Circum-Mediterranean fire activity and climate changes during the mid Holocene environmental transition (8500-2500 cal yr BP)

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The Holocene 2011 21: 53
DOI: 10.1177/0959683610384164

Holocene Special Issue

The Holocene
21(1) 53–73

DOI: 10.1177/0959683610384164
http://hol.sagepub.com

Circum-Mediterranean fire activity and climate changes during the mid-Holocene environmental transition (8500–2500 cal. BP)

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Abstract

A mid- to late-Holocene synthesis of fire activity from the Mediterranean basin explores the linkages among fire, climate variability and seasonality through several climatic and ecological transitions. Regional fire histories were created from 36 radiocarbon-dated sedimentary charcoal records, available from the Global Charcoal Database. During the mid-Holocene 'Thermal Maximum' around 7500–4500 cal. BP, charcoal records from the northern Mediterranean suggest an increase in fire while records from the southern Mediterranean indicate a decrease associated with wetter-than-present summers. A North–South partition between 40° and 43°N latitude is apparent in the central and western Mediterranean. Relatively abrupt changes in fire activity are observed *c.* 5500–5000 cal. BP. Records of Holocene fire activity appear sensitive to both orbitally forced climate changes and shorter-lived excursions which may be related to North Atlantic cold events, possibly modulated by an NAO-like climate mechanism. In cases where human–fire interactions have been documented, the regional coherency between fire occurrence and climate forcing suggests a dominant fire–climate relationship during the early–mid Holocene. The human influence on regional fire activity became increasingly important after *c.* 4000–3000 cal. BP. Results also suggest that: (1) teleconnections between the Mediterranean area and other climatic regions, in particular the North Atlantic and the low latitudes monsoon areas, influenced past fire activity; (2) gradual forcing, such as changes in orbital parameters, may have triggered abrupt shifts in fire activity; (3) regional fire reconstructions contradict former notions of a gradual (mid- to late-Holocene) aridification of the entire region due to climate and/or human activities and the importance of shorter-term events; (4) Mediterranean fire activity appears hightly sensitive to climate dynamics and thus could be considerably impacted by future climate changes.

Keywords

charcoal, fire, Holocene, insolation, Mediterranean, paleoclimate

Introduction

The Mediterranean is a region characterized by strong seasonal precipitation (Lionello et al., 2006) and extreme weather events including floods and droughts. The driest years, marked by summer heat-waves, are linked to extreme fire activity (Moriondo et al., 2006). For instance, during 2007, Greece experienced particularly large fires that resulted in over 226 000 ha of burned forests, olive groves, shrub lands and farmlands (Good et al., 2008). On average, 50 000 fires and between 700 000 and 1 000 000 ha burn per year within the Mediterranean basin, representing one of the globe's most significant wildland fire regions (Food and Agriculture Organization (FAO), 2001). Consequently, fire is one of the most relevant agents of Mediterranean ecosystem dynamics (Pausas, 2006). Since at least the last glacial period, fire has helped to shape biome distributions and to maintain the structure and function of fire-sensitive communities (Carrión, 2002; Colombaroli et al., 2009). The region also has an exceptionally long and complex history of human use, stretching back at least *c.* 10 000 cal. BP with the advent of Neolithic farming in the eastern Mediterranean (Bocquet-Appel et al., 2009). Indeed, the combined evaluation of charcoal-inferred paleofire activity with past hydrological, vegetation, and archaeological data reveals strong relationships between climate, fire, vegetation, and anthropogenic land use (Carrión et al.,

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Received 25 November 2009; revised manuscript accepted 1 July 2010

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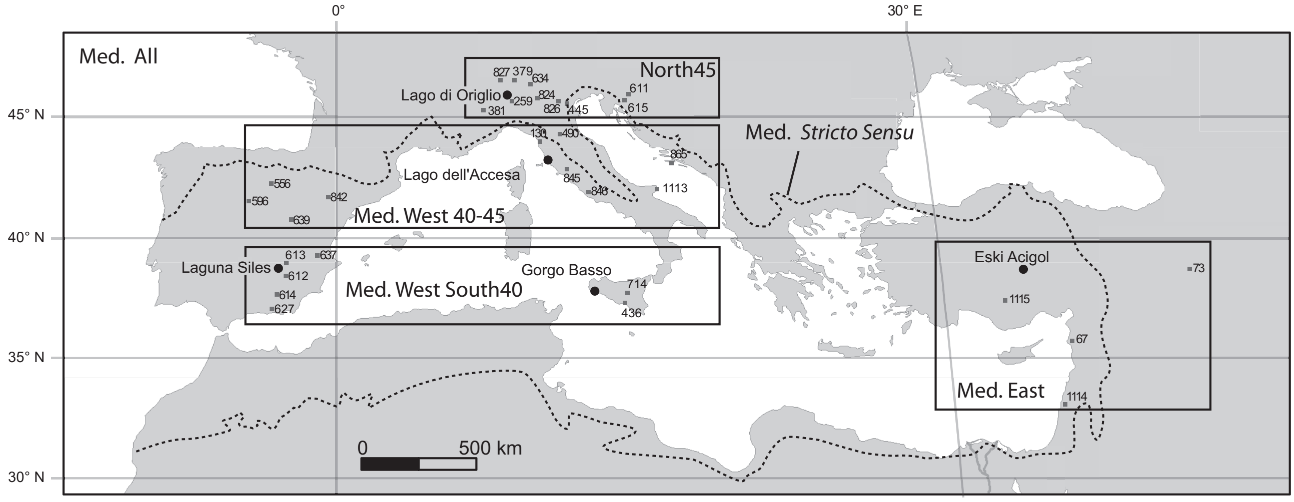

Figure 1. Mediterranean area with the limit (dashed line) of the Mediterranean *stricto sensu* biogeographical zone (Quézel and Médail, 2003), position of sites (see ID/Name in Table 1) used in this study and geographical grouping used for regional syntheses

2007; Turner et al., 2008, 2010). Furthermore, long-term records attest to past variability in fire including periods during the Holocene, with greater-than-present fire activity (Tinner et al., 2009; Vannière et al., 2008). However, despite the considerable increase in research and publications on Holocene fire history in the Mediterranean in the last ten years (Figure 1 and Table 1), there remains a poor understanding of basin-wide fire history. A Mediterranean-wide Holocene fire synthesis allows us to establish long-term trends and identify significant disturbance events.

At continental-to-regional scales, coherent patterns in fire activity are evident throughout the Holocene period and have been explained in terms of large-scale climatic controls (Marlon et al., 2009; Power et al., 2008) and coupled with large-scale atmospheric circulation patterns (Trouet et al., 2006; Veblen and Kitzberger 2002). Even within forested regions of the Mediterranean basin, where fire activity is closely linked to vegetation dynamics and fuel load (Pausas and Bradstock, 2007), past and present fire occurrence is ultimately controlled by seasonal hydrologic conditions (Telesca and Lasaponara, 2006; Vannière et al., 2008). Mediterranean fires occur during summer when climate conditions (typically expressed as the ratio between precipitation and evapotranspiration as a function of temperature) favour fuel flammability, and fire occurrence depends on the duration and intensity of this dry season (Pausas, 2004). For example, severe fire-weather (summer drought and autumn foehn winds) are of overriding importance in determining fire behavior in California chaparral (Mediterranean-type climate) where fuel management policy has been ineffective in fire supression (Keeley and Fotheringham, 2001a, b). Taking into account this dominant fire–climate relationship, this synthesis provides insights into the linkages between changes in paleofire activity and regional climate forcing.

The mid to late Holocene (in this paper early Holocene refers the period before 8500–8000 cal. BP, mid Holocene to the 8000–4000 cal. BP period and late Holocene to the period post 4500–4000 cal. BP) corresponds to the transition from Holocene thermal maximum to Neoglacial periods (e.g. Calvo et al., 2002; Matthews and Dresser, 2008). During these periods, orbitally forced changes in summer insolation affected the Northern Hemisphere (Berger and Loutre, 1991) and the Mediterranean region experienced important ecological changes. For example, the evergreen-broadleaf forests reached their maximum expansion before being disrupted by climate changes and/or human activities (Colombaroli et al., 2008; Gil-Romera et al., 2010). But contradictory interpretations of climate reconstructions appear, in particular about the so-called Holocene aridification trend and the establishment of the present-day Mediterranean climate (de Beaulieu et al., 2005; Frigola et al., 2007; Jalut et al., 2009; Magny et al., 2002, 2007a; Marchal *et al.*, 2002; Roberts et al., 2008; Sadori et al., 2008; Tinner et al., 2009; Tzedakis, 2007). This may reflect real inter-regional differences or contrasting sensitivities of different proxies, and/or the difficulties to distinct human versus climate influences on vegetation changes. However, most authors suggest this heterogeneity in climate reconstructions within the Mediterranean region are linked to changes in seasonality and the importance of geographic gradients (North–South and East–West, Davis and Brewer, 2009; Magny et al., 2003, 2007a, 2009; Roberts et al., 2008; Tzedakis, 2007). Furthermore, recent studies have identified climate oscillations that punctuated the Holocene in the Mediterranean area with potential links to the North Atlantic (Incarbona et al., 2008; Magny et al., 2007a, 2009; Rodrigues et al., 2009). Other studies indicate that the Mediterranean region has been particularly sensitive to past climate change linked to the North–South summer gradient and northward (or southward) displacement of the Intertropical Convergence Zone (ITCZ) (Gasse and Roberts, 2004; Tinner et al., 2009). The aim of this paper is to identify the long-term trends in fire activity for several Mediterranean subregions and discuss the similarity, synchronicity and/or discrepencies associated with forcing factors.

In this paper we present a synthesis of 36 radiocarbon dated time series from sedimentary charcoal records as an index of paleofire activity. These paleofire reconstructions combine individual records of total charcoal influx (paricles/cm^2 per yr) as an indicator of local to regional biomass burned (for discussion see the review by Conedera et al., 2009). Charcoal series were extracted from the Global Charcoal Database (Power et al., 2008) and improved by newly available records and standarized to correct for heterogeneity within the data (see Power et al., 2010).

Study area

Mediterranean climate zones are characterized by mild wet winters and warm-to-hot dry summers and occur on the west side of the continents between about 30°N and 45°N latitudes. The dry

Table 1. Charcoal records used in this study with geographical, bioclimate and vegetation information, site ID from the Global Charcoal Database, bibliography and the version of the database that contains the charcoal records

