Late Holocene vegetation changes in relation with climate fluctuations and human activities in Languedoc (Southern France).

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Abstract

Holocene climate fluctuations and human activities since the Neolithic have shaped present-day Mediterranean environments. Separating anthropogenic effects from climatic impacts to better understand Mediterranean paleoenvironmental changes over the last millennia remains a challenging issue. High resolution pollen analyses were undertaken on two cores from the Palavasian lagoon system (Hérault, southern France). These records allow reconstruction of vegetation dynamics over the last 4500 years. Results are compared with climatic, historical and archeological archives. A long-term aridification trend is highlighted during the Late Holocene and three superimposed arid events are recorded at 4600-4300, 2800-2400 and 1300-1100 cal BP. These periods of high frequency climate variability coincide in time with the rapid climatic events depicted in the Atlantic Ocean (Bond et al., 2001). From the Bronze Age (4000 cal BP) to the end of the Iron Age (around 2000 cal BP), the spread of sclerophyllous taxa and loss of forest cover result from anthropogenic impact. Classical Antiquity is characterized by a major reforestation event related to the concentration of rural activities and populations in coastal plains leading to forest recovery in the mountains. A major regional deforestation occurred at the beginning of the High Middle Ages. Around 1000 cal BP, forest cover is minimal while cover of olive, chestnut and walnut expands in relation to increasing human

influence. The present day vegetation dominated by Mediterranean shrubland and pines has been in existence since the beginning of the 20th century.

1. Introduction

Global climate projections (IPCC, 2014) show that the Mediterranean will be significantly impacted by 21st century temperature increases associated with a major drop in precipitation. The Mediterranean area is now included as one of the most sensitive regions to future climate change especially concerning moisture availability. Consequences for Mediterranean environments will be particularly important since they have been largely modified by humans during the last millennia and are therefore very vulnerable even to weak influences. In this context, deciphering climatic and human causes of environmental changes is a crucial issue for understanding vegetation response to both forthcoming climate change and present land management policies.

Various Holocene climate archives are available from the Mediterranean and the Atlantic, such as marine Ice Rafted Debris in the North Atlantic (Bond et al., 2001), lake-level fluctuations in the Alps and the Mediterranean (Magny et al., 2002, 2013; Magny, 2004, 2013), glacier oscillations in the Apennines (Giraudi et al., 2004, 2005, 2011), lake isotope records from the whole Mediterranean basin (Roberts et al., 2008) and changes in storminess (Sorrel et al., 2009; Sabatier et al., 2012). They highlight important climatic variations during the latter half of the Holocene which are correlated with vegetation changes. Nevertheless, in the Mediterranean region, separating the impact of human activities from climate remains a challenging task (Roberts et al., 2011). During the mid-Holocene climate optimum, deciduous trees dominated the Mediterranean forest but after 5 000 cal BP, evergreen sclerophyllous taxa expanded and replaced the deciduous vegetation in many places (Reille and Pons, 1992; Jalut et al., 2000; Carrion et al., 2003; Sadori et al., 2014). This major vegetation change could be attributed either to climate change or human impact because during the same period farming spread across the northwestern Mediterranean region (Vaquer, 2010). Over the last millennia, environmental changes have resulted from interactions between climate and human activities, and there is no clear understanding of their respective influence (De Beaulieu et al., 2005).

The Languedoc is located in southern France under both Mediterranean and Atlantic climatic influences. Numerous archeological and historical records are available in this region, including archeobotanical studies valuable for assessing human impact on the environment (Durand, 2003; Chabal, 2007; Jorda et al., 2008; Caveiro et al., 2010; Figueiral et al., 2010). Various studies focus on the rural world in the Languedoc from the Neolithic to Modern periods (Durand, 2003; Schneider et al., 2007; Gascò, 2010; Jallot, 2010; Janin, 2010; Ouzoulias, 2013). The variety of these archives may provide an extensive dataset to compare climatic, archeological and historical records with vegetation history in the Languedoc. Nonetheless, despite the existence of various Holocene pollen sequences in Languedoc such as those from Marsillargues (Planchais, 1982), Lez estuary (Planchais, 1987), Palavas (Aloisi et al., 1978) and Embouchac (Puertas, 1998), Capestang is the only record which provides chronologically well-constrained high-resolution pollen data (Jalut et al., 2009).

