	■	■	l			■	■			■	■							
		fission-tracks in crystal structure due to the fission of uranium	roc-soi-arc	▪	■	■	■	■	■	l			■	■			■	■							
	radiometric dating	electron spin resonance (ESR dating)	roc-soi-arc-ter				■	■	■	l			■	■			■	■							
		thermoluminescence (TL), optically or infrared stimulated luminescence (OSL or IRSL)	arc-soi-unb				■	■	■	l			■	■			■	■							
	weathering or surface metamorphism	hematite formed as a secondary mineral in soil or rocks exposed to high intensity wildfires	roc	■	▪	▪	▪	▪	■	l		■	■				■	■							
		fire-cracked rocks, exploded or exfoliated boulders, thermolithofractography	arc-soi-unb	▪	▪	▪	▪	▪	■	l			■				■	■	■						
		black pebbles, fire-blackened pebbles, blackened limestone pebbles	roc-unv-mar	▪	■	■	■	■	■	l		■	▪		▪			▪	▪						

For every approach we present the typical spatial and temporal domain of analysis, the degree of diffusion and utilization in the scientific community, and the types of information on past fire regime achievable.

Table 4
Scientific approaches to fire history and past fire regimes using fire proxies related to indirect fire effects on sediment flux or post-fire reactions of organisms.

kingdom	scientific field	specific approach, proxy, fire indicator, biomarker, marker	domain of analysis: spatial	temporal						use	type of information on fire														
				I	II	III	IV	V	VI		GloBioBu	IndiConFi	RecoFiEv	DataFiEv	Frequenc	Seasonal	SpatiDistr	Intensity	FireType	FireClima	FireCause	FuelType	Severity	Ecology	FiProCom
plant and fungi	lichenometry	fire resetting of lichen clock, characteristics of lichen populations as bioindicators of fire history	unb						■	l				■			■	▪	▪					▪	
	palynology, paleomycology	analysis of pollen assemblages, presence of fire-tolerant species	unv-var-pea-roc-etc		■	■	■	■	■	h		■	▪		▪			▪	▪	▪	■	■	■	■	■
		percentage of grass pollen, AP/NAP, total arboreal pollen influx	var				■	■	■	l		▪			▪			▪	■			▪	■	▪	▪
		cultural or anthropogenic pollen indicator (API), pollen indicators of slash-and-burn cultivation	soi-flu-var-unv-pea					■	■	m						▪					■			▪	▪
		spores of pyrophilous and coprophilous fungi and other non-pollen palynomorphs (NPP)	pea-soi-aeo-arc-etc				▪	■	■	m		■	■						▪	▪			▪	▪	▪
	palaeobotany of uncharred plant fossils	uncharred plant macrofossils, permineralised plant macrofossils	flu-unv-roc-pea-soi	■	■	■	■	■	■	l		■	▪		■				▪			▪	■	■	■
		phytoliths assemblages (uncharred phytoliths)	roc-soi-flu-aeo-etc			■	▪	■	■	m		■	■		▪		■	▪	■			▪	▪	■	■
	phycology (chrysophytes, algae, diatoms, etc.)	water acidity (pH), lake-water pH, alkalinity pulses due to increased fire activity	unv					■	■	l		▪	■										▪	■	
		phosphorus concentrations (estimated as a function of diatom assemblages)	var					■	■	l		▪	■										▪	■	
		species assemblage and richness, diatom concentration, benthic to planktonic ratio	unv-var					■	■	l		■	■		▪					▪			■	■	■
		quantification of sedimentary pigments with high performance liquid chromatography	var-unv					▪	■	l		■	■		▪					▪			■	■	■
	study of peat profiles	initiation of peat formation, variation in peat and carbon accumulation rates, hiatus in profiles	pea				▪	■	■	l		■	▪		▪		▪	▪	▪			■	■	▪	
animal	palaeoentomology	fossil insect remains (Coleoptera, pyrophilous insects, etc.) in fire-related layers	pea			▪	▪	■	■	l		■	▪				▪		■			■	▪	■	■
		study of chironomid assemblages and stratigraphy (aquatic insects: Diptera, Chironomidae)	unv					■	■	l		■								■		▪		■	▪
	paleomalacology	biostratigraphy of fossil land snails and malacofaunas, decline of shade-demanding taxa	roc-arc-soi				▪	■	■	l		■							▪			▪		■	■
	vertebrate taphonomy	indirect fire-induced massive mortalities, unburned skeletal deposits	roc-flu-unv	■	■	▪	▪	■	■	l		■	■			▪		▪	▪				■	■	
	biosedimentology	bioturbation interruption due to increased sedimentation rate following fire events	roc-mar-flu	■	▪	▪	▪	▪	▪	l		▪	■										▪	■	
	biodiversity	present biodiversity revealing some characteristics of past fire regimes	unb						■	l		■							▪				▪	■	■
mineral (sediment flux)	periglacial sedimentology, cryostratigraphy, geocryology	fire-induced increases in avalanche activity	unb						■	l		■	▪	▪			■		■				■	■	
		fire-induced increases in gelifluction or solifluction activity	aeo-soi					■	■	l		■			▪			▪	▪			▪	▪	■	
		fire-induced permafrost dynamics (degradation or aggradation) and thermokarst features	pea-soi				▪	■	■	l		■	▪				▪	■	▪			▪	■	■	
		fire-induced shallow landslides in slopes underlain by permafrost	soi-col					▪	■	l		■	■					▪					■	▪	
	physical sedimentology	peaks in fire-related mass movement processes (debris-flows, mudslides, landslides, etc.)	roc-flu	■	■	▪	▪	■	■	m		■	■	■	■			▪	▪				■	■	
		geomorphic impact of fire (asymmetric hanging valley, asymmetric slopes, etc.)	roc-soi-col				▪	■	■	l					■		■	▪	▪				■	▪	
		sedimentation rates, fire-induced erosion and sedimentation episodes, varve thickness	var-flu	■	■	▪	▪	■	■	l		▪	■				■	▪	▪				■	▪	
		sediment granulometry, grain size, particle size distribution	unv-pea				▪	■	■	l		■	■				▪	▪		▪			■	▪	
		loss-on-ignition (LOI), imput of mineral sediment, organic / inorganic matter ratio	unv-roc-flu-pea	■	▪	▪	▪	■	■	l		■	■				▪	▪					■	▪	
		archaeomagnetism, magnetic measurements (magnetic susceptibility, etc.)	var-unv-soi-aeo				■	■	■	m	■	■	■	▪	▪		▪	▪					■	▪	
		wind erosion, aeolian sedimentation, dune activity, datation of mobilization (OSL on quartz)	aeo-soi-pea-unv					■	■	l		■	■	■			▪	▪	▪				■	■	
		^{14}C dating anomalies caused by erosion after fire events	unv				▪	■	■	l		■	■				▪	▪					■		
	chemical sedimentology, geochemistry	silicon and titanium in peat profiles as indicators of erosion	pea				▪	■	■	l		■	■				▪	▪					▪		
		changes in total organic carbon (TOC) assessed by near infrared spectroscopy	var-unv					■	■	l		■	▪		▪		▪	▪		▪		▪	▪	■	
		substances indicating the amount of rock-forming material washing into the lake	pea-var-unv				▪	■	■	l		■	▪		▪		▪	▪					■	▪	

For every approach we present the typical spatial and temporal domain of analysis, the degree of diffusion and utilization in the scientific community, and the types of information on past fire regime achievable.

Table 5
Scientific approaches to fire history and past fire regimes using fire proxies related to conditions influencing fire events.

	scientific field	specific approach, proxy, fire indicator, biomarker, marker	domain of analysis: spatial	temporal: I	II	III	IV	V	VI	use	GloBioBu	IndiConFi	RecoFiEv	DataFiEv	Frequenc	Seasonal	SpatiDistr	Intensity	FireType	FireClima	FireCause	FuelType	Severity	Ecology	FiProCom
conditions for fire events	atmospheric paleochemistry	models of O_2 levels in the Late Paleozoic (fluctuations in atmospheric oxygen concentration)	roc-mar	■	■	■	▪			m	■	■			▪			▪			▪			▪	
	palaeoclimatology	reconstruction of past climate changes with specific climate proxies ($\delta^{18}O$, testate amoebae, peat humification, pollen, glacier termini, aragonite precipitation, quartz accumulation, etc.)	var-unv-ter-pea-mar	■	■	■	■	■	■	m	■	■			▪	■		▪		■	▪	▪		▪	
	lightning activity	lightning strikes on petrified trees, analysis of petrified fulgurites, plant cytoplasm preserved by lightning	roc-mar-unv-flu soi-ter-aeo	■	■	▪	■	■	■	l										▪	■				
	environmental archaeology	economic history of populations, study of the technical and cultural phases (conquest of fire, neolithic revolution, slash and burn methods,...)	arc-soi-flu-aeo-unv				■	■	■	l											■			▪	

For every approach we present the typical spatial and temporal domain of analysis, the degree of diffusion and utilization in the scientific community, and the types of information on past fire regime achievable.