Group Name	Country	Site Name	ID Site	Lat.	Long.	Elev.(m)	Bioclimate/Vegetation	Reference	GCD version
North45	Italy	Lago Basso	379	46.42	9.28	2250	Alpine meadows	Wick 1994	1
North45	Switzerland	Piano	827	46.32	8.62	1439	Temperate beech-fir forests	Valsecchi 2005, Valsecchi et al. 2010	2
North45	Italy	Pian di Gembro	634	46.16	10.15	1350	Temperate beech-fir forests	Pini 2002	2
North45	Switzerland	Lago di Origlio	258	46.05	8.94	416	Submediterranean chestnut-oak forests	Tinner et al. 1999	1
North45	Switzerland	Lago di Muzzano	259	46.00	8.93	337	Submediterranean chestnut-oak forests	Tinner et al. 1999	1
North45	Slovenia	Griblje Marsh	611	45.57	15.28	160	Submediterranean oak forests	Andric 2007	2
North45	Italy	Lago Lucone	824	45.55	10.48	249	Submediterranean chestnut-oak forests	Valsecchi et al. 2006	2
North45	Slovenia	Mlaka	615	45.50	15.21	150	Submediterranean oak forests	Andric 2007	2
North45	Italy	Lago di Fimon	826	45.47	11.53	23	Submediterranean oak forests	Valsecchi et al. 2008	2
North45	Italy	Lago della Costa	445	45.27	11.74	7	Submediterranean chestnut-oak forest / mesomediterranean evergreen oak (*Q. ilex*) forests	Kaltenrieder et al. 2010	1
North45	Italy	Lago Piccolo di Avigliana	381	45.05	7.38	356	Submediterranean chestnut-oak forests	Finsinger 2004, Finsinger and Tinner 2006	1
Med. West 40-45	Italy	Lago del Greppo	490	44.12	11.67	1442	Temperate beech-fir-spruce forests	Vescovi 2007	1
Med. West 40-45	Italy	Lago di Massaciuccoli	130	43.85	10.32	1	Mesomediterranean evergreen oak (*Q. ilex*) / submediterranean chestnut-oak forests	Colombaroli et al. 2007	1
Med. West 40-45	Italy	Lago dell'Accesa	1079	42.99	10.89	155	Mesomediterranean evergreen oak (*Q. ilex*) / submediterranean chestnut-oak forests	Vannière et al. 2008	2
Med. West 40-45	Croatia	Malo Jezero	865	42.78	17.35	24	Mesomediterranean evergreen oak (*Q. ilex*) / submediterranean oak forests	Colombaroli et al. 2009	2
Med. West 40-45	Italy	Lagaccione	845	42.57	11.85	355	Mesomediterranean evergreen oak (*Q. ilex*) / submediterranean chestnut-oak forests	Magri and Ciuffarella 1991, Magri 2008	2
Med. West 40-45	Spain	Las Pardillas	556	42.03	−3.03	1850	Temperate conifer (*P. sylvestris*) forests and shrubs (*Juniperus nana*)	Sánchez-Goñi & Hannon 1999	1
Med. West 40-45	Italy	Battaglia	1113	41.91	16.13	0	Mesomediterranean evergreen oak (*Q. ilex*) forests	Caroli and Caldara 2006	3
Med. West 40-45	Italy	Valle di Castiglione	846	41.73	12.76	44	Mesomediterranean evergreen oak (*Q. ilex*) forests	Magri and Ciuffarella 1991, Magri 2008	2
Med. West 40-45	Spain	Hoya del Castillo	842	41.48	−0.16	258	Mesomediterranean evergreen oak (*Q. coccifera* and *Q. rotundifolia*) forests	Davis and Stevenson 2007	2
Med. West 40-45	Spain	El Carrizal	596	41.32	−4.14	860	Mesomediterranean evergreen oak (*Q. ilex*) forests	Franco-Múgica et al. 2005	2
Med. West 40-45	Spain	Ojos del Tremendal	639	40.53	−2.05	1650	Temperate mixed (*Q. pyrenaica* - semi-deciduous / *P. sylvestris* and *P. Nigra*) forests	Stevenson 2000	2
Med. West South40	Spain	Navarrés	637	39.10	−0.68	225	Mesomediterranean evergreen oak (*Q. rotundifolia*) forests	Carrión and Van Geel 1999	2
Med. West South40	Spain	Villaverde	613	38.80	−2.22	870	Mesomediterranean evergreen oak (*Q. rotundifolia*) forests	Carrión et al. 2001b	2
Med. West South40	Spain	Siles Lake	301	38.40	−2.50	1320	Mesomediterranean evergreen oak (*Q. rotundifolia*) forests	Carrión 2002	1
Med. West South40	Spain	Cañada de la Cruz	612	38.40	−2.42	1595	Submediterranean conifer (*P. nigra*) forests	Carrión et al. 2001a	2
Med. West South40	Italy	Gorgo Basso	848	37.62	12.65	6	Thermomediteranean evergreen oak (*Q. ilex*) forests / evergreen *Pistacia* shrubs	Tinner et al. 2009	2
Med. West South40	Italy	Lago di Pergusa	714	37.52	14.30	674	Mesomediteranean evergreen oak (*Q. ilex*) / submediterranean oak forests	Sadori and Giardini 2006	2

(Continued)

Table 1. (Continued)

Group Name	Country	Site Name	ID Site	Lat.	Long.	Elev.(m)	Bioclimate/Vegetation	Reference	GCD version
Med.West South40	Spain	Baza	614	37.23	−2.70	1900	Temperate conifer (*P. nigra* and *P. sylvestris*) forests	Carrión et al. 2007	2
Med.West South40	Italy	Biviere di Gela	436	37.02	14.33	7	Termomediterranean evergreen oak (*Q. ilex*) forests / evergreen *Pistacia* shrubs	Noti et al. 2009	1
Med.West South40	Spain	Gádor	627	36.90	−2.92	1530	Submediterranean oak (*Q. faginea*) / mesomediterranean evergreen oak (*Q. rotundifolia*) forests	Carrión et al. 2003	2
Med.East	Turkey	Lake Van	73	38.56	42.54	1648	Submediterranean oak (*Q. pubescens* and *Q. robur*) forest-steppe	Wick et al. 2003	1
Med.East	Turkey	Eski Acigöl	772	38.55	34.54	1270	Submediterranean oak (*Q. pubescens* and *Q. robur*) forest-steppe	Turner et al. 2008	2
Med.East	Turkey	Akgöl	1115	37.30	33.44	1000	Submediterranean oak (*Q. pubescens* and *Q. robur*) forest-steppe	Turner et al. 2010	3
Med.East	Syria	Ghab	67	35.65	36.25	240	Thermomediterranean mixed (*P. brutia* and *Q. calliprinos-Crataegus monogyna*) forests	Yasuda et al. 2000	1
Med.East	Israel	Hula	1114	33.04	35.37	70	Thermomediterranean evergreen oak (*Q. ithaburensis* and *Q. ilex*) forest-steppe / evergreen *Pistacia* shrubs	Turner et al. 2010	3

season lasts between one and three months on the Italian coasts in the north of the Mediterranean, and more than five months below 40°N latitude, including Sicily, southern Spain or the Levant (Quézel and Médail, 2003). Annual precipitation for Mediterranean bioclimates (Quézel and Médail, 2003) varies between 100 mm/yr and greater than 2000 mm/yr, and is often dependent on elevation. In addition to the orographic controls of Mediterranean climate, latitudinal gradients occur from the northernmost part of Mediterranean region (e.g. northern Italy), characterized by submediterranean vegetation, to the mesomediterranean vegetation zone (e.g. central Italy), situated between 45°N and 40°N latitude, and to the southernmost thermomediterranean zone (e.g. southern Spain). Bioclimate and surrounding vegetation of each site are listed in Table 1. At low and middle elevations, in meso- and thermomediterranean regions, broadleaf-evergreen trees (e.g. *Quercus ilex*, *Q. suber*, *Chamaerops humilis*, *Laurus nobilis*, *Olea europea*) and shrubs (e.g. *Pistacia terebinthus*, *Arbutus unedo*) dominate. Outside the true Mediterranean region, at mid-latitudes, deciduous broadleaf trees dominate (*Quercus*, *Ulmus*, *Carpinus*, *Tilia*, *Corylus*) in the lowlands (e.g. North Italy). Submediterranean deciduous trees (e.g. *Quercus pubescens*, *Fraxinus ornus*, *Ostrya carpinifolia*, *Castanea sativa*) form a forest belt above (e.g. *c.* > 1000 m a.s.l. in Sicily) and north of the evergreen Mediterranean vegetation belt (e.g. northern Italy, northern Spain, northern Greece, Chiappini, 1988; Ellenberg, 1996; Reisigl et al., 1992; Thuiller et al., 2003). This vegetation belt is a transitional zone between the Mediterranean and temperate biomes. Submediterranean tree species are also co-dominant in mixed deciduous-evergreen stands in the lowlands of the true Mediterranean region (e.g. mesomediterranean Tuscany, Lazio). The relative abundance of evergreen and deciduous species in the transition zones depend mainly on exposure and soil characteristics. When these are favourable, evergreen, deciduous broadleaf trees, shrubs and annual herbs can grow together (Quézel and Médail, 2003).

The Mediterranean region is at the limit between high-latitude atmospheric circulation (Siberian high-pressure system, associated to the North Atlantic Oscillation NAO mechanisms in winter; Cullen and deMenocal, 2000; Xoplaki et al., 2003; Figure 2) and (sub-)tropical circulation, which is linked to the summer monsoon and trade wind activity (Lionello et al., 2006). The interhemispheric temperature gradient leads to a seasonal migration of the Intertropical Convergence Zone (ITCZ). The southern position in winter allows storm tracks coming from the Atlantic to bring rain over the Mediterranean, while the subtropical high-pressure blocks westerlies (and rainfall), when the ITCZ is at its northern position in summer (Weischet, 2002). The interannual variability of the Mediterranean summer climate is linked to the mean latitudinal position of the ITCZ and to the strength and position of the Atlantic subtropical anticyclone, which are in turn connected to the Northern Hemisphere summer monsoons (Dima and Wallace, 2003; Rodwell and Hoskins, 2001). The western and central Mediterranean basins are mainly influenced by a western extension of the African monsoon (Xoplaki et al., 2003), while the eastern most part of the basin is under the influence of the Asian monsoon (Ziv et al., 2006). This connection is necessarily only indirect (i.e. atmospheric circulation bridges: the tropical circulation cells and the mid-latitude stationary waves) and does not imply a northward extension of the monsoon over the Mediterranean (see the review by Tzedakis, 2007). As the summer monsoon intensifies, the meridional Hadley circulation, which descends over North Africa, begins to influence

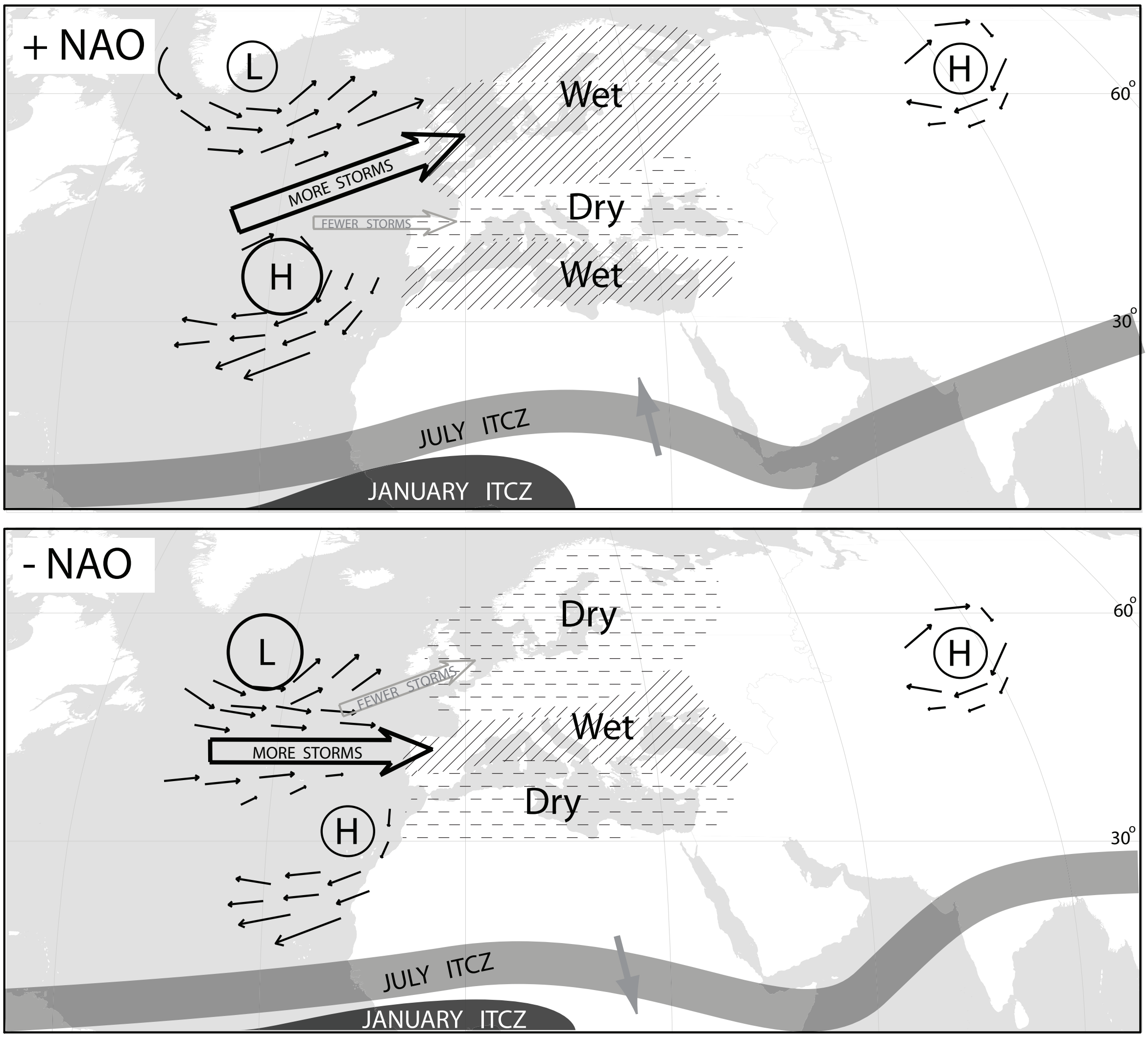

Figure 2. Stylized representation of positive and negative North Atlantic Oscillation (NAO) climate modes, the present-day January and July average location of the Intertropical Convergence Zone, and the location of the Siberian High. Top panel illustrates the positive NAO phase (+NOA), with a stronger-than-normal subtropical high-pressure center and a deeper than normal Icelandic low. The increased pressure gradient generates more and stronger winter storms following a more northern storm track, creating warm wet winters in Northern Europe and dry winters in the Mediterranean basin. The bottom panel illustrates the negative NAO phase (−NAO), with a weak subtropical high pressure and weaker Icelandic low. The decreased pressure gradient results in fewer and weaker winter storms in the north, bringing drier and colder conditions to northern Europe and increased storm tracks and moisture into the Mediterranean basin. In the top panel, the mean position of the summer ITCZ is at its (present-day) northern-most extension and brings the northern coast of the Mediterranean under the influence of the subtropical anticyclone and dryness. The shift of the ITCZ to the south (bottom panel) leads to a weakening of the subtropical anticyclone west of the Mediterranean, with increased summer precipitation in the northern part and drier conditions in the southern part of the Mediterranean (see discussion)