This paper presents a new high-resolution composite pollen record from a sedimentary sequence recovered from the Palavasian wetland complex. The chronologically well-constrained pollen sequence documents the last 4500 years cal BP, from the final Neolithic to the present. This detailed study enables identification of both climatic and anthropogenic impacts on vegetation dynamics. First, the comparison between this new vegetation record and climatic archives helps to identify the consequences of both long term and multi-decadal climate variability on Mediterranean environments. Second, the detailed correlation with archeological and historical archives from the Languedoc region allows understanding the link between vegetation history and land-use changes at historical and pre-historical times.

2. Physical settings

The Palavasian wetland complex is located on the southeastern French coast in the northwestern part of the Mediterranean Sea (Fig. 1). The complex consists of narrow lagoons, of 2 km width and between 4 to 8 kilometers long, which run parallel to the shoreline and have shallow water depths (less than 1 m). The lagoons are isolated from the sea by a continuous 150 m wide wave-produced sandy barrier.

The hydrographic network is composed of the Lez and Mosson rivers. The Lez flows directly into the sea while the Mosson splits into two branches near the coast, one flowing into the lagoons and the other joining the Lez before its mouth. Their respective watershed is quite small (653 km²), extending over 50 km inland.

The climate is Mediterranean with a four-month summer drought and mild and rainy winters. Mean temperature and rainfall are respectively 23°C and 26.2 mm in summer and 3.3°C and 58 mm in winter (Méteo France data, Montpellier Fréjorgues station).

The distribution of the main forest types classified by dominant taxa is drawn using vegetation maps from the IFN (Inventaire National Forestier, BD Forêt 1 (Fig.1). The regional vegetation forms altitudinal belts from the sea-shore to the southern part of the Massif Central (Cevennes range): the Meso-Mediterranean belt is dominated by *Quercus ilex* and *Pinus halepensis*; the Supra-Mediterranean belt is dominated by *Quercus pubescens* on limestone and by the introduced *Castanea sativa* on siliceous substrates; finally, the Mountain belt is dominated by mixed forests of *Abies alba* and *Fagus sylvatica*. Pine woods are present at all altitudes, and constituted by three main different species in the study area: *P. halepensis* forms extensive, mostly fire-induced pinewoods at low altitudes close to the coast, the endemic *P. nigra* subsp *salzmannii* occupied restricted areas on dolomitic limestones in the Causse region, and *P. sylvestris* developed as a pioneer in the Cevennes range. Each *Pinus* species has its own ecological requirements, and should respond differently to climatic changes. Unfortunately, these different species cannot be discriminated in routine pollen analysis, which complicates the interpretation of *Pinus* variations in terms of vegetation changes and climate changes. Halophytic vegetation is dominant in the vicinity of the coastal lagoons, mainly with Amaranthaceae such as *Arthrocnemum macrostachyum*, *Sarcocornia fruticosa*, *Salicornia europaea*, and *Halimione portulacoides*. The rivers supplying lagoons in freshwater are bordered by riparian forests composed of *Alnus glutinosa*, *Fraxinus angustifolia*, *Populus alba*, *Populus nigra*, and *Ulmus minor*. Finally, in the region, the Ericaceae are represented by an important diversity of species throughout the different altitudinal belt. The most frequent ones are *Erica arborea, E. scoparia, E. multiflora, E. cinerea, Calluna vulgaris* and *Arbutus unedo.*

3. Materials and methods

Pollen analyses were undertaken on two cores, EG08 (1.31 m long) and PB06 (7.71 m long), recovered from the adjacent lagoons of Prevost and Pierre Blanche (Fig. 1). Eighty eight pollen samples were analyzed from these two cores with a sampling resolution varying from 2 to 10 cm.

3.1. Lithology and sedimentation

Previous sedimentological and geochemical analyses of both PB06 and EG08 cores highlight a clayey-silty sedimentation with shell fragments and intercalated fine layers of sandy material (Sabatier and Dezileau, 2010; Sabatier et al., 2012; Dezileau et al., 2011). The complete studied record covers the last 5 millennia from the Mid-Holocene to the present day. During that time, the Palavasian complex was characterized by a lagoonal depositional environment with a recurrent marine influence through permanent connections with the sea. A major change in faunal content chronologically constrains the final closure between the lagoon and the sea at around 1000 cal BP (190-170 cm in PB06). From that time, the lagoon became more and more isolated.