Table 6
Chemical substances used as chemical markers and fire proxies in fire history reconstruction.

Chemical group	Chemical species (or subgroup)
Monosaccharide anhydrides	Levoglucosan, galactosan, mannosan
Lignin phenols	Vanillin, vanillic acid, syringyl aldehyde, syringic acid, etc.
Resin acids and derivatives	Dehydroabietic acid, methyl dehydroabietate, etc.
Phytosterols	β-Sitosterol
Triterpenoids	α-Amyrone and β-amyrone
Polycyclic aromatic hydrocarbons	PAHs, retene, pyrene, fluoranthene, coronene, benzo[*e*]pyrene, etc.
Fullerenes	C_{60} and C_{70}
Dibenzofurans	PCDDs (dioxins)
	PCDFs (furans)
Heterocyclic nitrogen compounds	Pyrrole-type molecules
	Pyridine-type molecules
Heavy carboxylic acids	Benzenepolycarboxylic acids (BPCAs)
Light carboxylic acids	Oxalic acid, oxalate, glycolic acid, glycolate, etc.
Simple ions	Cation ammonium (NH_4^+), anion formate (HCO_2^-), anion sulfate (SO_4^{2-}), etc.
Atomic substances	Potassium
	Boron and its isotopes
	Nitrogen
	Radiocarbon C^{14} for source identification (apportionment)
	Radiocarbon C^{14} for age determination
	Stable carbon isotopes ($\delta^{13}C$, C_3/C_4 forest/prairie vegetation)
	Stable oxygen isotopes (^{17}O, ^{18}O)

According to Tolonen (1983) fire history from peat is generally less powerful than that from lake sediments. In mires and bogs only local fires may leave detectable carbon horizons, and often only where the drier margins of the peat have burned. In addition, mires and bogs may burn during dry periods, leading to a substantial loss of information. Nevertheless peat sequences may provide very helpful insights where lacustrine sequences are lacking.

The main problems that the sedimentary approach still has to face are the lack of standardization of methods (sample preparation techniques, charcoal identification, methods of charcoal quantification, and sample calibration, see the reviews in Patterson et al., 1987; MacDonald et al., 1991; Novakov et al., 1997; Rhodes, 1998; Whitlock and Larsen, 2001) and limitations to the degree of spatial, temporal and event resolution that it can provide (Carcaillet et al., 2001; Whitlock and Larsen, 2001). Charcoal analysts have developed techniques to tackle these problems that vary in their approaches to site selection, laboratory techniques and statistical analyses (see below).

Charcoal may have local (within the watershed), extra-local (just outside the watershed), regional (distant), continental or even global origin depending on release (e.g. particle size), transport (e.g. air convection) and deposition (e.g. basin size) conditions. Patterson et al. (1987) suggested that the most useful records for reconstructing local fires are small lakes and forest clearings. According to Patterson et al. (1987) and Clark et al. (1998), charcoal particle size distribution may be used to help determine the distance of the source; large particles are likely to indicate a nearby source. Generally, it is assumed that microscopic charcoal (or microcharcoal) particles (ca 10–200 μm length) may be windborne over long distances from the deposition site and therefore mostly reflect regional fire history (Clark, 1988b; Clark and Royall, 1995; Tinner et al., 1998; Blackford, 2000). On the contrary, macrocharcoal particles (ca >100–200 μm length) are usually not transported far from fires, and are likely suitable for reconstructing local fire events (Clark, 1988b; Clark and Royall, 1995; Carcaillet et al., 2001; Whitlock and Larsen, 2001). This assumption is based on calibration studies (e.g. Clark, 1989, 1990; MacDonald et al., 1991; Millspaugh

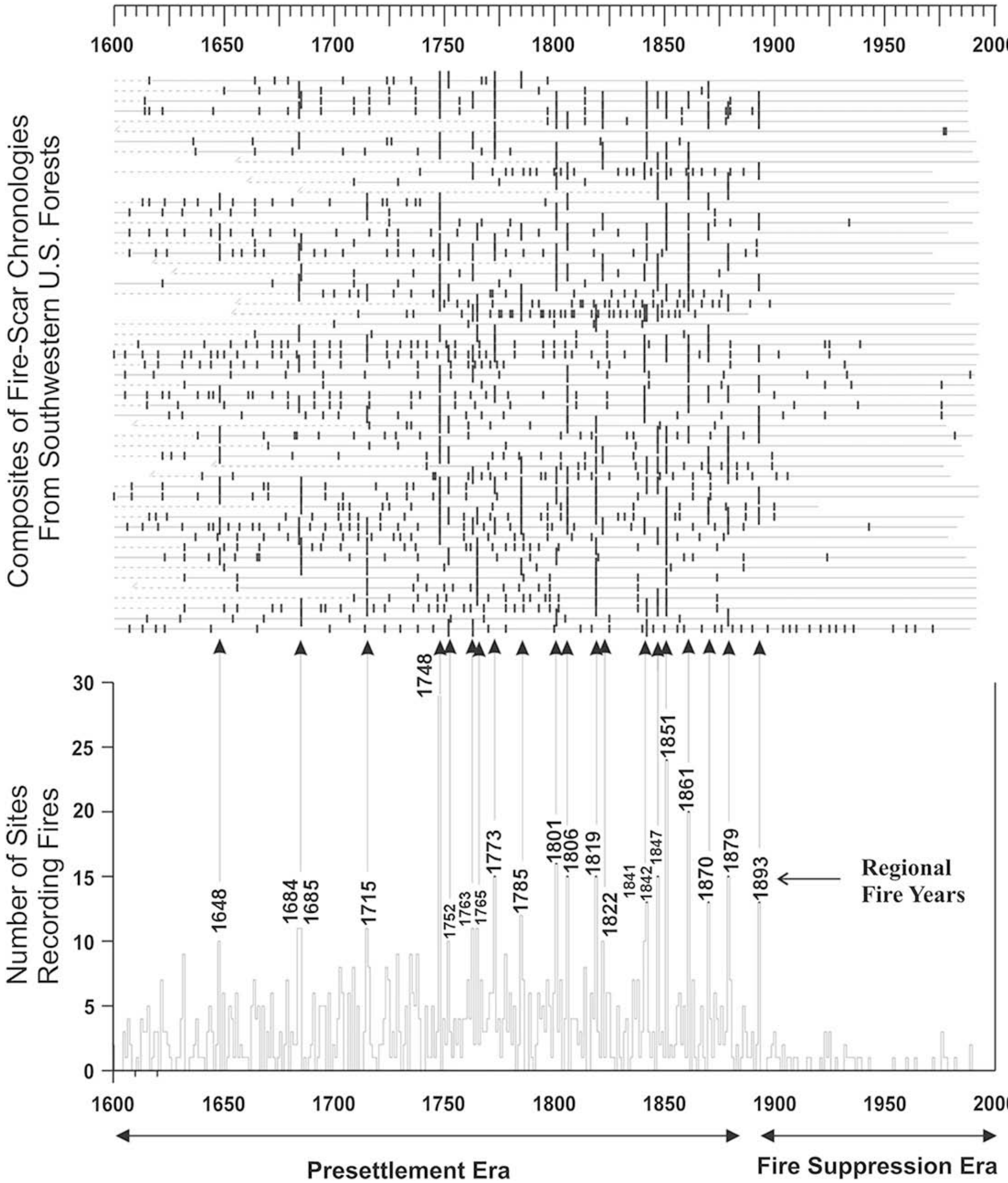

Fig. 3. Composite fire scar chronologies from 55 forest and woodland sites in Arizona, New Mexico, and northern Mexico (AD 1600–present) (source: Swetnam et al., 1999). In the upper chart, each horizontal line represents the composite fire chronology from a different site, and the tick marks are the fire dates recorded by 10% fire-scarred trees within that site. The long tick marks are fire dates recorded by 10 sites in the southwestern network. Most of the sites were in ponderosa pine or mixed conifer forests, and the sampled areas typically ranged from 10 to 100 ha, although a few sites exceeded 1000 ha. The average number of trees sampled per site was 20, with a maximum of 56 trees. Labelled (a, b, c) fire chronologies refer to specific local fire patterns. The line graph on the bottom shows the total number of sites recording fire dates each year. The years labelled with arrows were regional fire dates, i.e., fires occurred in 10 sites across the network. For more details see the original text in Swetnam et al. (1999).

and Whitlock, 1995; Tinner et al., 1998; Pitkänen et al., 1999; Mooney and Maltby, 2006) comparing charcoal data with unambiguously documented fires (Fig. 5). These calibration studies provide the empirical evidence for a local origin of macroscopic charcoal (mostly deriving from within a few hundred metres) and a regional origin of microscopic charcoal (mostly deriving from within 20–100 km). Recent field observations, however, highlighted that severe convection and vortices associated with high-intensity crown fires might be able to carry a considerable amount of centimetre-sized charred particles for several kilometres (Pisaric, 2002; Tinner et al., 2006a). A recent modelling approach performed by Peters and Higuera (2007) is in agreement with these observations and demonstrated that the variability in sediment charcoal records can largely be explained by the fundamental characteristics of charcoal release, transport and deposition. In particular, the pattern of charcoal deposition depends on the ratio between the potential charcoal source area (PCSA) and fire size on one hand, and on the absolute size and the location of the fire within the PCSA on the other hand.