the development and persistence of subtropical high pressure over the Mediterranean causing dry conditions. Note that ITCZ movement to the north during the early Holocene (10 000-8000 cal. BP) as a consequence of maximum boreal insolation exceeded the today's interannual variability (Figure 2; Fleitmann et al., 2003; Haug et al., 2001), but did not expand north of c. 25°N (Tzedakis et al., 2007). Changes in the mean position of the ITCZ, in the intensity of monsoons and in the pattern of the Hadley circulation influence the atmospheric circulation in the subtropical Atlantic and the Mediterranean realms with consequences for precipitation and temperature (Alpert et al., 2006; Baldi et al., 2005; Tzedakis et al., 2009).

Current state-of-the-art on Mediterranean fire history

The 36 charcoal-based fire history time series (Figure 1 and Table 1) document our current knowledge of Holocene fire history in the Mediterranean basin. Five representative multiproxy paleoenvironmental records were selected as a basis for summarising the current state-of-the-art on mid- to late-Holocene fire history in five Mediterranean regions, including Spain, Sicily, central Italy, the Southern Alps, and the eastern Mediterranean (Figure 3). Additional charcoal series are cited to illustrate regional homogeneity and/or diversity of fire activity in each subregion. For those sites included in this analysis, ID numbers are listed parenthetically after the first mention of a record (Figure 1; Table 1).

Spain

The Siles Lake (301) record from the Segura Mountains in southern Spain (Figures 1 and 3A; Carrión, 2002) illustrates a period between 8500 and 8000 cal. BP of high fire activity, also recorded further north in the Ebro valley (site of Hoya del Castillo (842) and Guallar, Davis and Stevenson, 2007; Figure 1 and Table 1, Guallar is located in the same region) regionally considered as more arid than today. After 8000 cal. BP, Siles Lake observes a period of low fire activity. This pattern has been confirmed by two other sites from southern Spain: Cañada de la Cruz (612) and Villaverde (613) (Carrión et al., 2001a, b). Low-elevation and/or northern Spain fire-history records, including: Navarrés (637), Ojos del Tremendal (639), Hoya del Castillo and El Carrizal (596) (Carrión and Van Geel, 1999; Davis and Stevenson, 2007; Franco-Múgica et al., 2005; Stevenson, 2000), suggest potentially opposite patterns with fire records in the south. High charcoal influx values have been observed during the period *c*. 7000–6000 cal. BP, which is coherent with increased aridity in the Ebro Basin during the mid Holocene (González-Sampériz et al., 2009). After 5000 cal. BP, records from Segura Mountains, including Siles Lake, Cañada de la Cruz, Villaverde and Navarrés (637) (Figure 1 and Table 1) indicate a significant increase in fire activity, whereas fire activity is absent at northern sites. After 2800 cal. BP, all charcoal series available from Spain, including Baza (614), Gádor (627) (Carrión et al., 2003, 2007) and Las Pardillas (556) (Sánchez-Goñi and Hannon, 1999) show a general increase in fire activity.

Sicily

The recently published pollen and charcoal record of the coastal lake Gorgo Basso (848) (Figures 1 and 3B) from southern Sicily by Tinner et al. (2009) offers a more or less similar environmental history to the Segura region (see above). Approximately 8000 cal. BP, a decline in evergreen *Olea europaea* woods and an increase in fire activity appear to reflect drier climate conditions. From 7000 cal. BP, evergreen broadleaved forest (*Quercus ilex-Olea europaea*) expanded at the expense of open communities and was associated with a lower fire activity as well as a decrease in human activities. This is consistent with results from two other records available in Sicily: the upland Lago di Pergusa (714) in the central part of the island (Sadori and Giardini, 2006; Sadori et al., 2008) and the southern coastal lake Biviere di Gela (436) (Noti et al., 2009), where fire was frequent during periods of open xeric vegetation and declined under mixed deciduous–evergreen forest between 7500 and 7000 cal. BP. Low fire activity within the rather dense coastal evergreen forests persisted until renewed human activity disrupted these forests and opened the landscape for agriculture by *c*. 5000 cal. BP at Lago di Pergusa, *c*. 4500 cal. BP at Biviere di Gela and 2700 cal. BP at Gorgo Basso.

Central Italy

The multiproxy diagram from Lago dell'Accesa (Figures 1 and 3C) has been drawn with charcoal and pollen data from Vannière et al. (2008; pollen analysis: D. Colombaroli), completed with lake-level fluctuations from Magny et al. (2007b) and summer precipitation reconstruction from Peyron et al. (2011, this issue) based on pollen data (Drescher-Schneider et al., 2007). From 8500 to 2000 cal. BP, five periods of fire activity increase have been identified in this high-resolution study (contiguous 20 year span samples): 8000–7500, 6500–6000, 5500–5000, 3500–3000 and 2700–2300 cal. BP. Reconstructed fire frequency and return interval suggest decreases in fire activity were contemporaneous with *Quercus ilex* recovery, forest expansion, increasing lake-levels and pollen-inferred summer precipitation increases. As a general trend, fire frequency decreases from 5800 cal. BP to reach minimum values *c*. 5000 cal. BP. After 3700 cal. BP, fire activity appears to have been independent of lake-level fluctuations and summer precipitation changes, but could be linked with human impact, well attested by pollen data (not shown here). Six other charcoal records have been identified from literature in central Italy and Croatia, including; Valle di Castiglione (846), Battaglia (1113), Lagaccione (845), Malo Jezero (865), Lago di Massaciuccoli (130), Lago del Greppo (490) (Figure 1, Table 1). Excluding the series from Lago di Massaciuccoli (Colombaroli et al., 2007), these sites either have low sample resolution or do not span the mid Holocene. Nevertheless, some common features are detectable. At Lago di Massaciuccoli and Malo Jezero, a reduction in fire activity is attested *c*. 5300–5000 cal. BP (Colombaroli et al., 2009). This trend is also recorded at Lagaccione (Magri 2008; Magri and Ciuffarella, 1991) and Lago del Greppo (Vescovi, 2007) from 6000 cal. BP. An increase of fire activity is then observed around/after 3500 cal. BP at Malo Jezero (Colombaroli et al., 2009) and Valle di Castiglione (Magri, 2008; Magri and Ciuffarella, 1991), 3000 cal. BP at Battaglia (Caroli and Caldara, 2006) and 2200 cal. BP at Lago di Massaciuccoli (Colombaroli et al., 2007).

North Italy, Slovenia and Italian Switzerland (Southern Alps)

Northern Italy, Slovenia and Italian Switzerland lie within the fire-prone region of the submediterranean transition, between Mediterranean and temperate biomes, and thus are not fully typical of the Mediterranean climate area (Conedera et al., 1998; Tinner et al., 1998). Given the outstanding relevance of fires, this region south of the Alps, below 45°–46.5°N latitude, has the best documentation of Holocene fire history in all of southern Europe. Eleven charcoal records have been identified and selected for this synthesis, including Lago Piccolo di Avigliana (381), Lago della Costa (445), Lago di Fimon (826), Mlaka (615), Lago Lucone (824), Griblje Marsh (611), Lago di Muzzano (259), Lago di Origlio (258), Pian di Gembro (634), Piano (827), Lago Basso (379) (Figure 1 and Table 1). The amplitude of the fire signal is highly variable, but this might be a function of sedimentary processes related to the distance from the fire source. At Lago di Origlio (Figures 1 and 3D) and Lago di Muzzano (Tinner et al., 2005) charcoal influx values slightly increase *c*. 6500–6000 cal. BP and 5000–4500 cal. BP, respectively, i.e. during the Neolithic, but regional fire activity reached a maximum *c*. 2500 cal. BP (Iron Age). During this last period fires were sufficiently frequent to induce fire-adapted vegetation and create openings in fire-resistant oak forest. This fire history is more or less the same at the regional scale, fire activity increased *c*. 6500 cal. BP, a decrease occurred *c*. 5000 cal. BP, followed by subsequent increases and decreases in fire, but charcoal influxes do not decline to initial values for most of the records. Whereas periods of low fire activity coincided with phases of cold-humid climate, the human control on fire is unambiguously documented by the positive correlation between charcoal particles and pollen types