Variations in marine mollusk abundance, granulometry and Zr/Al and smectite/(illite+chlorite) ratios highlight three paleostorm events in EG08 core and eight in PB06. (Dezileau et al., 2011; Sabatier et al., 2012). The three more recent overwash layers recorded in both cores can be correlated between EG08 and PB06. They are identified as single storm events matching with historical storms documented and dated in historical archives to 1742, 1848 and 1893 (Dezileau et al., 2011). The fourth overwash layer recorded in PB06 is interpreted as another single storm event and the four older ones are interpreted as high storm activity periods (Fig. 2).

3.2. Chronology and age model

The PB06 age model has been built using ^{137}Cs, ^{210}Pb and AMS ^{14}C dates on monospecific samples of *Cerastoderma glaucum* shells (Sabatier and Dezileau, 2010; Sabatier et al., 2012). ^{14}C ages were corrected according to reservoir age as defined by Sabatier et al. (2010) and then calibrated using the R-code package “clam” (Blaauw, 2010) and the Intcal09 calibration curve (Reimer et al., 2009) at 2 standard deviations (Sabatier et al, 2012). The whole core provides a high resolution record over the last 7000 years, however this particular study focus only on the late Holocene period.

The EG08 age model has been developed by stratigraphic correlation with core PB06 (Dezileau et al., 2011). Core EG08 records the last 300 years and allows reconstruction of a very high resolution vegetation history during the modern period.

3.3. Pollen analysis

Pollen analyses performed on PB06 and EG08 are combined in a composite record: 13 samples in EG08 for the last 200 years cal BP and 75 samples in PB06 from 200 to 4600 cal BP. The resulting average time between each samples is around 50 years for the whole sequence with variations from 10 to 100 years. There are two small gaps in the pollen sequence between 1555 and 1316 cal BP and between 622 and 202 cal BP (Fig. 2) because of insufficient pollen concentration in and below the storm sediments (<5000 grains.g^{-1}).

Pollen extraction followed a standard method modified from Faegri and Iversen (1989). For each sample, 1 g of sediment was sieved on 250 µm and 5 µm mesh, then processed with HCl and HF for mineral digestion and sodium polytungstate for density separation. One tablet with a known amount of Lycopodium spores was added to estimate pollen concentration (Stockmarr, 1971). Pollen counts were performed at x400 magnification though pollen grains were identified at x1000 magnification with pollen keys (Punt, 1976; Beug, 2004) and atlases (Reille, 1992). A minimum pollen sum of 300 grains excluding Pteridophyta and non-pollen palynomorphs (NPP) was reached for each sample (Berglund and Ralska-Jaciewiczowa, 1986). Proportions of each taxon were calculated using the total sum of identified pollen grains without considering NPP and spores. The simplified pollen diagram (Fig. 2) was drawn using PSIMPOL (Bennet, 1992). The category "arboreal pollen" includes all the tree taxa except the cultivated ones (*Olea*, *Castanea* and *Juglans*), the category "other deciduous trees" includes *Acer*, *Ulmus*, *Betula*, *Carpinus* and *Corylus*, the category "evergreen shrubs" includes *Pistacia*, *Cistus* and *Buxus* and finally the category "other riparian trees" includes *Fraxinus*, *Salix* and *Tilia*. The ratio deciduous/evergreen *Quercus* was computed in order to be compared with results of previous studies (Jalut et al., 2009) and the ratio *Fagus*/deciduous *Quercus* in order to highlight covariation of these two taxa.

4. Results

4.1. Pollen taphonomy

Pollen concentration in the composite sequence is generally high, ranging from 1 000 to 100 000 grains.g^{-1}. Major drops in pollen concentration with distorted pollen proportions are recorded in the three sandy overwash layers in EG08 and in the four layers corresponding to single storm events in PB06. Surprisingly the clayey layers just below these storm events also contain low pollen concentrations. It is assumed that during a storm event, the clayey surface sediments at the bottom of the lagoon were disturbed before the deposition of the sandy layer. This resulted in partial to total removal of the polleniferous material, with huge declines in pollen concentration through the sequence. Samples from the recent overwash layers in EG08 and PB06, identified as single storm events, represent sediments deposited within a few hours and naturally record no environmental information. Consequently, pollen analyses from these overwash layers and the samples from immediately underlying sediments with pollen concentrations lower than 5000 grains.g^{-1} have been discarded from the pollen record to avoid taphonomic perturbations. On the contrary, no taphonomical issues are detected in the four older high storm activity periods in the lower part of PB06.