Timing of the charcoal (and macrocharcoal in particular) deposition may greatly vary according to weather, geomorphological features of the area, season of the fire, combustion, and woody species involved. Sediment characteristics may even differ within a coring site (Edwards and Whittington, 2000). In certain cases, deposition does not occur during or shortly after the fire (primary charcoal, arrows with broken lines in Fig. 4) but may occur over many years following the event (secondary charcoal, arrows with dotted lines in Fig. 4), depending on the runoff, transport and

Table 7
Selected examples of fire-regime descriptors used in dendrochronology (see Supplementary Material for related bibliography).

Basic parameter sub-parameters	Acronym	Definitions
Mean fire interval	MFI	Average number of years between successive fires in a given area over a given time period
Point mean fire interval	PMFI	Calculated on fire data recorded on an individual tree
Composite mean fire interval	CMFI	Calculated on the complete record of fire dates in an area
Filtered composite mean fire interval	FMFI	Calculated on the filtered record of fire dates in an area (including only fire dates that that occur on a percentage greater than a defined threshold)
Average interval between major fires		Mean fire interval between selected or filtered fire dates
Mean fire occurrence period	MFOP	Total length of the period of time considered divided by the number of fire events in the composite fire scar chronology
Weibull median probability interval	WMPI	Fire interval at which there is a 50% probability of longer (or shorter) fire intervals occurring, based on the fitting of a Weibull-type curve (model) to the fire interval distributions
95% and 5% Exceedance intervals		Fire intervals delimiting significantly short or long intervals identified by calculating the theoretical fire interval associated with the .95 and .05 exceedance probability levels
Maximum hazard fire interval	MaxHI	Time in years at which the 100% probability level is reached in the Weibull distribution, representing the maximum fire-free period possible in the modeled distribution
Origin-to-scar interval	OS	Interval between the year of origin of the tree and the occurrence of the first fire scar
(Natural) fire rotation	FR	Average number of years required (in nature) to burn-over an area equivalent to the study area
Fire cycle	FC	Number of years required to burn-over the total area (expressed as negative exponential distribution)

drainage patterns of the watershed. This may result from charcoal release from burned logs, secondary re-suspension and redeposition of charcoal particles inside the lake as well as sediment remixing and sediment focussing (Whitlock and Millspaugh, 1996; Edwards and Whittington, 2000; Whitlock and Anderson, 2003). Recent systematic radiometric studies unambiguously document that macrocharcoal sedimentation may be severely affected by reworking (Oswald et al., 2005).

Appropriate sampling, analytical and interpretation methods and techniques must be used to gain reliable data and information. For instance, thin section and sieving techniques have proven to be a good proxy for local fire history reconstruction (Tinner et al., 1998). However, thin sections are an expensive and time-consuming approach, whereas the sieving method is much more convenient but still needs to be standardised (e.g. minimum sieving mesh diameter for excluding charcoal from distant fires, minimum

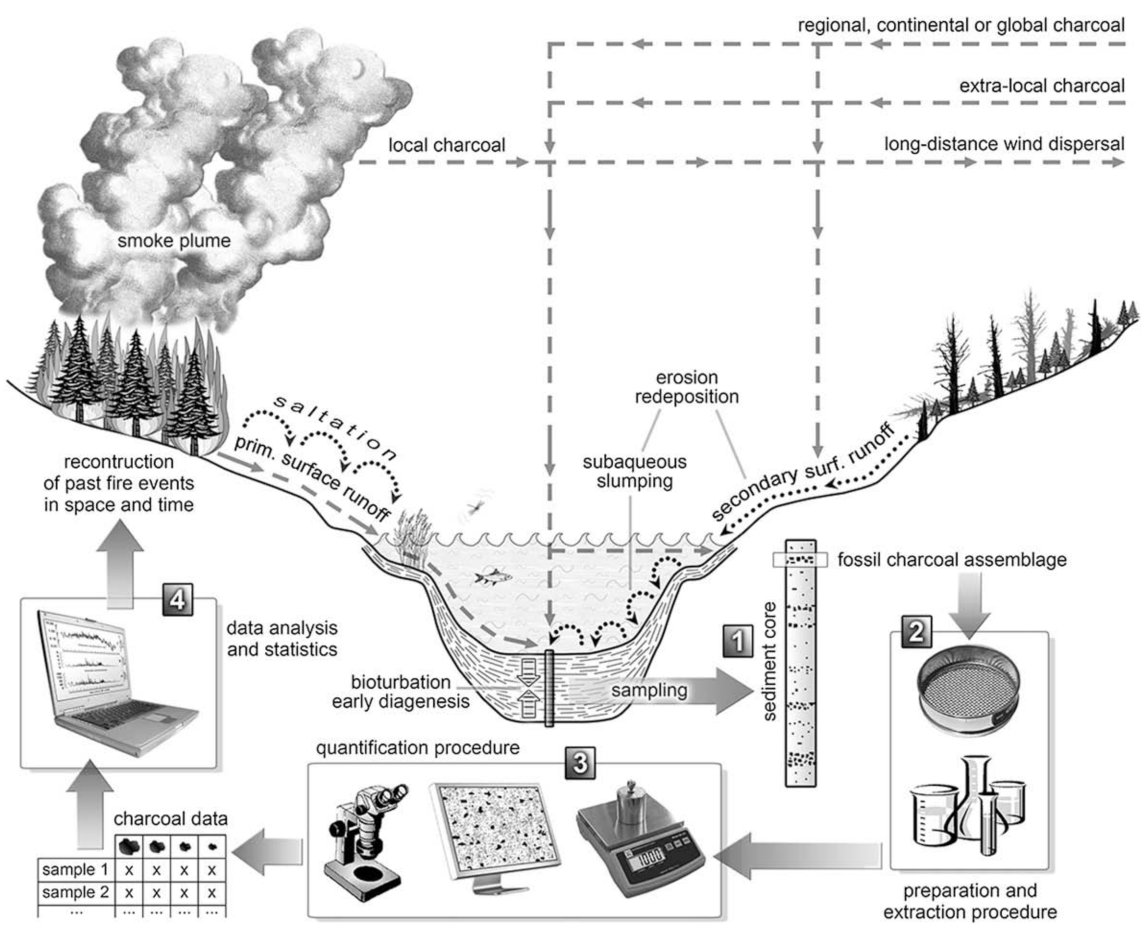

Fig. 4. Reconstructing fire history from lake sediments. In the upper part: charcoal production, transport and deposition in lacustrine sediments (including taphonomy); In the lower part: paleofire-regime reconstruction by [1] charcoal collection (sampling techniques and procedures), [2] preparation and extraction of the sediment fraction of interest using physical (sieving, filtering, washing, etc.) or chemical processes (oxidation, digestion, etc.), [3] quantification and characterization of the pyrogenic fraction (manual counting, automatic counting, weight measurements, spectrometry, chromatography, NMR spectroscopy, thermogravimetry, differential scanning calorimetry, scanning electron microscopy, etc.), [4] analysis and processing of the data. Modified from Patterson et al. (1987), Whitlock and Larsen (2001), and Whitlock and Anderson (2003).