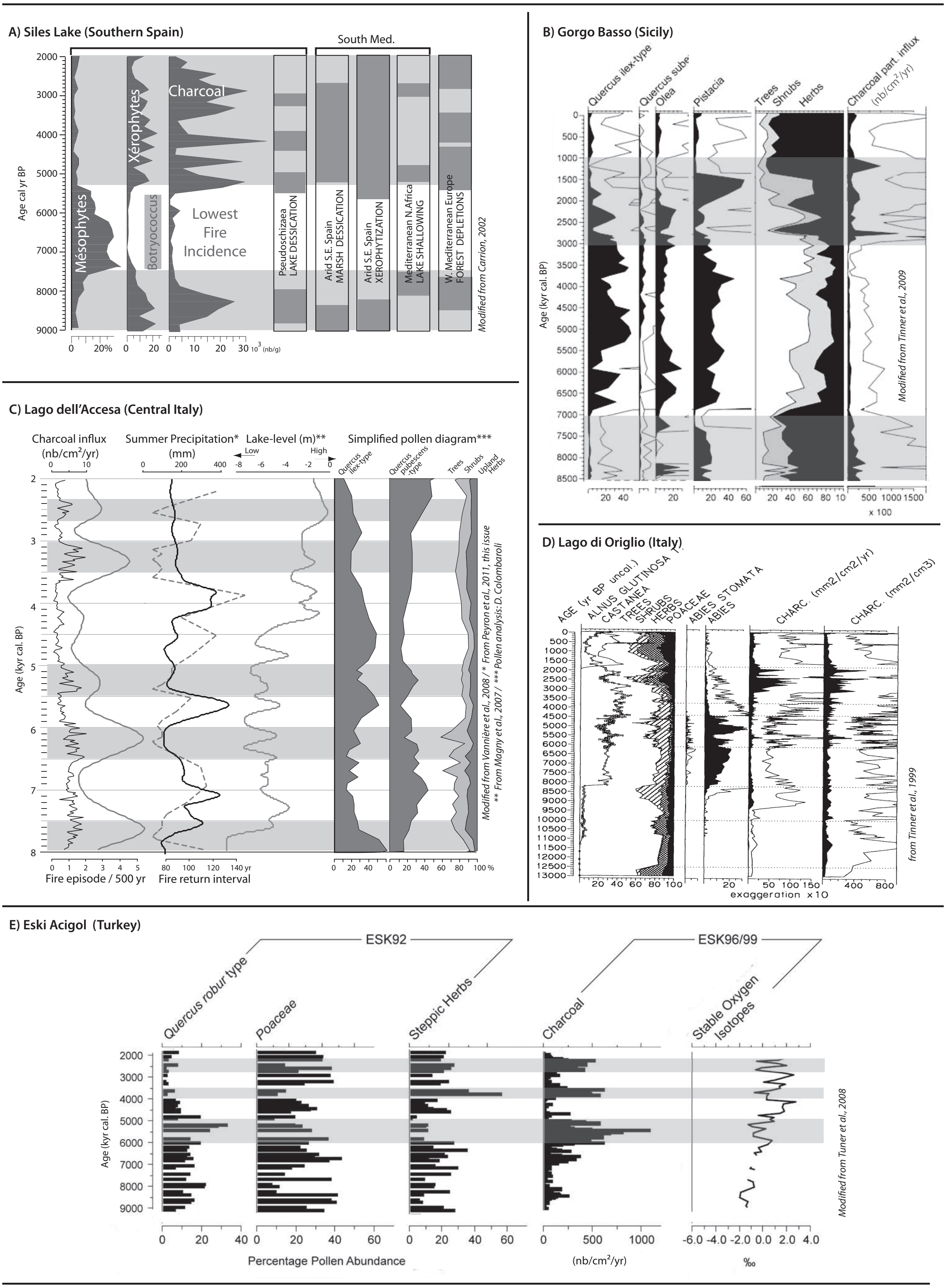

Figure 3. Selected series with high-resolution charcoal records from the main Mediterranean regions. Lake Siles from Southern Spain (Carrión, 2002), Gorgo Basso from Sicily (Tinner et al., 2009), Lago dell'Accesa from central Italy (lake levels from Magny et al., 2007, pollen data from Colombaroli et al., 2008, mean fire interval from Vannière et al., 2008, summer precipitation from Peyron et al., 2011, this issue), Lago di Origlio from Italian Switzerland (Tinner et al., 2005) and Eski Acıgöl from Turkey (Turner et al., 2008)

indicative of human activities (Andric, 2007; Finsinger, 2004; Finsinger and Tinner, 2006; Kaltenrieder et al., 2010; Pini, 2002; Tinner et al., 2005; Valsecchi, 2005; Valsecchi et al., 2006, 2008; Wick, 1994).

Turkey, Syria and Israel (eastern Mediterranean)

The eastern Mediterranean region is more limited in terms of published fire records. Recently, Turner et al. (2008) published a high-resolution series from lake Eski Acıgöl (772) (Figures 1 and 3E) in order to assess the changing role of climate and human impact on fire activity in the oak parkland zone of central Turkey. In this upland region biomass availability and humidity appear to have been the main factors controlling the timing of fire activity during the mid Holocene. Around 5000 cal. BP, the positive shift in $\delta^{18}O$ values reflects climatic aridification towards modern conditions in accordance with other western Asian climatic records (Roberts et al., 2008). The tree cover reached its maximum extent *c*. 5500 cal. BP, afterwards declining to be replaced by steppe herbs and grasses. Relative highest charcoal influx values have been detected during this time of relatively dense tree cover. Nevertheless, high fire activity is recorded later when oxygen isotope-inferred precipitation increased and herb cover developed, which might indicate increased winter or spring (rather than summer) precipitation. Three other series are available from the eastern part of the Mediterranean: Akgöl (1115) in Turkey (Turner et al., 2010), Ghab (67) in Syria, (Yasuda et al., 2000) and Hula (1114) in Israel (Turner et al., 2010). Despite these time series having lower sample resolution, they all indicate a clear negative trend in fire activity after 6000 cal. BP, reaching minimum values *c*. 5500–4500 cal. BP. Between 4000 and 3500 cal. BP, charcoal abundance at these sites show increased fire activity. Lake Van (73) from eastern Turkey confirms this last period of fire activity increase which could be linked more to changes in human impact and land uses (Wick et al., 2003).

Materials and methods

Data sources

The regional analysis of charcoal records from the Mediterranean region was accomplished through exploring records contained within the Global Charcoal Database (Table 1, GCD version 1, 2 and 3, http://gpwg.org). To improve the regional coverage of GCD version 1 (Power et al., 2008) an additional 25 sites were obtained from members of the Global Paleofire Working Group or digitized from the published literature (B. Vannière and M. Power) and have been incorporated into a new version of the GCD (version 2). An additional three records were recently added to the GCD and will be incorporated into GCD version 3. The GCD contains charcoal records from a variety of site types. Records from marine sediments, alluvial fans and soils were excluded because these records generally have lower temporal resolution than lakes and bogs and can be biased toward local (soils, alluvial deposits) or continental (marine) fires and the effect of preservation on charcoal, and are less well-suited for reconstructing biomass burning at regional scale. Archaeological charcoal records were also excluded because these often reflect anthropogenic or cultural choices in fuel wood and not the effects of naturally occurring fire on the landscape. Records with low sampling resolution, less than 1 sample every 400–500 years, were also excluded as they correspond more to discrete data than time series. Six others series, published in the literature have been kept out of this synthesis as they were outside our chronological window (8500–2500 cal. BP): Krimda (Morroco, Damblon, 1991), Sebkha Mhabeul (Tunisia, Marquer et al., 2008), Guallar (Spain, Davis and Stevenson, 2007), Pian Segna (Switzerland, Valsecchi, 2005), Bereket Basin (Turkey, Kaniewski et al., 2008) and Nar (Turkey, Turner et al., 2008).

Age controls

The radiocarbon corpus for the group of 36 records included in this study contains 168 dates (Figure 4). A maximum of 18 radiocarbon ages are available for the period 6000–6500 cal. BP, and eight radiocarbon dates per 500 years time-span is the minimum reached for the 8500–2500 time-window considered. The chronological framework of this synthesis seems to be well supported and appropriate for a time-reconstruction of fire activities changes with an uncertainty ± 150 years which is 1.5× the mean of calibration interval from all radiocarbon ages available.

All charcoal records used in this synthesis have been converted to a common time scale, in calibrated years BP (cal. BP) using either the original authors' published chronology or newly created age models from calibrated ^{14}C dates. Age models were constructed using all available calibrated ages, including dated tephra layers, and the 'best fit' age model was selected for individual records, based on goodness-of-fit statistics and the appearance of the resulting curve (Power et al., 2008, 2010).

Data analysis

A number of issues could influence the fidelity of overall charcoal influx as an indicator of fire activity. Particularly, the large variability in natural processes involved in sedimentary charcoal deposition within lake or mire basins and in the methods used to quantify charcoal, results in a wide range in individual data values within and between sites. To make possible meaningful comparisons within and between records, a protocol was used for the transformation and standardization of individual records (Power et al., 2010). This protocol included: (1) rescaling the values using a minimax transformation, (2) transforming and homogenising the variance using the Box-Cox transformation, and (3) rescaling values once more to Z-scores (Figure 5). The minimax transformation rescales charcoal values from each record to a range between 0 and 1 by subtracting the minimum charcoal value in the record from each charcoal value, and dividing by the range of values:

$$c_i' = (c_i - c_{\min}) / (c_{\max} - c_{\min}) \tag{1}$$

where c_i' is the minimax-transformed value of the *i*-th sample in a particular record, c_i, and $c_{\max}$ and $c_{\min}$ are the maximum and minimum values of the c_i's. The minimax transformation does not alter the pattern of variability or change the distribution of the data values through time in a particular record, but it permits records with different ranges of values to be compared on a common scale.

The generally skewed distribution of charcoal values, with a long, or heavy, upper tail, would produce a disproportionate

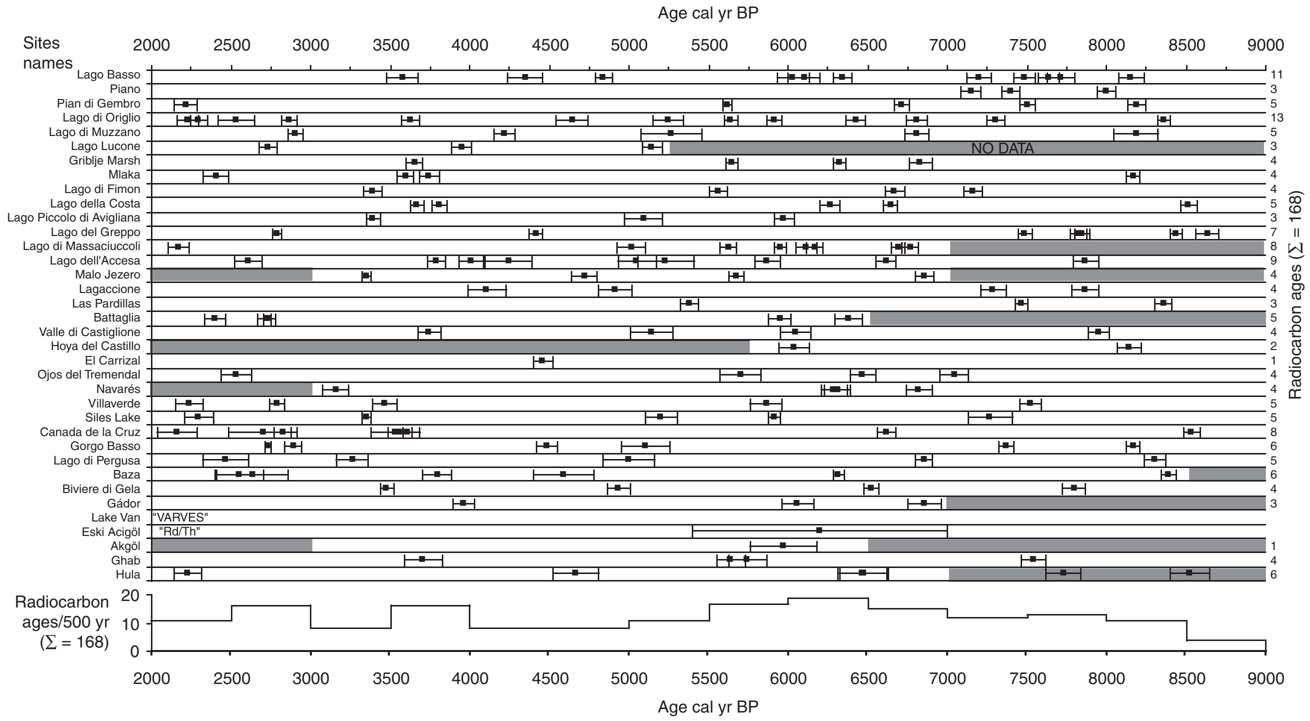

Figure 4. Corpus of radiocarbon dates available from the 36 series (references are listed in Table 1). Chronological distribution of ages with the calibrated interval and 500 yr window quantification curves for each region. Grey zones indicate the absence of data within the series

number of negative anomalies (or deviations from the mean of a particular base period) without further transformation. The rescaled values were thus transformed using the Box-Cox transformation:

$$c_i^* = \begin{cases} ((c_i' + \alpha)^{\lambda} - 1)/\lambda & \lambda \neq 0 \\ \log(c_i' + \alpha) & \lambda = 0 \end{cases} \qquad (2)$$

where c_i^* is the transformed value, λ is the Box-Cox transformation parameter and α is a small positive constant (here, 0.01) added to avoid problems when c_i' and λ are both zero. The transformation parameter λ is estimated by maximum likelihood using the procedure described by Venables and Ripley (2002). In practice, the optimization involved in selecting λ can be seen as an attempt to produce data values that are normally distributed, with few unusual or outlying points. The Box-Cox transformation is also known as a variance-stabilizing transformation because it usefully reduces the dependence of variability in the data on the level of the values (see Emerson and Stoto, 1983). Note that Box-Cox transformations of both the 'raw' and mimimax-rescaled data produce the same results. Because the specific combination of values being transformed and the transformation parameter λ can result in negative values in the transformed data, and because these values may seem counterintuitive, the transformed data can be rescaled again using the minimax transformation. For instance, Figure 5 shows that the impact of the Box-Cox transformation on the charcoal influx data from one site, Lago dell'Accesa, is relatively modest overall (Figure 5). A comparison of raw charcoal influx (Figure 5B) and transformed charcoal influx (using the whole Holocene as the base period, Figure 5B) shows a curvilinear relationship, as would be expected for a power-function transformation like the Box-Cox. The impact of the transformation and the distribution (Figure 5C) of the data do not affect the overall trends or pattern of variability within the data. Note that the optimal value of λ (0.02 here) 'normalizes' the distribution, and makes the variability of the data less dependent on the local level.