4.2. Pollen transport vectors

Alnus is the only riparian taxa which is well represented in the sequence, reaching almost 10% between 2000 and 1000 cal BP (Fig. 2). However studies interested in quantifying the relative contribution of different taxa to the pollen rain show that *Alnus* is a high pollen producer (Broström et al., 2008). Therefore, it is unlikely that this taxa could represent the rivers contribution to Palavas pollen assemblages. The other riparian taxa display very low pollen proportions in present as in past pollen assemblages in agreement with the small size of the Lez and the Mosson rivers (Fig. 2) and the position of the cores located far away from their mouths. This suggests that fluvial sources represent only a minor contribution to pollen assemblages. Moreover, despite that the lagoons were in permanent connection with the sea before 1000 cal BP, no vegetation change is contemporaneous from the sandy barrier closure. Thus, even if a marine influence existed it probably not influences the pollen spectra with the exception of storm events already discussed. Finally, the main pollen transport vector into the Palavasian lagoon system is assumed to be associated with wind.

4.3.Vegetation history in Palavas area

The pollen record from the EG08 and PB06 cores illustrates vegetation dynamics over the last 5 millennia. Eleven pollen assemblage zones were visually determined, describing the sequence of vegetation changes (Table 1, Fig. 2).

Tree pollen (50 – 90 %) dominates the pollen spectra for almost the entire sequence, mainly comprising deciduous *Quercus* (10 - 40 %) associated with *Pinus* (1 - 20 %), evergreen *Quercus* (3 - 20 %) and *Fagus* in the lower part of the sequence (up to 20 %) (Fig. 2). *Alnus* is present in significant proportions (up to 10 %) as well as *Abies* (up to 3 %) at the base of the sequence.

Between 4700 and 4000 cal BP, *Pinus* proportions decrease and the first occurrence of *Cerealia*-type pollen is recorded (Pal-I and first part of Pal-II, Fig. 2). *Vitis* is recorded sporadically throughout the sequence. After 4000 cal BP, *Fagus*, *Abies* and the deciduous/evergreen *Quercus* ratio show a long term downward trend (Fig.s 2 and 3). *Fagus* displays several fluctuations superimposed on this overall decline. *Fagus* minima coinciding with deciduous *Quercus* maxima occur at 4600-4300 cal BP (Pal-I), 2800-2400 cal BP (Pal-III and Pal-IV) and 1300-1100 cal BP (Pal-VII) (Table 1, Fig. 2). Such oscillations are particularly highlighted by changes in the *Fagus*/deciduous *Quercus* ratio (events 3, 2 and 1 in Fig. 3). At

3300 cal BP, arboreal pollen proportions start to decline (85 to 70 %) (Pal-II, Fig. 3). *Abies* pollen disappears almost completely from the record around 2500 cal BP. Just before 2000 cal BP, arboreal pollen proportions rise sharply to their maximum (up to ca. 85 %). However after 300 years, tree pollen abundance decreases again to 55 % (Pal-III and IV, Fig. 3). Around 1300 cal BP, a short-lived peak in deciduous *Quercus* interrupts this general decline (Pal-VII, Table 1, Fig. 2). After this brief reforestation event, forest decline begins again and appears more intense (Pal-VI, Fig. 3). Arboreal taxa reach their minimum (45% of arboreal pollen) around 1000 cal BP. While cultivated tree pollen such as *Olea*, *Castanea* and *Juglans* start to increase (Pal-VII, Fig. 3), *Fagus* disappears (Pal-VIII). At the same time, Ericaceae and herbaceous taxa including Poaceae (up to 15 %) and *Cerealia*-type pollen (up to 3 %) reach their highest values (Pal-VIII and Pal-IX, Table 1, Fig. 2). During the 19th century arboreal pollen proportions remain relatively low (~50%) compared to the rest of the sequence and *Castanea* pollen percentages sharply increase (Pal-X, Table 1, Fig. 2). In the last hundred years *Pinus* and evergreen *Quercus* pollen become the dominant trees of the Mediterranean forest while cultivated trees abundance (*Olea*, *Castanea* and *Juglans*) decrease.

5. Climate interpretation

5.3. The long term aridity trend

In the Mediterranean basin, the Early and Mid-Holocene are characterized by enhanced moisture and precipitation increases until ~5000 cal BP (Carrion et al., 2002; Fletcher et al., 2007; Magny et al., 2012), then followed by long term aridification throughout the region, recorded by many proxies such as palynology, geochemistry, lake-levels, semi-mobile dune systems and Saharan eolian dust (Zazo et al., 2005; Jalut et al., 2009; Perez-Obiol et al., 2011; Roberts et al., 2011; Jimenez-Espejo et al., 2014; Jimenez-Moreno et al., 2015). This aridification trend has been linked to a decrease in summer insolation which could have resulted in reduced lower sea-surface temperatures, reduced land-sea contrast and thus lower precipitation during the fall-winter season (Marchal et al., 2002; Jimenez Moreno et al., 2015).