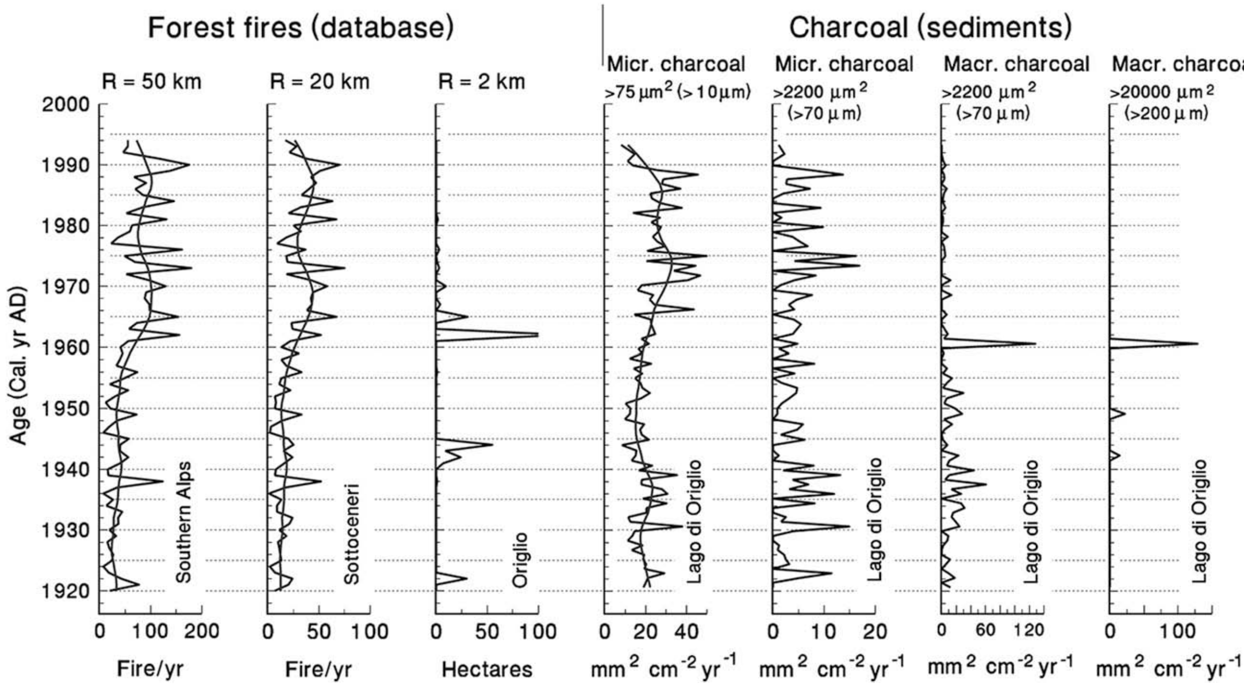

Fig. 5. Yearly number of fires at different radii from a paleoecological study site (Lago di Origlio, southern Switzerland). The number of fires is compared with microscopic (pollen-slides method) and macroscopic (thin sections method) charcoal influx. Regional fire frequency ($R = 20$ and 50 km) is correlated with microscopic charcoal and the local fire frequency ($R = 2$ km) with macroscopic charcoal influx. Note the complete absence of particles >20,000 μm^2 (>200 μm) in the (pollen-slide) microscopic charcoal record. This absence is explained by physical treatment of the pollen samples (e.g. decanting, sieving, see Tinner and Hu, 2003), which would have destroyed these large particles. Pollen laboratory procedures may also explain the much lower influx values of charcoal >2200 μm^2 (>70 μm), if compared with the influx of charcoal >2200 μm^2 (>70 μm) according to the thin-section method (source: Tinner et al., 1998).

sample size for assuring replicable data, criteria for discriminating single fire events; Clark, 1988b; Carcaillet et al., 2001; Tinner et al., 2006b; Black and Mooney, 2005). Yearly charcoal data may be obtained in annually laminated (varved) sediments. In unvarved sediments, variations in sedimentation rates and radiocarbon-dating errors make it difficult to reach such precision (Olsson, 1986; Oldfield et al., 1997). Independent of resolution, macrocharcoal records should be sampled contiguously, typically at least every 1 cm, corresponding to deposition times of 10–30 yr or less. Usually, 2 cm^3 is the minimum sampling volume. Most analysts prefer to measure areas or count the number of particles >100–200 μm. Using areas instead of numbers influx values has the advantage that larger particles (which have a higher likelihood to derive from local fires) are more heavily weighted. Macrocharcoal series may be affected by reworked (i.e. older) charcoal. According to Vannière et al. (2003), problems related to reworked charcoal may be partially mitigated by detailed surface observations and shape measurements of the dark remains under reflected light (LR). Regular shaped and non-porous particles (ratio length/width around 1) usually originate from post-depositional fragmentation and contain a fire signal inherited from soil erosion, whereas elongated and porous particles which have been immediately deposited appear as an unambiguous signature of a fire event. Recently, Enache and Cumming (2007) showed the potential of morphological studies of macroscopic charcoal particles, demonstrating that some macroscopic charcoal morphotypes associated with secondary transport to the sediments seem to be less suitable for the reconstruction of past fire activity. Furthermore, it is difficult to define events in areas where fire return intervals are short, especially if the studied basin has low sedimentation rates, when sampling is not annual or contiguous (Swain, 1973; Patterson et al., 1987) or where fire intervals are shorter than sampling resolution.

Microcharcoal series used to reconstruct regional fire history are usually obtained by analysing pollen slides. Pollen slides are prepared according to (time-consuming) standard palynological techniques (see e.g. Moore et al., 1991), which include several chemical and physical procedures. For instance, sediment samples are usually sieved using mesh-widths between 200 and 500 μm in order to extract large particles (e.g. sand, wood pieces) which would prevent careful pollen determination. Thus, charcoal particles, which exceed the mesh-width size (e.g. >200 μm), are completely missing from the microscopic charcoal series (Tinner and Hu, 2003). Only microcharcoal particles that appear under a normal light microscope as black and completely opaque, angular fragments with sharp edges should be considered (Clark, 1988b; Moss and Kershaw, 2000; Hope et al., 2004). Most (pollen-slide) analysts measure the areas or count the number of charcoal particles ca >10 μm. Besides the practical aspects of correct charcoal identification, setting this minimum size also means that smaller charcoal particles that may have been transported from extra-regional sources are excluded from analysis. Recent systematic quantitative analyses show that there is little value in quantification of size-classes or estimation and measurement of areas (e.g. point-count estimation following Clark, 1982; image analysis) of charcoal particles in pollen-slides (Tinner et al., 1998; Tinner and Hu, 2003). Counts of particle numbers are sufficient, given that the pollen-slide method heavily affects the original size distribution of charcoal. In particular, the systematic elimination of large charcoal particles makes it very hard to derive information about local fires from standard pollen-slide charcoal. Charcoal influx number values (i.e. particles cm^{-2} yr^{-1}) can be obtained by using ordinary pollen techniques (e.g. by determining charcoal concentrations with the aid of samples spiked with marker grains like *Lycopodium* spores, see Maher, 1981; Moore et al., 1991). Recent quantitative studies showed that counting 200 items (i.e. charcoal particles and *Lycopodium* spores) is sufficient to provide reliable concentration estimates (Finsinger and Tinner, 2005). Investigating past regional fire incidence using microscopic pollen-slide charcoal records requires contiguous sampling (e.g. every cm, corresponding to deposition times of 10–30 yr or less). Due to the intense laboratory requirements of the method, however, most (pollen-slide) microcharcoal records do not fulfil this prerequisite, showing gaps >1 cm (usually up to 10–50 cm) between adjacent samples. Such big gaps make it impossible to estimate past regional fire frequencies; nevertheless, fragmentary records may be used to gain insight into long-lasting fire-regime trends (e.g. higher levels of fire activity after Neolithization in Europe).

Very small particles <10 μm may be analysed via rapid quantification of surface area of microcharcoals in sediment slides using an automated light microscope coupled with a digital camera sensor (Beaufort et al., 2003; Daniau et al., 2004, 2006, 2007; Thevenon et al., 2004). Every pixel represents about 0.2 × 0.2 μm (see also Beaufort and Dollfus, 2004), approaching the best resolution obtainable with an optical microscope. This allows the quantification of very fine dark particles. However, as finer and finer particles are quantified, the risk of including elements that do not derive from vegetation fires, such as opaque minerals (Daniau et al., 2006) or soot particles deriving from coal (Valdés et al., 2004), increases. Daniau et al. (2004, 2007) verified the pyrogenic nature of such fine particles by micropetrographic analysis, and Thevenon et al. (2003b) found good correspondence between ultra-fine (0.2–1 μm) and coarse (>150 μm) charcoal curves in Lake Masoko sediments. These studies suggest that such analyses of the finest particles may be useful in some environments, particularly when combined with independent confirmation of the pyrogenic origin of the particles.