Paleoenvironmental time series, expressed as anomalies, or deviations from some long-term average, often provide a meaningful context for interpreting past environmental change. The conventional approach to create such anomalies is to standardize the data, expressing the values as Z-scores:

$$z_i = (c_i^* - \bar{c}^*_{(4\text{ka})}) / s^*_{c(4\text{ka})} \qquad (3)$$

where, for example, $\bar{c}^*_{(4\text{ka})}$ is the mean minimax-rescaled and Box-Cox transformed charcoal value over a predefined base period, such as the interval 4000 to 200 cal. BP, and $s^*_{c(4\text{ka})}$ is the standard deviation over the same interval. The resulting Z-scores have a mean of 0.0 and standard deviation of 1.0 (over the base period), which provides an intuitive interpretation of individual values as above or below the long-term mean. When the data are approximately normally distributed, the relative frequency of values of different magnitude can also be inferred. Because the rescaling is linear, the appearance of the standardized time series is identical to the transformed series.

Results

Four criteria were used for delineating several key fire history regions within the Mediterranean basin (Figure 1), including: (1) Mediterranean climate zones (e.g. number of dry month per year, see 'Study area' above), (2) biogeographic vegetation classes (e.g. evergreen-broadleaf vegetation dominance), (3) current knowledge of fire history (see 'Current state-of-the-art on

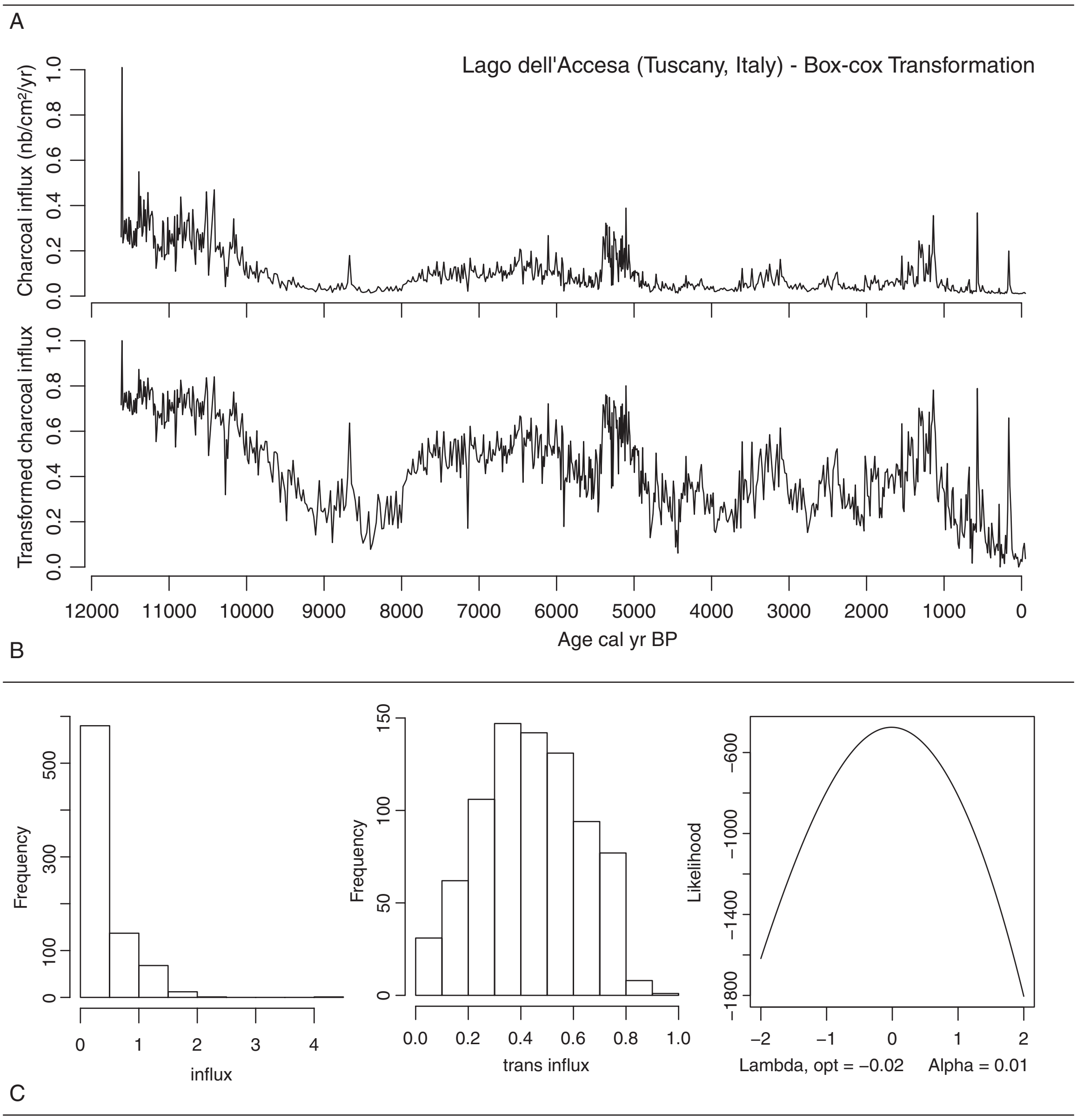

Figure 5. Charcoal record from Lago dell'Accesa (Tuscany, Italy); (A) raw data; (B) Box-Cox transformed data; (C) raw influx values distribution diagram, transformed influx distribution diagram, diagram showing curvilinear relationship between both groups of values and Box-Cox transformation parameters (λ and α)

Mediterranean fire history, above), (4) and the quality and quantity of available charcoal records. Four groups of sites were defined: a west–east partition of the Mediterranean region was used to group all records from southwestern Asia (Turkey, Syria and Israel) and second, a north–south partition based on 40°N latitude was used to separate southern Spain and southern Italy from northern Spain and central Italy (Figure 1 and Table 1). The group of sites above 45°N latitude corresponds to sites in the fire-prone submediterranean zone (northern Italy, Slovenia and Italian Switzerland), which, similar to other submediterranean areas in Europe (e.g. northern Spain, southwestern France), is outside the limit of the Mediterranean region *stricto sensu* (Quézel and Médail, 2003; Figure 1). The 36 transformed charcoal records from the Mediterranean region (Figure 6) are presented in a Hovmöller diagram (Hovmöller, 1949). Each region is well documented, except the northern part of Spain ('Med. West 40–45') for the period after 5000 cal. BP and to a lesser extent the 'Med. East' region where Eski Acıgöl is the only high-resolution series. Colour areas reveal homogeneous Z-scores' periods (mainly positive or negative) which confirm common regional patterns in fire activity changes over the studied period.

Regional groupings of 250 year smoothed Z-scores of transformed charcoal influx are used to reconstruct regional trends in fire activity for the period 8500–2500 cal. BP (Figure 7). 'Med. All' represents all records included in this study (n = 36, see Table 1). 'Med. *stricto sensu*' relates to those charcoals records occurring within the Mediterranean *stricto sensu* zone (n = 25). These two reconstructed curves appear quite similar, and values fluctuate around the average throughout the period. Two periods of above average values can be identified between 8000 and 5300 cal. BP and between 4500 and 2800 cal. BP, interrupted by a sharp decrease *c*. 5300–5000 cal. BP. Several departures toward lower values mark general trends at *c*. 8200, 6700, 5900, 4200 and 3100 cal. BP. Except for the 8200 cal. BP event, records of these

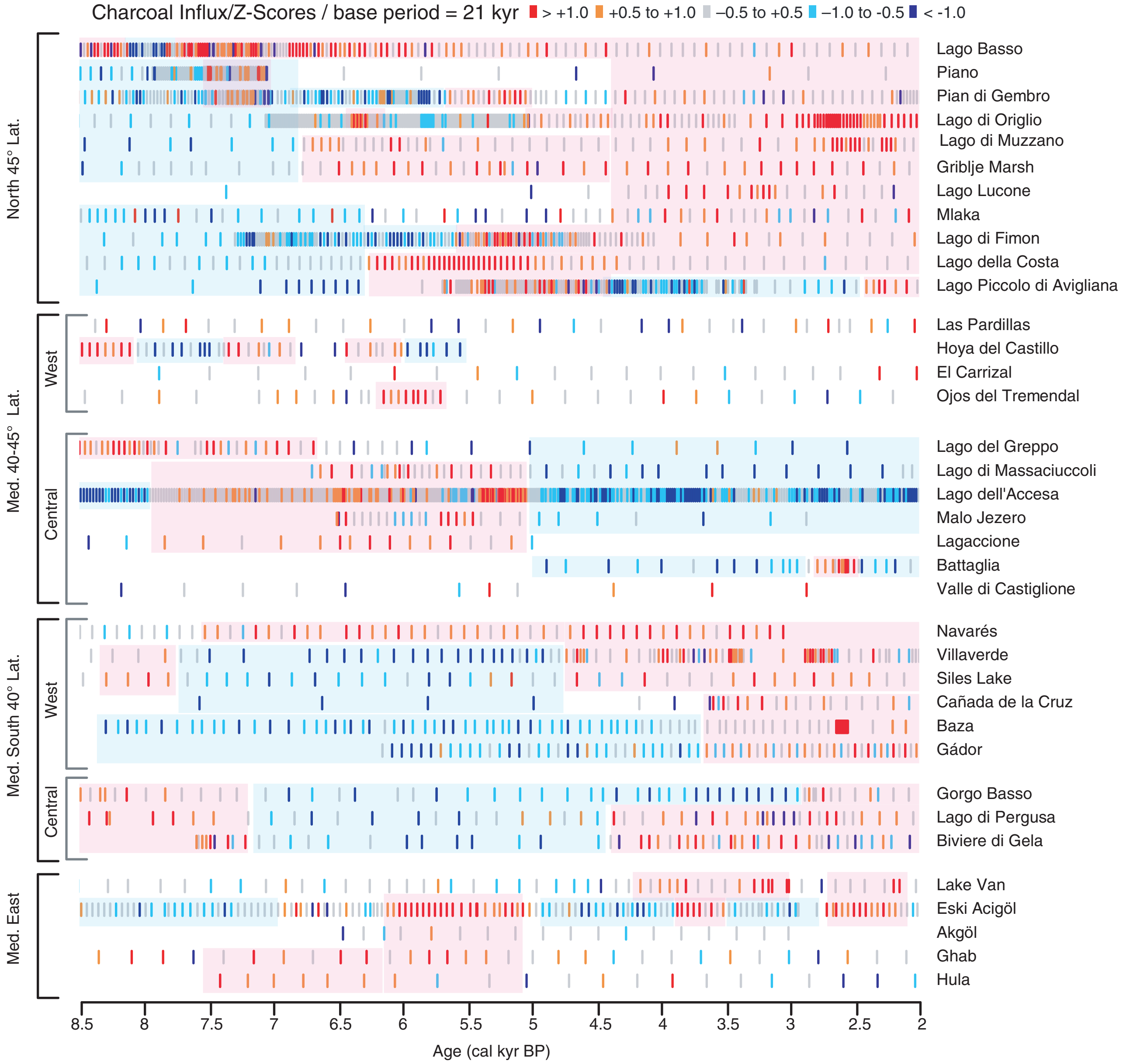

Figure 6. Hovmöller-type diagram with Z-scores of transformed charcoal influx from the 36 series included in this study (series are organized by region and latitude). Tick marks represent individual samples with a Z-score value shown in colour. Shading underlines periods and groups of site with dominant positive (pink) or negative (blue) Z-score values

centennial-scale changes in fire activity, presented as a composite of Z-score of transformed charcoal influx, show fairly broad confidence intervals, i.e. changes are less than the range of variability seen by the upper and lower Z-score confident intervals (see shaded areas in Figure 7). In these cases, the pattern arises from strong fluctuations at particular sites and a regional interpretation appears difficult. The uncertainty may be related to the compositing of several low-resolution records with several detailed time series (e.g. Pian di Gembro, Lago di Fimon or Lago dell'Accesa), suggesting the above centennial-scale decreases in fire activity may persist as more detailed series become available.