Between 4500 and 2000 cal BP, the noteworthy occurrence and/or high abundance of *Abies* and *Fagus* pollen at the base of the Palavas pollen record suggests their presence close to the Palavasian Lagoon (Fig. 2). The occurrence of *Fagus* at low altitude in southern France is also recorded in Lez delta pollen sequence and in the Rhône valley anthracological record (Planchais, 1987; Delhon et al., 2005). It matches well with the mid Holocene enhanced moisture recorded in the western part of the Mediterranean basin. In fact, *Abies* and *Fagus* are now found only on the mountainous hinterland, more than 70 km north of the lagoon (Fig. 1). Therefore, in the Palavasian pollen record, high percentages of *Abies* and *Fagus* before 2 800 cal BP may be linked to their broader expansion towards the south at lower elevations. Such a conclusion is corroborated by charcoal data recovered from coastal archeological contexts, indicating that 1) *Fagus* was present at ca. 3000 cal BP (Etang de l'Or Tonnerre I) and 2000 cal BP (Port Ariane), and 2) *Abies* was present at ca. 2000 cal BP (Lattara and Port Ariane) (Chabal, 2007; Jorda et al., 2008; Caveiro et al., 2010). These two species do not tolerate summer dryness and their expansion to lower altitudes in southern France implies that more humid conditions prevailed in the Languedoc at least locally (Quezel, 1979 ; Delhon et al., 2005).

From 4500 to 3000 cal BP, *Pinus* declined steadily. This might express a range contraction toward the north in *Pinus sylvestris* associated with the onset of Late Holocene aridification (Fig. 2). The parallel long-term downward trend expressed in the *Abies* and *Fagus* abundance curves from 3000 to 1000 cal BP surely follows the Holocene long-term aridification (Figs. 2 and 3). At the same time, deciduous *Quercus* proportions remain very high around Palavas (Fig. 2). No clear decrease in *Quercus* is evidenced which is inconsistent with results from other sites in the Languedoc. For instance, in the Capestang sequence, less than 100 km from Palavas, deciduous *Quercus* begins to decline at 4 000 BP cal in correlation with an increase in evergreen *Quercus* (Jalut et al., 2009). Such a replacement of deciduous forest by sclerophyllous evergreen forest is lacking in Palavas at the same period, occurring only during the last century. The Capestang core was sampled in a wetland area with small ponds (Jalut, 1995). Considering the size of these ponds (around 100m wide), the pollen record at this site probably documents a more local scale vegetation history compared to Palavas sequence with its much larger basin (around 2km wide) (Sugita, 1993). Actually, in the Palavas region, the mountainous hinterland massifs might have favored the continuation of relatively humid conditions and hence the persistence of deciduous *Quercus* forests until the historical period. The same deciduous *Quercus* forests were disadvantaged in the plains surrounding Capestang, resulting in the absence of a deciduous *Quercus* pollen signal. A similar situation is recorded at lake Skodra (Albania/Montenegro) where a strong altitudinal gradient, combined with sufficient moisture availability, favored the development of deciduous forest throughout the Late Holocene (Sadori et al., 2014).

Around 2000 cal BP, *Abies* almost disappears from the palynological record and definitively from the Languedoc lowlands, and *Fagus* persists up to 1000 cal BP. Late Holocene climate changes have hence caused the northward range contraction in *Abies*, *Fagus* and probably also

Pinus sylvestris towards their present-day mountainous location. These same changes favored the development of deciduous *Quercus* forests and Mediterranean Pines at the studied location.

5.4. Short-term climatic fluctuations

Sharp decreases in *Fagus* pollen proportions coinciding with deciduous *Quercus* maxima occurred at 4600-4300 cal BP, 2800-2400 cal BP and 1300-1100 cal BP (Fig. 2), and are highlighted through sharp decreases in the *Fagus*/deciduous *Quercus* ratio (Fig. 3). Oscillations might be linked to repetitive *Fagus* retreats toward higher altitudes coinciding with repeated expansions of deciduous *Quercus* close to Palavas at lower altitudes (Figs. 2 and 3). These decreases might also correspond to major drops in *Fagus* pollen productivity caused by enhanced environmental stresses. In the French mountainous area of the Mediterranean, *Fagus* is at the limit of its geographical range (Quezel, 1979) and it's therefore very sensitive to climatic variations, especially regarding moisture availability (ref). Since *Fagus* is less tolerant to dryness than deciduous *Quercus*, each fluctuation may be related to repeated arid episodes.