Different approaches have been suggested to solve the problem of fire-event identification (Clark, 1988a). In macrocharcoal series, peaks (representing fire events) and the background component (representing several factors such as regional fire activity, changes in the fuel load in the area and/or in secondary charcoal delivery) may be separated using statistical methods. Smoothing techniques (e.g. LOWESS, weighted average functions) are used to distinguish between peak (i.e. the residuals) and background (i.e. values below the smoothing function) influx values. The smoothed background is then subtracted from the raw data to derive residual peaks. The examination of the statistical distribution of residuals can be used to estimate the proportion of peak accumulation values above a threshold value P (see e.g. Lynch et al., 2002), and sensitivity analyses can be used to identify how the proportion of peak accumulation rates changes with P. This analysis is used to identify an intermediate range of charcoal influx between background and the largest peak values (Clark et al., 1996; Lynch et al., 2002), and thus to allow a more conservative identification of past fire events. The past fire frequency is estimated by comparing the number of fire events with the age of a record (e.g. 10 fires/1000 yr). Other important parameters are the fire return interval, which is the time between two adjacent events, and the mean fire return interval (MFI) within a period, which is the average of all fire return intervals of that period. These calculations can be made with ordinary statistical programs or with the aid of specific programs which are available on-line (CHARSTER; CharAnalysis). Microscopic charcoal series (in the best case: charcoal influx values) must not be treated in this way. All calibration studies showed that peaks of microcharcoal correspond to high regional fire frequencies (or large burned areas), whereas troughs are mirroring low regional fire frequencies (or small burned areas). This makes it clear why smoothing and residual peak identification is not applicable for regional fire reconstruction.

Concerning the reliability problems of the charcoal-analysis methods, the existing comparative studies between methods indicate some difficulties in reconstructing similar fire histories based on charcoal time-series from the same sediment core using different methods (MacDonald et al., 1991; Clark et al., 1998; Pitkänen, 2000; Carcaillet et al., 2001). Edwards and Whittington (2000) used multiple profiles covering many thousands of years from Black Loch (Fife, eastern Scotland) to test variability within a coring site and found that different profiles yielded similar patterns of charcoal deposition (same qualitative outcome of fire history) but different numerical values (different quantitative results).

Finally, pollen records in lake sediments may also be used to complement reconstructions from charcoal data, highlighting changes in the surrounding vegetation as a possible consequence of fires (MacDonald et al., 1991; Whitlock and Larsen, 2001; Tables 2 and 4). Swain (1973) suggested the use of indicators such as the ratio of charcoal influx to pollen influx or the ratio of coniferous to resprouter pollen for detecting peaks due to fire events (when the charcoal influx increases and the pollen source is reduced) or an advance in the vegetation towards resprouters as a consequence of a forest fire. For the conditions in Scandinavia, declines in the influx of large and heavy pollen of dominant species such as spruce (*Picea abies*) coincide with charcoal peaks as indicators of local fires (Tolonen, 1978; Pitkänen and Huttunen, 1999; Pitkänen, 2000). Gobet et al. (2003) found significant positive correlations between fire-favoured plants (e.g. green alder, *Alnus viridis* and fireweed, *Epilobium*) and the microscopic charcoal influx in high-resolution sequences from the Alps. Significant correlations between green alder, fireweed and microscopic charcoal were also found at Grizzly Lake in Alaska (Tinner et al., 2006b, Fig. 6). Sugita et al. (1997) suggested the use of quantitative pollen models to estimate fire size and proximity based on the analysis and simulation of pollen changes within the pollen source area. However, fire reconstruction should never be based on pollen or vegetation reconstructions alone, since many other ecosystem disturbances (e.g. windthrow, avalanches, landslides, clear-cutting) can lead to a vegetational signal that may be confused with fire impact.

2.5. Black carbon analysis in marine sediments

The ocean floors preserve very long sequences of sediments that may contain a vast amount of different information on past fire activity (e.g. Goldberg, 1985; Herring, 1985; Daniau et al., 2006, 2007). Combustion residues found in marine sediments are generally termed "black carbon" (BC) and may contain both charcoal (and char), the solid residues of combustion, and soot, combustion condensates (Masiello, 2004). As a rule these are fire proxies derived from materials delivered to sediments by long-distance transport processes such as rivers, winds and ocean currents, often involving numerous erosion–redeposition cycles and long storage periods in intermediate terrestrial or marine deposits (Kuhlbusch, 1998; Gélinas et al., 2001; Tables 2 and 3, and Fig. 2). Moreover, very fine BC particles could spend a long time within the operationally defined oceanic dissolved organic carbon (DOC) pool (Mannino and Harvey, 2004). Consequently BC in some sediments has been observed to be up to 14,000 yr older than the organic carbon of the same sedimentary horizon (Masiello and Druffel, 1998).

The temporal and spatial resolution in marine sediments is generally too coarse to permit the identification of single fire events or precise definition of the place of fire occurrence. It is therefore assumed that proxies in offshore sediment may yield indirect evidence of the biomass burning activities in a wide geographic area. In the case of deep ocean sediments we may even find proxy information for "global biomass burning", that is, for fire activity at the geographic scales of wide parts of continents, entire ocean basins or even of the whole planet (Verardo and Ruddiman, 1996; Suman et al., 1997). Fire proxies from marine sediments, and especially from relatively undisturbed deep-sea sediments, are thus

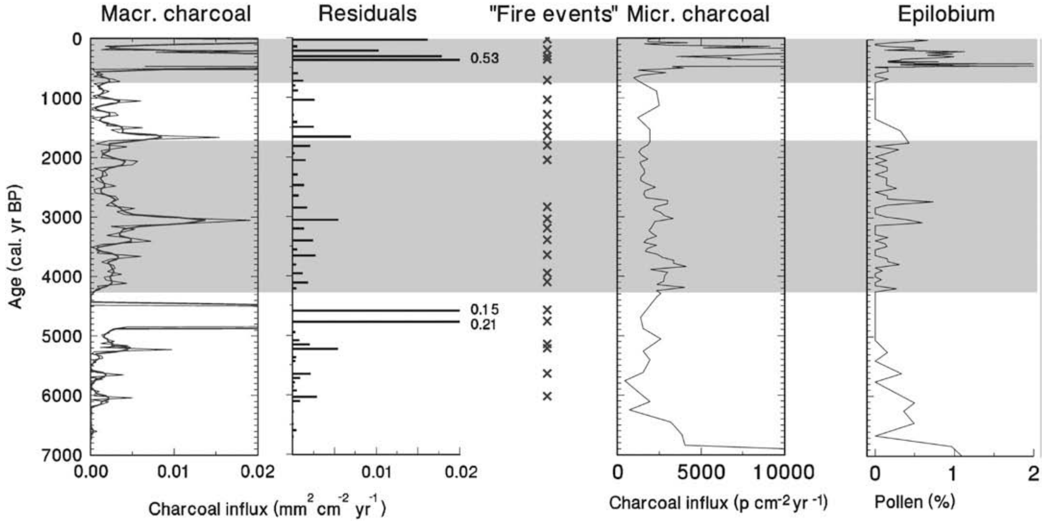

Fig. 6. Macroscopic charcoal influx (sieving technique) and residual peaks (×) used for MFI estimation compared with microscopic charcoal influx (pollen-slide method) and pollen percentage of *Epilobium* (fireweed) at Grizzly Lake, Copper River Basin, Alaska. Note the correlation between reconstructed regional fire frequencies (microscopic charcoal) and the abundance of *Epilobium* (fireweed), suggesting similar spatial provenances of microscopic charcoal and pollen. Interestingly, there is no evidence of local fires in the macroscopic charcoal record for the period 7000–6000 cal. BP, though the microscopic charcoal and the pollen record suggest increased regional fire frequencies and considerable post-fire responses of vegetation (e.g. high abundances of fire-favoured *Epilobium*) (for further methodological details see Tinner et al., 2006b).

precious indicators of global biomass burning for wide spatial and temporal units (Bird and Cali, 1998; Goldberg, 1985).