'Med. East' is the smallest group with only five records available between 8500 and 2500 cal. BP (which leads to a large uncertainty envelope). This Z-score curve shows the greatest variability. Before 8000 cal. BP values appear relatively high, and then decrease reaching a first minimum *c.* 7400 cal. BP. A general increasing trend is observed until *c.* 5700 cal. BP, abruptly followed by a strong decrease to reach the lowest values of the analysed period *c.* 4500 cal. BP. A new trend toward positive values begins after 4500 cal. BP.

Fire activity from the north 45°N latitude group of sites ('North 45', *n* = 11) presents a pattern characterized by multimillennial trends of increasing fire over the entire period punctuated by relatively high magnitude negative events. Z-scores from charcoal data have their lowest values (−0.4) *c.* 8200 cal. BP and other negative excursions are recorded *c.* 6600, 5900, 4200 and 3400 cal. BP. A strong shift is also observed *c.* 5200 cal. BP after a first maximum (+0.7), and values reach a second maximum at the end of the study period.

The group of sites located in the western part of the Mediterranean basin and between 40°N and 45°N latitudes show a bimodal pattern of fire activity ('Med. West 40–45', *n* = 11). After a short negative event recorded *c.* 8200 cal. BP, increasing Z-scores of transformed charcoal influx indicate high fire activity between 7500 and 5300 cal. BP with a brief decrease *c.* 6000–5800 cal. BP. An abrupt change is recorded just before 5000 cal. BP (the uncertainty range is relatively good for this period). Afterwards, Z-score values appear very low (uncertainty range is relatively large, reflecting a high variability between records) until 3500 cal. BP, when a slight increase occurs. Two other periods of decreased fire activity are noted at *c*. 4200 and 2900 cal. BP.

The composite charcoal curve for the southwestern group ('Med. West South 40', *n* = 9) suggests an inverse pattern to the Med. West 40–45 region. After an initial period of high charcoal influx values *c*. 8000 cal. BP, a decreasing trend is recorded. A relatively long period of low fire activity occurs between 7500 and 5000 cal. BP, with lowest values reached *c*. 6000–5500 cal. BP. Conversely, values show a progressive trend towards high fire activity between 5000 and 3000 cal. BP. Short, rapid negative fluctuations *c*. 4500, 3600 and 3200 cal. BP temporarily break this general tendency.

To summarise, several common features can be mentioned from these results or reconstructed fire activity (Figure 7):

- A general trend toward increasing fire activity is recorded during the entire period studied in the submediterranean region above 45°N latitude (Figure 7, 'North 45').
- Western Mediterranean sites located north 40°N latitude record an increasing trend after 8000 cal. BP which reached a maximum between 6000 and 5500 cal. BP.
- Changes observed in eastern Mediterranean fire activity are more or less similar to those observed in the higher latitudes.
- There is an opposite pattern between areas south and north of 40°N–43° latitude in the central and western part of the Mediterranean basin.
- A centennial-scale decrease in fire activity (lowest values reached within trends) is identified within all records above 40°N latitude at c. 8200 cal. BP.
- In all regions a strong reversal is identified c. 5500–5000 cal. BP.
- After 4500–4000 cal. BP, all regions appear to be affected by enhanced fire activity, except 'Med. West 40–45' where Z-score of charcoal influx remain below the long-term average.
- Several brief decreases in fire activity (lowest values reached within trends) are observed within all records north of 40°N latitude at c. 5900, 4200 and 2900 cal. yr BP.

This can be supported by Figure 8, where 500-year mean Z-score values for each region are mapped at a Mediterranean scale. The north–south opposition is particularly apparent between *c*. 8000–8500 and 7000–5000 cal. BP. A general, low fire activity is recorded between *c*. 4500 and 4000 cal. BP. Maximum fire activity occurred in the east and north of 40°N latitude between 5500 and 5000 cal. BP and after 4000 and 3000 cal. BP.

Discussion

Forcing factors of Mediterranean fire activity

It appears that there is spatial coherency in fire histories within different parts of the Mediterranean (Figures 6 and 7), however, Figure 8 shows that there are also inconsistencies between areas. These regional differences might be explained by several different causes.

(i) Contrasting climatic histories within the Mediterranean basin. If all Mediterranean vegetation types had similar controls on their fire activity, and if climate was the principal agency determining changes in fire activity during the period from 8500 to 2500 cal. BP, then inter-regional contrasts in fire history should reflect different histories of climate and seasonality (e.g. on a north–south gradient). The possibility of such a paleoclimatic contrast was raised by Magny et al. (2007a) in respect of southern and northern Italy using paleohydrological lake indicators. In a similar way, but based on lake-isotope data, Roberts et al. (2008) suggest a contrast between a wetter southeastern and a drier northwestern Mediterranean during the early Holocene. Climatic reconstructions from vegetation data focusing on the mid-Holocene climate (6000 BP) for Europe show a latitudinal gradient (Cheddadi et al., 1997; Davis et al., 2003) and/or a north–south partition around 40°–43°N latitude. Latitudinal temperature anomaly reconstructions in the Afro-European sector indicate negative values at lower latitudes and positive or near zero values at high latitudes (Davis and Brewer, 2009). This partition of the Mediterranean area may also be observed from most of the simulated distribution of biomes (with a northern zone of cool/temperate/broadleaf open woodlands and a southern warm/temperate open woodlands) and the soil water availability simulation (Brewer et al., 2009). Brayshaw et al. (2011, this issue) using a numerical simulation model of Mediterranean paleoclimate, confirm that there could have been significant spatial heterogeneity in patterns of precipitation change during the early and mid Holocene. A negative fire signal is observed *c*. 8200–8000 cal. BP in the records above 40°N latitude which could be linked with the cold 8.2 ka BP event (Alley et al., 1997; Magny et al., 2003; Wick and Tinner 1997) well known in North Atlantic region. Conversely, fire activity seems to be high in southern Mediterranean areas and in dry western Mediterranean regions including the Ebro valley, Spain (Davis and Stevenson, 2007). This is in accordance with the paleohydrological pattern at this time. Dry conditions in the Mediterranean South of 43°N latitude seems to coincide with cold and wet phases in and around the Alps (Magny et al., 2003, Marchetto et al., 2008). By *c*. 7500 cal. BP, fire activity increased (decreased) in northern (southern) Mediterranean regions. An inverse situation is documented after 5000 cal. BP.

(ii) Similar climatic histories but contrasting fire responses in different types of vegetation/land use. Because Mediterranean vegetation varies from deciduous and evergreen woodland to scrub and semi-desert, different regional plant functional types and or species composition have differing controls on fire activity. Most forest ecosystems are not fuel-limited, so that fire increases during periods of dry climate (e.g. Vannière et al., 2008). In regions with more open vegetation (e.g. grassland), fire is potentially fuel-limited and likely to increase during wet climate phases (e.g. Turner et al., 2008). Overall, northern Mediterranean sites are more forested, especially in Italy. If biomass were the only control on paleofire activity, we might expect the same climatic history to result in a contrasting pattern of burning between wetter (northern) and drier (southern) regional sequences. In reality, this explanation does not seem to apply to the north–south paleofire gradient in the western-central Mediterranean in any simple way. For example, even at lowland and upland southern sites (e.g. Siles, Carrión, 2002; Gorgo Basso, Tinner et al., 2009; Figures 3A, B and 9) the period of lowest fire activity is linked to maximum mid-Holocene forest development. By contrast, burning appears to have been biomass-limited in eastern Mediterranean sites, where

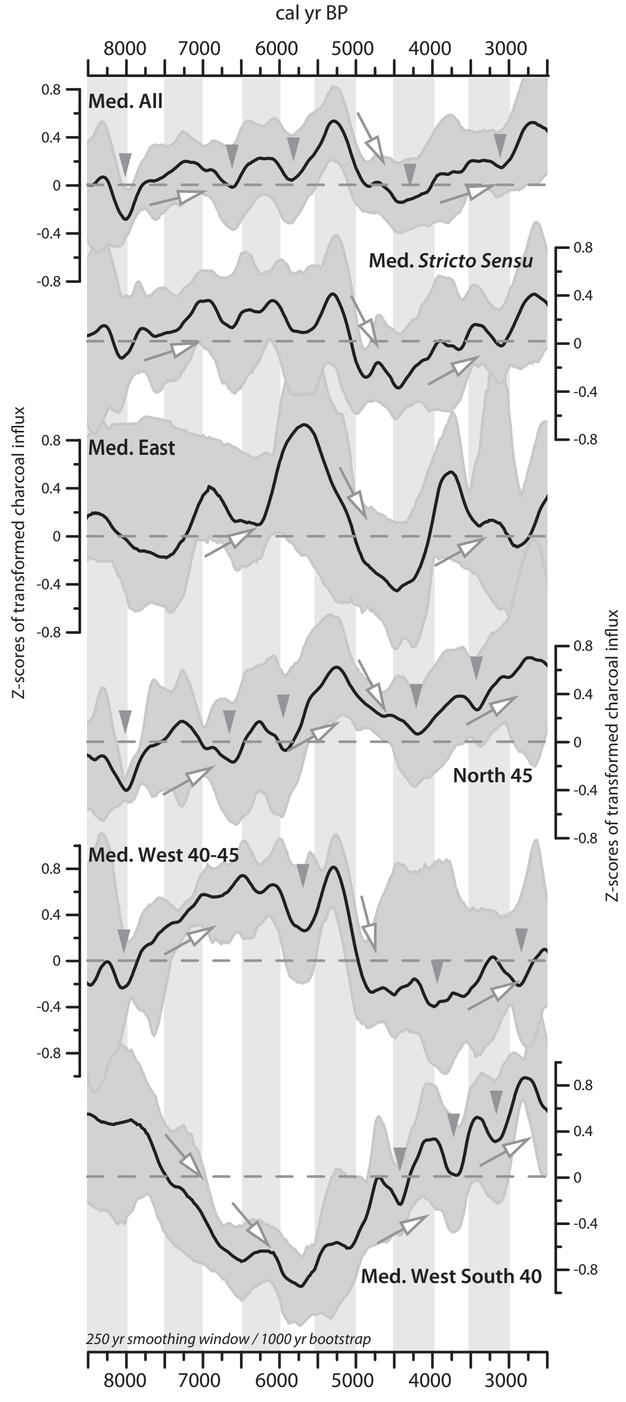

Figure 7. Average Z-scores of transformed charcoal influx per region (250 yr smoothing window/1000 yr bootstrap). Grey envelopes represent the upper and lower 95% confidence intervals from the bootstrap analysis. White arrows underline tendencies and grey ones mark short events. The dotted line corresponds to the mean values of the base period: 21 000–200 cal. yr BP

Z-score maxima coincide with the period of greatest woodland development in the mid Holocene (Turner et al., 2008, 2010; Figures 3 and 8). This may also apply to some lowland southwestern Mediterranean sites with a strong moisture deficit, such as Navarrés (Spain) which experienced increased fire frequencies during the mid-Holocene with increased precipitation (Carrión and Van Geel, 1999). This indicates strong regional-scale differences in terms of species composition and vegetation structure/funtional types, expecially between the western and central Mediterranean and since the early Holocene which are not explainable by land-use only. For instance, in Spain, *Pinus* sp. has played a dominant role in long-term forest development. In Italy instead, rather mesophilous taxa like *Ostrya, Abies, Fagus,* and *Carpinus* were more important (e.g. de Beaulieu et al., 2005). Differences in dominant species observed in palynological records across a west–east gradient have not affected the regional fire history as common trends have emerged between charcoal series from Italy and Spain ('Med. West 40–45' and 'Med. West South 40'). Table 1 presents the vegetation and bioclimate surrounding each site, from this table and from Figure 6 (results data), it appears that regrouping records according to vegetation type does result in common trends in fire activity.