Arid events have been already reported in the central and western Mediterranean from lake Skodra (Albania/Montenegro) soon before 4000 cal BP, around 2900 cal BP and around 1450 cal BP (Sadori et al., 2014) and in southwestern Spain at 4 000 cal BP, 3000-2500 cal BP and 1000 cal BP (Jimenez-Moreno et al., 2015). Discrepancies in the chronology of these events between sites are probably due to age model uncertainties. Furthermore, these arid events correspond in time to Calderone glacier extension phases in the Appenines around 4200 cal BP, between 2855-2725 cal BP and 1410-1290 cal BP (Fig. 3) (Giraudi, 2004, 2005; Giraudi et al., 2011). They are also concurrent with the rapid vegetation and marine environment changes recorded in Mediterranean (e.g. Cacho et al., 2001; Fletcher et al., 2007; Frigola et al., 2007; e.g. Kotthoff et al, 2008 ; Schmiedl et al., 2010; Combourieu-Nebout et al, 2009, 2013; Desprat et al., 2013; Fletcher et al, 2013). These climatic events fit with the general picture of climate change depicted by lake level fluctuations in central Europe and the northern Mediterranean (Magny, 2013; Magny et al, 2013). Moreover they are contemporaneous with North Atlantic Bond events around 4200, 2800 and 1400 cal BP, underlining the efficient climatic coupling between the North Atlantic and the Mediterranean during the Late Holocene (Fig. 3).

Variations in clay mineralogy in the core PB06 provide a proxy of past storm frequency in Palavas region complementary to pollen data which may give useful information to investigate mechanisms of these climatic oscillations (Sabatier et al., 2012). Arid events depicted by vegetation are contemporaneous with sharp variations in storminess. They occur during transition periods, before (event 3) or after (event 1 and 2) high storm activity periods (Fig. 3). Increases in storm frequency have been interpreted as periods during which westerlies, and thus storm tracks, were shifted to the south, bringing more precipitations in the Mediterranean. These situations are similar to persistent negative NAO-like periods (North Atlantic Oscillations) and may be caused by the southward displacement of the polar front linked to a weakening of the Atlantic Meridional Overturning Circulation (AMOC) during colder periods (Dezileau et al., 2011; Trouet et al., 2012). Such an interpretation is consistent with the humidity recorded in PB06 during high storm activity periods and with the Calderone glacier expansion phases (Giraudi et al., 2004, 2005, 2011). Conversely arid events 2 and 1 might correspond to persistent positive NAO-like periods. According to this mechanism, these events might correspond to warmer periods with a decreasing storm frequency when westerlies and storm tracks are shifted to the north. The closeness in time of arid events 2 and 1 with respectively high storm activity periods 2a and 1 within the Bond event 2a and 1 time windows, suggests that these two Bond events might be divided in two phases, a humid one followed by an arid one. A similar schema is reported during older arid episodes, Heinrich events 4, 2 and 1 (Naughton et al., 2009). A two-phase pattern occurs within these three Heinrich events with a change from wet and cold to dry and cool conditions. The proposed mechanism involving the succession of opposite persistent NAO-like periods is very similar to the one developed for the Late Holocene rapid climatic events (Trouet et al., 2012), despite Heinrich events are recorded in a glacial period. The arid event 3 remains more difficult to interpret because it seems contemporaneous with a storminess increase. However; it is difficult to define its lower boundary because it is located at the bottom of the sequence. Further analyses are needed to determine properly its chronological extension and link to high storm activity periods.

Bond events have been correlated with fluctuations in 14C production rate, suggesting a solar forcing (Bond et al., 2001) (Fig. 3). However, no exceptional residual 14 C excursions are depicted around 4200 and 1400 cal BP and the variability in solar activity cannot explain all the observed changes (Debret et al., 2007; Sabatier et al., 2012). Wavelets analysis performed on Bond et al (2001) IRD time series and other marine paleoclimatic proxies highlight three major climate cyclicities: 1000, 1500 and 2500-year. The two cyclicities of 1000 and 2500 years are solar related, while the 1500-years climate cycles, dominant during the second part of the Holocene, appear to be clearly linked with the oceanic circulation (Debret et al., 2007). In the Mediterranean, the succession of stormy/humid periods and arid events close in time within some Bond events time windows bring new elements to characterize Late Holocene climatic oscillations that should be taken into account in the future attempts of understanding the mechanisms involved in climate variability.