BC analytical methods, used for marine sediments as well as soils and other matrices, generally define BC operationally as the fraction of carbon resistant to chemical, thermal, or photo-oxidative oxidation, with or without other chemical or physical treatments (Schmidt and Noack, 2000; Masiello, 2004). They hold the promise of determining the amount of pyrogenic carbon present, something not generally determined from microscopic methods, ideally more rapidly than charcoal counting and with the possibility to analyze smaller particles than are routinely measured microscopically. These methods could also be used to isolate a fraction of combustion-derived carbon which can be further analysed for isotopic and spectroscopic properties (e.g. Dickens et al., 2004b; Haberstroh et al., 2006; Masiello and Druffel, 1998; Reddy et al., 2002), yielding further characterization of the fuel and combustion conditions. However, this field has been plagued by methodological issues, and the achievement of this potential remains distant. For instance, the necessary reliance on operational definitions has made it difficult to be entirely certain what a given method is measuring and has led in response to the creation of a vast array of BC analytical methods, all of which have their weaknesses and all of which yield a different quantification of the black carbon content (Schmidt et al., 2001; Currie et al., 2002; Hammes et al., 2007). This can be caused by including non-pyrogenic organic matter (Gélinas et al., 2001; Simpson and Hatcher, 2004) or fossil fuel-derived particles (Brodowski et al., 2005a; Stoffyn-Egli et al., 1997) (overestimation), by losing pyrogenic particles during chemical and physical manipulations (underestimation; Elmquist et al., 2004), or simply by measuring a different fraction of the BC continuum (Hammes et al., 2007). Similarly, problems exist in discriminating petrogenic from pyrogenic particles, especially in case of highly condensed graphitic particles (Dickens et al., 2004a; Haberstroh et al., 2006).

Application of the palynological methods of charcoal analysis commonly applied to lake sediments within the ocean presents its own set of challenges and problems. Most noteably, the common approach of counting only particles larger than 5–10 μm (as described above) effectively eliminates the vast majority of the fine pyrogenic particles likely to make their way to open-ocean sediments. This point may be especially crucial when focussing on global processes, as calibration studies suggest that particles <5–10 μm primarily originate from global sources (see Moore, 1989). However, some authors studying only the fraction over 5–10 μm have obtained interesting charcoal profiles from deep-sea cores (more that 1000 m water depth and 100 km offshore), although these sites may still have received some influence from the continent (Sun and Li, 1999; Wang et al., 1999; Sun et al., 2000; Luo et al., 2001; Van der Kaars and De Deckker, 2002; Daniau et al., 2007).

Efforts to determine the sources and movement of BC in marine environments are further complicated by the complexity of transport and sedimentation processes. Sediment fluxes to the seafloor range dramatically over both time and space, making it difficult to compare sediments from different environments, or even different horizons from the same core. This is especially the case near the coasts (Freitas et al., 2003), particularly near river outlets (Sommerfield et al., 2002) and along the continental margin owing to the instability of continental slope sediments (Lewis et al., 2004). Over long time scales, even the abyssal plains are subject to important changes in the origin and intensity of sedimentary fluxes in response to perturbations such as changes in ocean circulation (Fairbanks, 1989; Kuijpers et al., 2003; Su and Wei, 2005). Such changes in sedimentation will affect the distribution of BC in the ocean and suggest the importance of constraining bulk sedimentary parameters in conjunction with analysis of BC itself. Similarly, comparison of different aspects of sedimentary BC content itself, such as concentration relative to total sedimentary mass, may prove instructive in interpreting the origin of trends in BC concentrations (e.g. Dickens et al., 2004a).

A further uncertainty in using marine sedimentary records for tracing biomass burning is that post-depositional oxidation may slowly overcome the supposed inertness of black carbon, differently degrading the various black carbon fractions (Middelburg et al., 1999; Masiello and Druffel, 2003; Brodowski et al., 2005a; Wakeham and Canuel, 2006). Sedimentary organic carbon (SOC) oxidation is apparently driven by the residence time in the top, oxic layer of sediments and by the availability of oxygen in sediment porewaters (Middelburg et al., 1999; Hartnett et al., 1998; Hedges et al., 1999). A number of recent studies suggest that BC is also subject to such oxidative degradation (Forbes et al., 2006; Czimczik and Masiello, 2007), implying that oxygen exposure in sediments is also likely to affect sedimentary BC. The differentiated degradation in time and space of SOC should be considered when using it as reference quantity to establish BC content (Masiello and Druffel, 1998; Jia et al., 2002; Masiello, 2004), even if assuming BC to be absolutely indestructible.

These many difficulties may explain existing flagrant disagreements between BC profiles from different studies covering roughly the same spatio-temporal frame, such as the results from Bird and Cali (1998) which differ dramatically from those of Verardo and Ruddiman (1996). However, a number of studies display converging results that also agree with other fire parameters, mostly in continentally influenced sites. For example, the coastal marine profile of Mensing et al. (1999) confirms the previous record of Byrne et al. (1977) and corresponds quite well to area burned statistics and dendrochronological precipitation signal. Other studies show corresponding records for the sudden rise in charcoal about 51,000 yr BP (and subsequent long period of high charcoal values) in a core from near the Philippines and the earliest arrival of *Homo sapiens* to the islands of Southeast Asia and Oceania (Beaufort et al., 2003; Beringer et al., 2005).

The strategic interest in fire proxies in marine sediments is thus very high because of both the availability of long-term records in currently accumulating marine sediments and the largely unexplored potential of using widely exposed marine sedimentary rocks to construct deep time-series records of combustion (e.g. Scott et al., 2000a). However, any such exploration of fire proxies in marine sedimentary rocks should refer to the developing fund of oceanographic knowledge of processes affecting BC in the modern ocean in order to better interpret the rock record.

2.6. Charcoal and black carbon analysis in soils

Buried charcoal fragments from natural (i.e. non-archaeological) soils provides valuable direct evidence of local fires (Tables 2 and 3) because transport of charcoal fragments >1–2 mm in size is limited by their large size. Such charcoal generally derives from an area of a few hundred to a few thousand square metres, although soils may also contain smaller charcoal particles transported long distances via the atmosphere before being deposited (Carcaillet, 1998; Ohlson and Tryterud, 2000; Tinner et al., 2006a). Unfortunately, soil charcoal records are more difficult to interpret in terms of past fire regime than are those of sediments, in large part because virtually all soils lack an inherent stratigraphy due to the complex processes at work in them (erosion, freeze and thaw cycles, bioturbation, uprooting, etc.; Vernet et al., 1994, 2005; Carcaillet and Talon, 1996; Carcaillet, 2001a,b; Lertzman et al., 2002; Holliday, 2004). This means that horizon dates cannot be simply interpolated, and radiocarbon dating is required to yield any convincing temporal information. Furthermore biotic and abiotic degradation of charcoal and soot (Bird et al., 1999; Hamer et al., 2004; Cheng et al., 2006; Hockaday et al., 2006) may progress with very different rates depending on the characteristics of the soil and of the horizon, introducing further uncertainty to the process of reconstructing past fire regimes using soils.

Pedo-anthracology, the analysis and radiocarbon dating of macrocharcoal in soil, is a valuable approach for reconstructing local fire history over long time scales (Figueiral and Mosbrugger, 2000; Ohlson and Tryterud, 2000; Lynch et al., 2002; Titiz and Sanford, 2007). When using soil charcoal for dating fires, factors such as the inbuilt age of charcoal (i.e. age of tree upon combustion), consumption of the existing charcoal by successive fires, difficulties in specific identification of the charcoals, and the accuracy of radiocarbon-derived estimates of fire dates have to be taken in account (Gavin, 2001; Figueiral and Mosbrugger, 2000; Gavin et al., 2003; Oswald et al., 2005). Additionally, in most instances the dating of a single particle is not sufficient to establish the age of the assemblage in the same horizon, especially if the particle is a relatively mobile small piece of charcoal, and the high cost of these analyses may therefore limit the feasibility of these studies.

Black carbon in soils is difficult to use for reconstruction of fire histories, due to both the difficulties in black carbon qualification and quantification (see discussion of BC in marine sediments above) and to the lower length and precision in time offered by a soil profile in comparison with a lacustrine or marine sedimentary sequence (Schmidt and Noack, 2000). An additional problem related to the microscopic dimension of the most fine black carbon particles derives from their high mobility and differential degradation. While even charcoal fragments may undergo vertical movements in the soil profile (Carcaillet, 2001a; Preston and Schmidt, 2006), soot is by far the most mobile and difficult to trace (Hockaday et al., 2006; Brodowski et al., 2007; Leifeld et al., 2007) such that there are still many open questions as to how it enters and exits a soil (Gerlach et al., 2006).

It is thus not surprising that some of the most interesting contributions to fire history of black carbon in soils come from the study of very particular and exceptional soil profiles. These include, for instance, reconstruction of very long temporal profiles from successions of paleosols (developed under moist and warm climatic conditions) alternating with loess layers (aeolian soils deposited under dry and cool climatic conditions) that extend a few million years back in time (Chen et al., 2007; Wang et al., 2005; Zhou et al., 2006). Nevertheless, interpretation of charcoal and black carbon records in soil remains limited by the complexity of the matrix and methodological problems but has the potential to provide important insight into fire reconstruction.