(iii) Human intervention in burning activity. It is well-known that fire was used as a principal means of forest clearance for agriculture and pastoralism since Neolithic times (e.g. Rius et al., 2009; Tinner et al., 1999; Vannière and Martineau, 2005). In densely forested Mediterranean landscapes, the first 'Landnám' clearance horizon is usually associated with a reduction in tree pollen, and an increase in charcoal and anthropogenic pollen indicators (e.g. Noti et al., 2009). Evidence of forest clearance first appears as early as *c*. 8000 cal. BP at sites in central and northern Italy, such as Lago di Massaciuccoli and Lago dell'Accesa (Colombaroli et al., 2007, 2008). In records from the southern and eastern Mediterranean, the early anthropogenic use of fire is more difficult to be distinguished from paleoecological data, because landscapes were less densely forested and pollen types of crops and weeds such as *Cerealia*-type and *Plantago lanceolata*-type are not necessarily diagnostic of human activity. The spread of agriculture in the Mediterranean area probably proceeded in leaps, outwards from the 'Fertile Crescent region' (eastern Mediterranean) and westwards into Greece, southern Italy and then beyond to central and northwestern Europe. The different leaps are dated to *c*. 12000, 8700–8100 and 8100–7000 cal. BP, corresponding to the crossing of the Taurus Mountains (Turkey), the southern Adriatic Sea (Greece–Italy) and western Mediterranean basin (Bocquet-Appel et al., 2009), respectively. But it is only from 4000–3500 cal. BP onwards, that large-scale land-use conversion by Bronze Age and later cultures permanently changed biomass availability and burning activity across the Mediterranean (Carrión et al., 2007; Sadori et al., 2004, 2008; Vannière et al., 2008) and most particularly in the northern Mediterranean region (southern Alps, Cruise et al., 2009; Favilli et al., 2010; Finsinger and Tinner, 2006; Tinner et al., 2005; Valsecchi et al., 2006). Therefore, after this time, it is difficult to attribute trends in paleofire activity to climatic control with absolute confidence. Prior to 4000–3500 cal. BP, on the other hand, climate appears to have acted as the main pacemaker for the regional-scale timing of biomass burning regardless if human activity was recorded at specific sites (Turner et al., 2010; Vannière et al., 2008) or not. From Figures 8 and 9, the synchronicity of short-term decreases in fire activity *c*. 8200, 5900, 4200 cal. BP and the shift *c*. 5500–5000 cal. BP observed in all regions provides a good supporting argument for this hypothesis.

Climatic conditions and mid- to late-Holocene fire activity

Sea surface and summer temperature reconstructions suggest that the Holocene Thermal Maximum in the Northern Hemisphere

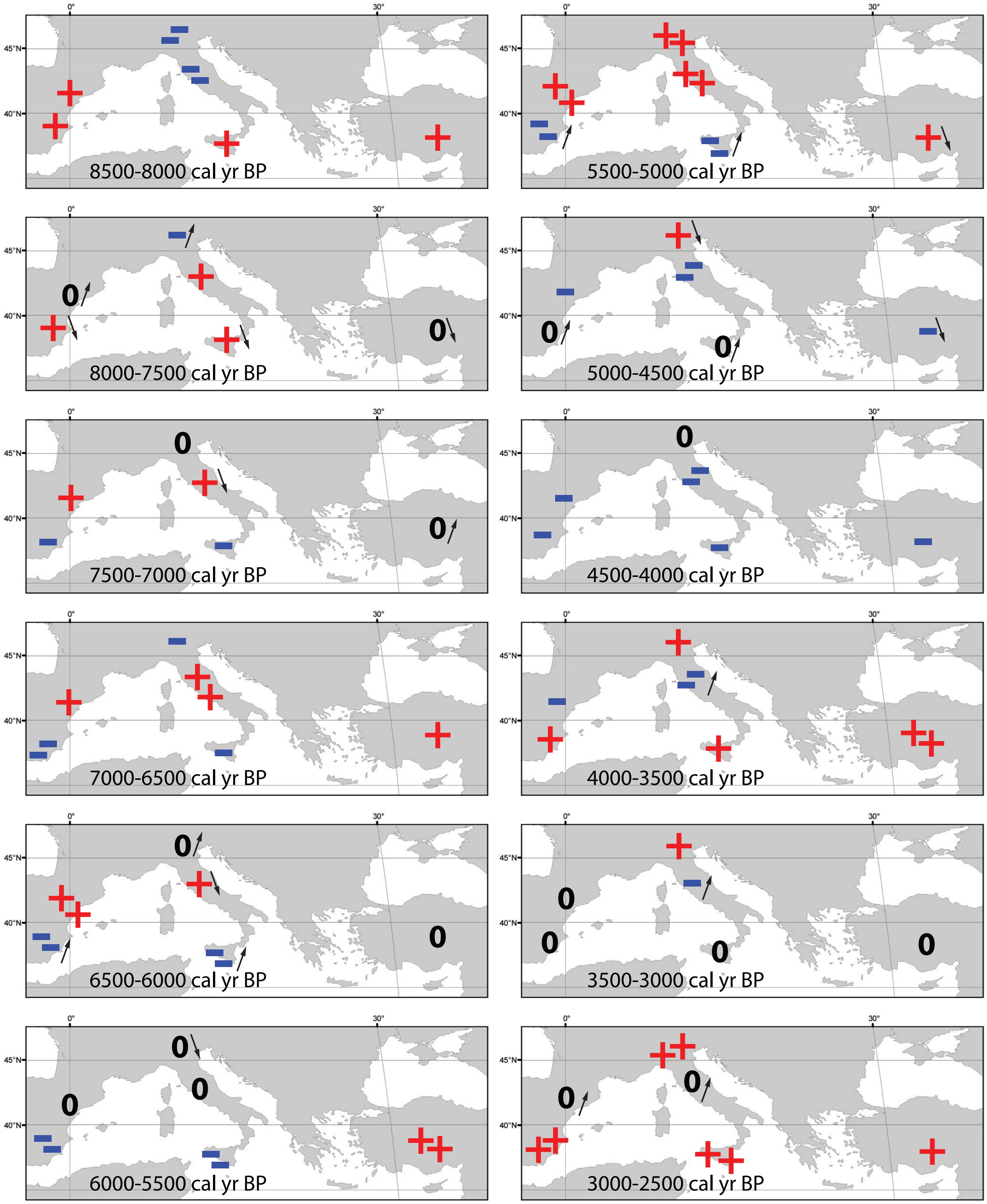

Figure 8. 500 year time slices map of mean regional fire activity. Positive indicates mean Z-scores higher than the Holocene average (dotted lines), double positive corresponds to very high values, zero indicates values around the average, minus shows low values and double minus indicates very low values. Arrow indicates tendency

occured between *c*. 8000 and 5000 cal. BP (Calvo et al., 2002; Renssen et al., 2009, respectively). By *c*. 6000 cal. BP, seasonality was 20–30 W/m² higher than present in the Northern Hemisphere and gradually decreased toward present. Fom Scandinavia, glacier variations suggest a three-partite Holocene: an early Holocene before 9500 cal. BP marked by enlarged glaciers, a mid Holocene between 9500 and 5000 cal. BP, characterized by relatively small or absent glaciers, and a late Holocene Neoglacial period, with glacial re-advances (Matthews and Dresser, 2008). In the same way, during the Holocene, three periods of glacier recession were

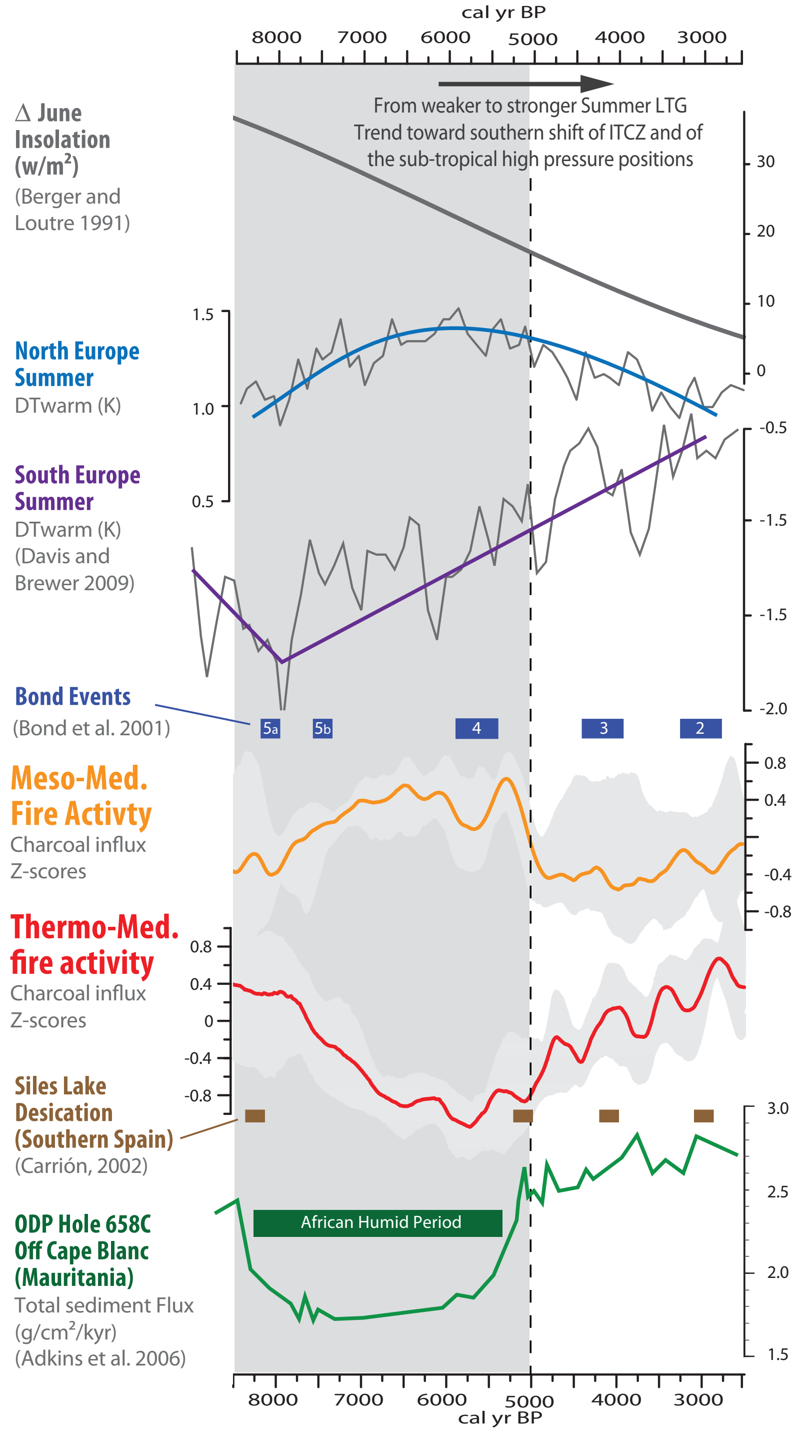

Figure 9. Mid-month June insolation over the region (Berger and Loutre, 1991); reconstructed warmest month (summer) temperatures (Twarm) for north and south Europe (Davis and Brewer, 2009); LTG, latitudinal temperature gradient; North Atlantic Bond Events (Bond et al., 2001); mean Z-scores of transformed charcoal influx for 'Med. West 40–45' and 'Med. West South40' regions; Siles lake desiccation periods (Carrión, 2002); total sediment influx from the Atlantic ODP Hole 658C (off Cape Blanc, Mauritania) and chronology of the African Humid Period (Adkins et al., 2006)

detected in the eastern Swiss Alps at 9200, between 7450–6650 and 6200–5650 cal. BP (Joerin et al., 2008). This implies a summer temperature increase of about 1.8°C assuming unchanged precipitation or of about 1°C taking into account a precipitation decrease of 250 mm/yr, or 2.5°C with a precipitation increase of 250 mm/yr. All these data attest to the importance of higher-than-present seasonality and summer drought, which is regionally coherent with a gradual increase in fire activity beginning at *c.* 8000 cal. BP in the northern (40°N) latitude Mediterranean zones and particularly in the 'Med. West 40–45' region (Figures 8 and 9). Glacial dynamics are also in accordance with regional fire reconstructions with fire activity increasing up to a maximum at *c.* 5300 cal. BP, being briefly interrupted by lower values *c.* 6000–5500 cal. BP. In a similar way, pollen-based biome reconstructions are characterized by a general expansion of woodland during the early to mid Holocene in Europe (Davis et al., 2003). Generally, fire activity depends on fuel-moisture levels, which are the result of the ratio between precipitation and evapotranspiration as related to temperature. Within this context, simulations of soil-water availability suggest negative anomalies in the northern part of the Mediterranean (Brewer et al., 2009) which might have promoted increased fire activity in the region north of 40°N latitude during the mid Holocene. Therefore, between 8000 and 6000 cal. BP, vegetation distribution suggests a reduced north–south gradient in climate over Europe and a lowering of the Earth's Latitudinal Temperature Gradient (LTG), particularly during summer (Davis and Brewer, 2009; Figure 9). The subsequent decreasing (increasing) trend in summer temperature in the north (south) implies a progressive change toward an enhanced summer LTG. These geographical partitions and temporal tendancies in summer temperature may help explain the observed time-transgressive changes in fire activity from the northern to southern Mediterranean region (Figure 9).