6. Anthropogenic impact on vegetation

6.1. Ecological significance of evergreen *Quercus* development during the Late Holocene in southern France

During the Late Holocene, in the north-western Mediterranean, sclerophyllous evergreen forest development has been controversially interpreted either as an effect of Late Holocene aridification (Jalut et al., 2000, 2009) or as a consequence of increasing anthropogenic impact (Triat-Laval, 1978; Planchais, 1982; Reille et al., 1992; Tinner et al., 2009; Henne et al., 2015).

In the Palavas record the deciduous/evergreen *Quercus* ratio displays a regular decrease through the sequence which could result from the Late Holocene aridification trend (Fig 3). However, after 2000 cal BP, deciduous and evergreen *Quercus* forests both decline at the same time. This simultaneous decline of evergreen and deciduous *Quercus* is not consistent with variations driven by the increasing aridity. Moreover, no correlation can be found between increases in evergreen *Quercus* proportions and the short arid events discussed before (Figs. 2 and 3) which conversely correspond to deciduous *Quercus* increases. The transition from deciduous to evergreen forest is not clearly recorded in Palavas before the last century. Therefore climate variability cannot explain alone the evergreen *Quercus* dynamic around the Palavasian wetland complex, and other factors have to be considered.

6.2. Influence of human societies on forest composition before Classical Antiquity

At the end of the Neolithic, between 4500 and 4000 cal BP, the decrease in the deciduous/evergreen *Quercus* ratio might be the first evidence of anthropogenic impact on Mediterranean forest composition (Pal-I in Fig 2 and event a in Fig. 3). In fact, more than a hundred small villages were present during this period in the Palavas region (Jallot, 2011). Farming societies were very wealthy and dynamic with a higher influence and control of the environment than during previous periods (Jallot, 2010). The increase in agricultural activities may thus have favored the evergreen *Quercus*, a tree taxon which is especially resilient to high frequency disturbances (Barbero et al., 1990).

After 3300 cal BP, at Port Ariane (Chabal, 2007) and Tonnerre I (Cavero et al., 2010), the anthracological records display higher abundances of evergreen *Quercus* in comparison to the

Palavas pollen data (Figs. 2 and 3). These results illustrate the over-representation of evergreen *Quercus* in the areas surrounding human settlements during Bronze Age and confirm that evergreen *Quercus* forests were already favored by humans.

Between 2800 cal BP and 2000 cal BP, the deciduous/evergreen *Quercus* ratio decreases again (event b in Fig. 3). At that time, evergreen *Quercus* dominates the Port Ariane and Lattara anthracological assemblages (event b in Fig. 3) (Chabal, 2007; Jorda et al., 2008). Evergreen *Quercus* abundance around archeological sites reinforces the link between increases in evergreen *Quercus* pollen and the enhanced anthropogenic influence since 2800 cal BP. These changes correspond to the Bronze Age/Iron Age transition, a crucial period in Languedoc prehistory. During the Iron Age, the coastal area around the Palavasian lagoons became an important trading area with Mediterranean civilizations. The development of Lattara city near the lagoon shores attests to the significant increase in human activities between 2500 and 2000 cal BP (Cavero et al., 2010). Nevertheless, the second arid event recorded between 2800 and 2400 cal BP in the Palavas sequence may have triggered forest changes or exacerbated human impact on vegetation. As well as changes in forest composition, human activities also began to affect forest cover through deforestation.

6.3. Classical Antiquity

During Classical Antiquity, the maximum expansion of forest recorded at Palavas (event c in Fig. 3) does not seem to fit with widespread economic development in the Languedoc. However, settlements migration from the hinterland to the coast, beginning during the Iron Age, allowed forest expansion in the hinterland. Archeologists observed a decrease in the number of small settlements in mountainous areas while the coastal cities such as Lattara expanded (Janin, 2010). Thus, during Classical Antiquity, most of the *villae* in this part of the Languedoc were located in coastal plains (Ouzoulias, 2013; *carte archéologique nationale BD patriarche* http://www.villa.culture.fr/#/fr/annexe/ressources/t=Ressources). Therefore the forest expansion possibly corresponds to forest recovery in the mountains which were less densely populated at this time. Reforestation was probably also favored by enhanced humidity attested by the relative importance of *Fagus* in the deciduous forest (Fig. 2).