2.7. Molecular markers of combustion

An emerging group of fire proxies, called “chemical markers”, consists of different molecules that can act as chemical tracers of fire events (Simoneit, 2002; Tables 1, 3 and 6). These compounds can be directly produced and volatilized during combustion (Simoneit, 2002; Reid et al., 2005; Koppmann et al., 2005; Preston and Schmidt, 2006) or may rapidly condense and remain trapped in charcoal, ash and other heavy particles (Oros et al., 2002; Preston and Schmidt, 2006) or in semi-fluid residues such as tar (Shafizadeh et al., 1979; Demirbaş, 2000; Morf, 2001). Molecular markers may also derive from the decomposition, diagenesis, or other chemico-physical transformation of fire products and may be in this case considered second degree fire proxies. For instance, chemical markers such as benzene polycarboxylic acids (BPCAs; Glaser et al., 1998; Brodowski et al., 2005b) may derive from the char structure itself and be released during chemical processing in the laboratory.

The research on molecular markers of burning activities has primarily focused on their role as pollutants (Villeneuve et al., 1977; Samanta et al., 2002; Wright and Welbourn, 2002). Some such compounds (e.g. resin acids, polycyclic aromatic hydrocarbons, dibenzofurans and others) are recognised as highly allergenic, carcinogenic and mutagenic (Boffetta et al., 1997; Szu-Chich and Chung-Min, 2006). The broad scientific use of molecular markers for reconstructing past wildfire occurrence has taken place only recently and is still in the trial stage. In this context, the list of biomarkers candidates of fire events is already large and continuously increasing (see Table 6), but manifold methodological problems still exist. One of the most promising of these is levoglucosan, a monosaccharide anhydride sometimes associated with its isomeric compounds galactosan and mannosan, which appears to derive only from pyrogenic sources (Otto et al., 2006).

One problem in the use of some molecular markers results from the difficulty of quickly and precisely measuring very low quantities of chemical compounds in a complex sediment matrix. Consequently chemical markers deriving either from vegetation fires or from anthropogenic pollution are often studied only in relation to their presence in greater quantities in recent, postindustrial sediments. Few studies have attempted an accurate analysis of the low preindustrial quantities of these compounds (Kawamura et al., 1994; Hashimoto et al., 1990).

Finally, there is still a lack of knowledge concerning the stability, durability and degradation mechanisms that may affect molecular markers under different sedimentary and diagenetic conditions. This is probably one of the reasons why most of the existing markers are used as present-time proxies for the identification of recent fire-event residues in aerosols, rain, snow, rivers, surface sediments and others transport vectors or fresh deposits rather than as fire proxies in longer sedimentary records. As a general rule we can assume that fast burial should increase their durability and sequester them below the surface oxic zone. On the other hand, the majority of molecular markers seems to degrade more rapidly than black carbon particles (Alexis et al., 2006), although this is difficult to ascertain with precision and cannot be generalized for all marker compounds.

The reliability of the molecular markers as fire proxies may be a function of the age of the matrix in which molecular markers are found, with high reliability in freshly produced aerosol, less in a 10-yr-old lake varve, and least in a very old sedimentary rock. Additionally, biodegradation, diagenesis or early metamorphic processes further complicate the use of these markers because, over long time scales, these processes can mimic certain rapid chemical fire effects (González-Pérez et al., 2004). Two factors combine thus in weakening the indicative power of the markers over time: a possible loss due to transformation of compounds (molecular degradation) and a possible additional source from alternative modes of generation (diagenetic production).

Some attempts to enhance the diagnostic power of the molecular markers have been made, primarily consisting of the use and analysis not only of individual substances but of specific indices that represent the total concentration of selected compounds or the ratio between two single or groups of compounds (Parrish et al., 2000). Such ratios have the potential to provide additional qualitative information about the combustion residues, such as the degree of condensation, extent of oxidation, and source (e.g. vegetation fires versus fossil fuel combustion). These efforts have then compared the obtained chemical profiles with those of different input matrices or source materials such as aerosols derived from urban environments, savannah fires or conifer forest fires (Wilcock and Northcott, 1995; Favaro, 1998; Parrish et al., 2000).

2.8. Magnetic parameters

Fire may directly or indirectly modify the magnetic properties of the environment (Tables 2–4). During burning, weakly paramagnetic iron minerals in soil (Ketterings et al., 2000) or traces of iron present within the fuel (Lu et al., 2007) are converted to secondary, strongly ferrimagnetic oxides related in composition to magnetite and maghemite (Le Borgne, 1960; Longworth et al., 1979; Crockford and Willett, 2001; Evans and Heller, 2003). After burning, erosion of fire-induced magnetic regoliths from a catchment area may produce an important inflow of ferrimagnetic particles, creating magnetically distinct layers in lake bottom sediments.

Fire-induced ferromagnetic conversion depends on fuel characteristics, atmospheric conditions, temperature of burn, availability of pre-existing iron minerals (especially iron hydroxides) and soil porosity (Rummery et al., 1979; Rummery, 1983; Peters and Thompson, 1999; Blake et al., 2006). Unfortunately, although heating, even at modest temperatures, has been clearly identified as a cause of magnetic enhancement of several orders of magnitude in superficial soil layers (Mullins, 1977; Peters and Thompson, 1999; Gedye et al., 2000; Linford and Canti, 2001), other factors may also cause in situ enrichment of magnetic minerals in soil. For instance, the magnetic susceptibility signal in loess–paleosol sequences likely reflects long-term pedogenic or weathering processes within soils rich in Fe-bearing minerals that are exposed to high precipitation and temperatures (Maher and Thompson, 1995; Dearing et al., 1996; Liu et al., 1999; Ortega-Guerrero et al., 2004), even though fire-induced magnetic susceptibility could result in an identical signal (Kletetschka and Banerjee, 1995). Ubiquitous magnetotactic bacteria may also form magnetic minerals in soils and other sedimentary environments (Fassbinder et al., 1990; Simmons et al., 2004; Lefèvre et al., 2007). Furthermore, peaks in magnetic mineral concentration may also be due to airborne magnetic pollution (Oldfield et al., 1983), non-fire related events of increased erosion, especially when bedrocks contain high quantities of primary magnetic minerals (Thompson et al., 1975; Oldfield et al., 1978; Oldfield, 2007), remobilization of previously burnt material stored in intermediate deposits (Owens et al., 2006), or other direct or indirect causes.

The discussed difficulties make it almost impossible to derive an unambiguous magnetic fire signal from a single basic magnetic quantity such as magnetic susceptibility (χ) or saturation isothermal remanent magnetization (SIRM), suggesting the necessity of using an enlarged pool of parameters to indicate the magnetic fingerprint of burning (Oldfield, 1991; Oldfield and Crowther, 2007). So, for instance, bacterial magnetite can be clearly discriminated by comparing additional parameters such as anhysteretic remanent susceptibility (χARM), low-field susceptibility (χlf), and frequency-dependent susceptibility (χfd) in the same diagram (Oldfield, 1994; Oldfield and Crowther, 2007). Furthermore, fire-induced magnetic enhancement in soil or sediment layers usually exhibits peak χ value alongside minimum remanence/susceptibility ratios (ARM/χ and SIRM/χ), relatively high χfd percentages and low SIRM/ARM quotients (Oldfield, 1988; Higgitt et al., 1991). Additional composite parameters revealing the presence of fire-produced ferromagnetic nanoparticles are the *T*-ratio ($IRM_{290\ K}/IRM_{77\ K}$; Hirt et al., 2003), the percentage fractional conversion (χ_{conv}; Crowther, 2003; Oldfield and Crowther, 2007), and the *S*-ratio ($IRM_{-100\ mT}$/SIRM; Sandgren and Thompson, 1990; Blake et al., 2006). On the other hand, discrimination of industrially derived magnetic contaminants can be achieved through specific magnetic grain size parameters (Sandgren and Thompson, 1990). Finally, problems related to selective magnetic mineral dissolution in different sediments, such as saltmarshes (Wheeler et al., 1999) or ombrotrophic peat (Williams, 1992), may be bypassed by the analysis of sedimentological and diagenetic conditions or by the identification of revealing magnetic characteristics (Oldfield et al., 1995; Vigliotti et al., 1999).