In opposition to the northern Mediterranean region, a period of low fire activity from *c*. 7500 to 5000 (begining of the fire activity increase) cal. BP in the 'Med. West South 40' region (Figures 8 and 9) corresponds to a humid climate period. On the basis of high lake-levels in the uplands of southern Spain (Carrión, 2002; Reed et al., 2001) and expansion of evergreen-broadleaf forest in coastal Sicily (Tinner et al., 2009), this period has been interpreted as characterized by increased precipitation in the southern Mediterranean region. In agreement with mid-Holocene reconstructions from the Iberian Peninsula, pollen data from the southern coast of Sicily suggests expanded shrub and forest cover occupied areas previously dominated by Mediterranean scrubs and grasslands after 7000 cal. BP (Tinner et al., 2009). Similarly, mid-Holocene lake-level maxima in the northern latitudes of Africa are consistent with widespread evidence of wetter-than-present climate conditions at *c*. 6000 cal. BP (Gasse, 2002). Decreased fire activity between 7500 and 5200 cal. BP in the 'Med. West South 40' region suggests the southern Mediterranean experienced significantly different environmental conditions compared with present. Pollen and fire records both suggest climate became wetter than present during the mid Holocene not in response to the northward extension of the monsoon (see the review by Tzedakis, 2007), but from precipitation originating within the Mediterranean (Arz et al., 2003; Bar-Matthews et al., 2000) and/or, in the western part of the region, from advection of Atlantic moisture.

In the Northern Hemisphere tropics, the most significant environmental change during the early Holocene was the intensification and subsequent decline of the African and Asian Monsoons (e.g. Adkins et al., 2006; Morrill et al., 2003; Figure 9). Mid-Holocene climate change is attributed to a weakening of orbital forcing in the Northern Hemisphere summer, which led to a transition from humid to arid conditions in North Africa (Cole et al. 2009; deMenocal et al., 2000), and a cooling trend over northern continental land masses (Renssen et al., 2009) and the North Atlantic (Kim et al. 2004; Marchal et al., 2002). At latest after 5500 cal. BP, the redistribution of insolation (an orbitally driven decrease of summer insolation in the Northern Hemisphere) was responsible for the southward migration of the ITCZ and continued weakening of the Afro- and Asian-monsoon system (Broccoli et al., 2006; Fleitmann et al., 2003; Haug et al., 2001; Figure 9). In fact, evidence suggests by 8000 cal. BP, as seasonality decreased, the weakening of the Afro-Asian summer monsoon had already caused widespread aridity in subtropical Africa and Asia, and became ineffective as a dominant climatic control by 5500–5000 cal. BP (Adkins et al., 2006; Cole et al., 2009; deMenocal et al., 2000; Fleitmann et al., 2003). In contrast to subtropical Africa and Asia, the Mediterranean region was not directly linked to the monsoon, but indirectly as an intensified meridional Hadley circulation, associated with the African monsoon strengthened the North Atlantic anticyclone and blocked moister advection eastward toward the Mediterranean. The weakening of the African monsoon from 8000–5500 cal. BP and the resulting southward migration of the subtropical high-pressure field may have allowed westerlies to gradually deliver more humidity to the southern Mediterranean area (e.g. Spain, Sicily) during the mid Holocene (Tinner et al. 2009; Tzedakis 2007).

Between 5500 and 5000 cal. BP fire activity abruptly changed across the Mediterranean (Figures 8 and 9) as fire decreased in northern and eastern regions and a progressively increased in southern regions. Changes in fire activity in the northern Mediterranean region may be linked to a long-term trend toward cooler/wetter summers, related to the Neoglacial period, in central Europe, the nearby Alps and North Central Italy (Magny et al., 2006, 2007b, 2009; Matthews and Dresser, 2008; Tinner, 2006). These findings stand in contrast to a well-documented progressive aridification of the central and southern Mediterranean regions (Carrión, 2002; Gasse, 2002; Magny et al., 2006; Peyron et al., 2011, this issue; Reed et al., 2001; Sadori et al., 2008) although this trend appears to be absent in coastal Sicily and Tuscany, where conditions remained rather stable during the late Holocene (Colombaroli et al., 2007; Marchetto et al., 2008; Noti et al., 2009; Tinner et al., 2009). During the late Holocene, a reduction in winter precipitation may have resulted in drier conditions across the northern Mediterranean region, while wetter summers would explain decreased fire activity in areas North of 40°N latitude, through the promotion of moist habitats. The southern region, experiencing drier summers at this time, would not have been affected by increased precipitation. On the contrary, an increase in summer temperature (Davis and Brewer, 2009; Figure 9), may have favoured increased evapotranspiration, fire activity and aridity. Despite climatic controls, the late Holocene was a period of increased vegetation disturbance with the development of pine forests (some planted), a partial (human-induced) spread of drought-adapted plant communities and an overall increase in land use (Carrión et al., 2007; Cruise et al., 2009; Favilli et al., 2010; Sadori et al., 2004, 2008; Vannière et al., 2008). Anthropogenic disturbance associated with demographic population expansion likely explains at least part of the increasing trend toward greater fire activity in the Mediterranean around 4000 to 3000 cal. BP.

Between 8500 and 2500 cal. BP, several transient declines in fire activity were observed above 40°N latitude, including decreases at 8200, 6600, 5900, 4200 and 2800 cal. BP (Figures 8 and 9). Continental and marine paleoecological studies have emphasized the importance of rapid climate oscillations, originating in the North Atlantic, and their downstream impacts on the Mediterranean ecosystems during the Holocene (Cacho et al., 2001; Incarbona et al., 2008; Kotthoff et al., 2008; Magny et al., 2007a, 2009; Rodrigues et al., 2009). These apparently short-lived oscillations may be related to climatic mechanisms driving Bond cold events first identified in the North Atlantic (Bond et al., 2001). Increased moisture availability, mainly driven by a change in the westerlies at high latitudes, was likely modulated by an NAO-like climate mechanism (Frigola et al., 2007; Piva et al., 2008; Figure 2). For instance, *c*. 4000 cal. BP the entire Mediterranean experienced a period of low fire activity, with the exception of a few southern sites (e.g. Lake Siles, Figure 3A, Carrión, 2002; Figure 8). Lower-than-present fire activity may also be connected with a prolonged wet phase from 4300 to 3800 cal. BP, identified from central Italy to the Alps and recently discussed by Magny et al. (2009).

Conclusion

Motivation for this research was to identify possible patterns and causes of changing fire activity in the Mediterranean region. Even if the role of human in fire occurrences is clearly attested, the regional synchronicity among reconstructed fire histories and climate support the prominent role of climate in shaping the Mediterranean fire environment during most of the Holocene. The human influence on fire activity seems insignificant at continental to regional scales before *c*. 4000–3000 cal. BP. In a similar way, vegetation, which differs between sites from within the same region (e.g. vegetational zones along elevational gradients), appears to have a limited influence on regional fire activity. This analysis also suggests fire activity was regionally coherent within the Mediterranean bioclimate zone, including: the submediterranean region (mostly located above 45°N latitude), the mesomediterranean region (mostly located between 40° and 45°N latitude), the thermomediterranean region (mostly located below 40°N latitude) and eastern Mediterranean forest-steppe biome.

Beyond state-of-the-art paleoecological results, as presented in section 'Current state-of-the-art on Mediterranean fire history', this study highlights the importance of adopting a regional perspective to understand the linkages among Holocene fire activity, ecosystem dynamics and climate variability. While northern Mediterranean regions were fire prone during most of the mid-Holocene 'Thermal Maximum', the southern Mediterranean generally experienced reduced fire activity associated with wetter-than-present summers. This north–south climatic boundary occurs between 40° and 43°N latitude in the central and western Mediterranean. The 8200 cal. BP event is well documented by this regional fire reconstruction and is characterized by a north–south partition with higher fire activity in the south and an abrupt decrease in the northern Mediterranean region. This study also suggests that millennial-scale trends in fire activity were abruptly interrupted *c*. 5000 cal. BP by a widespread centennial-scale climate shift characterized as a mid- to late-Holocene fire-climate transition. After *c*. 5000 cal. BP, with the onset of the Neoglacial cooling in the Northern Hemisphere, a weakening (enhancement) of fire activity was observed in the northern (southern) regions of the Mediterranean. The decrease in fire activity in southern Mediterranean area from 8000 to 7500 cal. BP may be linked to a weakening of Asian and African monsoon driven by the orbitally induced summer cooling trend. We hypothesize the relatively abrupt changes in fire activity between *c*. 5500 and 5000 cal. BP are linked to a threshold response reached in the southward migration of the ITCZ and of the collapse of the Afro- and Asian-monsoon system. At centennial timescales, several abrupt and/or short-lived negative excursions in fire activity were observed in the western Mediterranean and may be related to climatic mechanisms driving Bond cold events, but require further investigation. This analysis of Mediterranean fire activity has been possible by compositing many existing and new charcoal records from the Mediterranean and southern Alpine regions and should serve as point-of-departure for future synthesis efforts.

Finally, this synthesis of Mediterranean fire activity from 8500 to 2500 cal. BP offers five major contributions to understanding fire–climate linkages in the region:

(1) Climate change appears to dominate the fire record, at least in the western Mediterranean in the mid Holocene and fire activity reveals seasonal timing and availability of moisture changes during.
(2) There are long-term teleconnections between the Mediterranean area and other climatic regions, in particular the North Atlantic and the low latitude monsoon regions, which strongly influenced past fire activity.
(3) Gradual climate forcing, such as changing orbital parameters, may trigger abrupt shifts in fire activity, either directly or indirectly through these teleconnections.
(4) Regional fire reconstructions contradict former notions of a gradual Holocene aridification of the entire region due to climate and/or human activities and the importance of shorter-term (i.e. decadal) events occurring across space and time during the mid to late Holocene.
(5) Fire activity appears highly reactive to climate dynamics and could be considerably impacted by future climate changes especially in the Mediterranean area where increasing drought is expected.

Acknowledgements

This study is a part of the Global Paleofire Working Group (GPWG) effort and of the French ANR-LAMA project on Holocene Mediterranean paleoclimate changes and ecosystem responses. The UMR 6249 CNRS-UFC funded a part of this study. Authors thank O. Peyron for useful and enriching discussions and S. Harrison for full support of GCD. The GPWG is supported by the UK Natural Environment Research Council's QUEST (Quantifying Uncertainty in the Earth System) programme, and workshop support for developing the Global Charcoal Database has been provided by QUEST, the ARC-NZ Research Network for Vegetation Function, the University of Bristol, the University of Oregon, the International Geosphere-Biosphere Programme (IGBP), and by the IGBP Integrated Land Ecosystems and Atmospheric Processes (iLEAPS) and Past Global Changes (PAGES) programmes. Authors thank Donatella Magri for her contribution to the Charcoal Database. The authors are also grateful to the anonymous reviewers for their constructive comments on the manuscript.

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