The use of magnetic parameters in soils and sediments thus represents an interesting and promising approach to fire history and palaeoecology. The technique is more rapid and less disruptive than charcoal and pollen analysis and may be very useful in initially detecting fire traces in sediment profiles (Higgitt et al., 1991; Gedye et al., 2000) or may play a complementary role to the other techniques (Oldfield, 1991). In addition the in-depth study of magnetic parameters may offer new possibilities such as estimating the intensity and type of past fire events (Ketterings et al., 2000; Blake et al., 2006; Oldfield and Crowther, 2007), the recurrence of fire episodes on archaeological soils (Linford and Canti, 2001; Crowther, 2003), the conditions of use of archaeological structures involving combustion processes (Aidona et al., 2001; Schmidt, 2007), the sources of fuel ash residues (Peters and Batt, 2002; Church et al., 2007), or even the discrimination of wildfire and fire resulting from human activities (Bellomo, 1993).

2.9. Sedimentology

The passage of fire can provoke an increase in soil hydrophobicity, a decrease in water infiltration capacity and thus an increase in surface runoff of rainfall and snowmelt and of the associated surface erosion (Letey, 2001; Huffmann et al., 2001; Tables 2 and 4). The importance of these effects has been found to be generally proportional to the intensity of the fire (Giovannini, 1994). When severe fires affect a significant part of the watershed, the resulting alterations may consist in a substantial modification of the hydrogeological characteristics of the area, enhancing channel and overland topsoil transport and the risk of debris-flows in the period immediately following the event (Cannon et al., 2001, 2008; Conedera et al., 2003). In such cases, runoff and erosion processes may bring a large amount of inorganic and organic (including charcoal) remains to sediments, causing an abrupt increase in varve thickness (Cwynar, 1978; Clark et al., 1989; Pierce et al., 2004). As the soil surface is stabilized by vegetation regrowth, the effects on erosion and the varve thickness may gradually decrease as the system returns to normal sedimentation rates. However, as other factors can also cause increases in erosion, it is best to couple such measurements with other independent indications of fire. For example, the correspondence of prominent charcoal peaks with abrupt increases in the varve thickness and, in certain cases, even peaks in the influx of inorganic elements such as aluminium and vanadium (Swain, 1973; Cwynar, 1978) or an increase in clastic sediments and the occurrence of turbidites (Ramrath et al., 2000; Sadori et al., 2004), may be used as an indicator of local fires.

Additionally, Pierce et al. (2004) used debris-flow deposits to reconstruct past fires. The authors conservatively defined "large fire related events" as those with relatively coarse grained debris-flow units with abundant coarse angular charcoal that comprise at least 20% of the thickness in a stratigraphic section. In contrast, "small-fire related event" deposits contained abundant charcoal but did not meet all of the above-mentioned criteria.

2.10. Multi-proxy studies for reconstruction of long-term fire ecology

A detailed understanding of long-term climate–fire–vegetation interactions and post-fire reaction patterns of ecosystems requires a multi-proxy approach. Carefully designed multi-proxy studies have the potential to provide unique records of fire ecological dynamics over time and to contribute to our understanding of ecosystem variability (Birks, 1997; Birks and Birks, 2006). Tying paired pollen and charcoal analysis from the same core to quantitative methods such as redundancy (Odgaard, 1992) or cross-correlation (Green, 1981; Tinner et al., 1999; Gobet et al., 2003; Colombaroli et al., 2007) analysis is one very useful multi-proxy approach for examining the long-term linkage between climate, vegetation, fire and, in some cases, past anthropogenic activities. Multi-proxy, long-term fire-ecology studies may include other proxies than pollen and charcoal (e.g. macrofossils, magnetic analysis, diatom analyses; Tinner et al., 2008) or rely on non-sedimentary approaches such as vegetation relévés or dendroecology. Multi-proxy results may be combined with static or dynamic modelling to gain valuable insights into long-term fire ecology (Keller et al., 2002; Flannigan et al., 2005; Schumacher and Bugmann, 2006; Wick and Möhl, 2006). Nevertheless, some methodological problems have to be taken into account, especially in relation to the different spatial scales covered by the different sedimentary proxies (Davis et al., 1984). However, given the comparable size of the particles, it is plausible that macrofossils and macrocharcoal may both have similar, primarily local spatial scales of origin and thus may be readily compared. Likewise, pollen and microcharcoal may both originate from extra-local to regional sources (Tinner and Hu, 2003). A further complication is that pollen percentages do not correspond linearly to vegetation abundance, as they are affected by production and dispersal biases (Prentice, 1985), as well as variation in the catchment area according to the lake size (MacDonald et al., 1991; Conedera et al., 2006; Orloci et al., 2006).

The spatial scale of fire reconstructions can be addressed by linking adjacent fire-history study sites (e.g. Clark, 1990; Morgan et al., 2001; Whitlock et al., 2003b; Stähli et al., 2006), whereas spatial resolution of the vegetation palaeorecords can be significantly improved by considering small-scale sites and especially by including macrofossils in the analysis (e.g. Hofstetter et al., 2006). Useful temporal resolution may be achieved using dendrochronology, varved sediments or contiguous high-resolution stratigraphic analysis of well-dated sedimentary sequences (e.g. Swetnam, 1993; Clark et al., 1989). Sedimentary fire ecological studies should reach <10–20 yr of resolution for all proxies involved (e.g. pollen, macrofossils, charcoal, magnetic analyses), and time intervals between samples should be as stable as possible to allow time-series analyses (Green, 1981; Birks, 1997).

3. Conclusions

Creating effective land management approaches requires having a sound understanding of past forest stand and landscape dynamics, and in particular a well-grounded knowledge of the natural range of variability in the disturbances and processes that have shaped such ecosystems before the appearance of the most recent, "disturbance of disturbances" caused by the ascent and supremacy of technological humans. This is a prerequisite to understanding the nature and impact of disturbance regimes and designing management activities that work in concert with, rather than counter to, these natural dynamics (Morgan et al., 1994; Peacock et al., 1997). Fire, as one of the major drivers of ecological change and dynamics, is no exception in this context: natural variability provides a context for the search for reference conditions for forest restoration (Morgan et al., 2001). The review presented in this paper demonstrates how the extraction and analytical techniques and the general knowledge related to fire proxies have improved in the last decades and how this development is likely to accelerate in the future. Standardised and concerted application of such palaeoenvironmental fire proxies represents the best way to acquire the necessary knowledge of long-term climate–fire–vegetation interactions at different spatial and temporal scales. In this context, particular attention should be paid to some key points that have not been sufficiently considered up to this point:

- discriminating natural from anthropogenic fires and understanding possible interactions in the past. One line of evidence of anthropogenic disturbance centers on the appearance of ecological processes operating at unprecedented rates that are associated with anthropogenic indicators in the pollen assemblage and/or contemporaneous archaeological evidences (Tinner et al., 1999, 2005; Carcaillet et al., 2007). Another indicator is the detection of fires scars on vegetation from seasons where lightning-induced fires are mostly non-existent (Kaye and Swetnam, 1999; Fry and Stephens, 2006; Parker, 2002);
- achieving an organic understanding of post-fire processes, especially of the long-term fire ecology of ecosystems, for instance by using a multi-proxy approach that incorporates high-resolution contiguous palaeo-environmental proxies;
- defining suitable or target fire regimes and finding temporal and spatial scales of reference in past fire history. In fact, exceptional events that are unprecedented in human lifetimes can be business-as-usual when viewed over longer time

frames. Similarly, non-equilibrium dynamics at one spatial scale can be incorporated within a steady-state or equilibrium dynamics on a broader scale (Swetnam, 1993; Morgan et al., 1994; Whitlock, 2004). However, simply keeping ecosystem dynamics within their historical range of variation may not meet the needs of forest managers. In some regions, fire regimes are currently much more human than naturally controlled, which implies the inclusion of social and cultural aspects into fire management decisions (Pyne et al., 1996). Thus, although the objective of natural disturbance-based management is to consider the historical range of variability, in practical terms, it may be more focused on defining a socially and economically acceptable and sustainable target fire regime that will reduce the risk of negative consequences (Angelstam, 1998; Bergeron et al., 1999).

- improving and standardizing descriptors of all components of the fire regime and promoting the use of an extended definition of this concept (Morgan et al., 2001), including whenever possible not only the descriptors of when, where and which fires occur (frequency, seasonality, size, type, behavior, intensity, etc.), but also descriptors of the conditions under which fires occur (fuels characteristics, fire weather, causes, ignition sources, synergisms, etc.), the immediate effects of fires (severity), and the dynamics (variability) of fire parameters over long time span, among other factors.

Addressing such key points, together with further development and standardization of the use of new and emerging fire proxies, such as molecular markers, and an increased implementation of multi-proxy approaches are significant tasks in terms of the organization and complexity of scientific research. However, these would provide the best foundation for a holistic understanding of all aspects of fire regimes. Such efforts would provide the basic information required to model possible consequences of global change on fire disturbance and help to implement sound forest and fire management plans.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2008.11.005

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