6.4. Transition between Classical Antiquity and Early Middle Ages

The collapse of the Roman Empire is generally considered to have been a major crisis of the rural world, leading to widespread land abandonment and reforestation (Kaplan et al., 1994). However, the Palavas pollen record clearly shows a major deforestation (event d in Fig. 3), which is consistent with the most recent historical and archeological studies carried out in the Languedoc, but does not support the theory of a major crisis. Historians now interpret the decrease in *villae* (roman farms) numbers at the end of Classical Antiquity as the result of an agrarian system transformation in the Gallia Narbonensis province. Numerous small *villae* were replaced gradually by larger ones, fewer in number but less vulnerable to economic hazards. At the beginning of the 5th century (1550 cal BP), while the number of *villae* sharply decreased in the Languedoc, important extensions of the Loupian *villae* (Fig. 1) are recorded on the lagoon shore (Schneider et al., 2007). Moreover recent archeological excavations in this area have discovered a new type of rural housing which developed during the Early Middle Ages on, and alongside, the former Roman territorial network. Two new settlements of this type were founded near abandoned *villae* in Lune-Viel and Verdier between the 4th to the 5th centuries (Fig. 1) (Schneider et al., 2007). During the same period, the Roc de Pampelune village started to develop in the mountains where territories were free of human occupation during Classical Antiquity (Fig. 1) (Schneider et al., 2007). Finally a new diocese was established in the 6th century in La Maguelone isle (Fig. 1) (Schneider, 2008). In such a context of human occupation, the major deforestation event recorded at Palavas (Figs. 2 and 3) is consistent with the archeology, which provides evidence of a very dynamic rural world despite the collapse of the Roman Empire.

6.5. Crisis of the rural world ?

Following the major forest decline associated with Classical Antiquity-Early Middle Ages transition, significant reforestation occurred between 1300 and 1200 cal BP (650 and 750 cal AD) (Pal VII in Fig. 2 and event e in Fig. 3). This event timely coincides with a gap in the archeological record between the 7th and the 8th centuries. In fact, during this period, many archeological settlements are abandoned in the Languedoc. For instance, Roc de Pampelune village and Dassargue farm, near Palavas, were abandoned between 1350 and 1300 cal BP (600 and 650 cal AD) while new settlements were founded in their vicinity approximately one hundred years later (Schneider et al., 2007) (Fig. 1). For now, this settlement abandonment alone does not demonstrate a rural decline at this time (Schneider et al., 2007). On the other hand, the reforestation recorded in the Palavas pollen sequence attests to a major crisis during this period and confirms that human activities caused forest loss before the 7th century (Fig. 3). This reforestation is characterized by an important increase in most of deciduous trees pollen proportions including deciduous *Quercus*, but excepting *Fagus* which display very low abundances related with the arid event 1 discuss previously (Fig. 2). In spite of the Late Holocene aridification and the arid event 1, the increase in deciduous *Quercus* indicate that climatic conditions in the hinterland were still favorable to deciduous forest development except *Fagus*.

6.6. The High Middle Ages

During the High Middle Ages (11^{th}, 12^{th} and 13^{th} centuries), new types of human settlements are identified in the Languedoc (Durand, 2003; Schneider et al., 2007). Historical studies have identified 128 new fortified villages (*castra*) in the region with at least eight of them within the watershed of the Palavasian lagoon. Thirty three new (or innovative) rural settlements called "*Mansus*", specifically located in or close to recently deforested areas, were located near Palavas. Two major abbeys were established at Aniane and St-Gilhem and developed intensive land use practices. Feudal lords deforested river banks to extend their lands in order to grow cereals. At least 27 of these cereal fields were present along the Mosson and Lez rivers. Finally the city of Montpellier was also established during this period and became an important city in France in the 13th century (Britton et al., 2007). These settlement expansions explain the major forest loss (event f in Fig. 3) and the evergreen shrubland extension (Fig. 2) recorded in the Palavas pollen record from 1150 to 850 cal BP (from ca. 800 to 1100 AD). Historical and palynological studies both highlight the strong human influence on the environment during the High Middle Ages.

Just like during the reforestation of the 7^{th} and 8^{th} centuries, *Fagus* abundance changes around 1100 cal BP are not consistent with variations in proportions of other forest taxa. *Fagus* is the only pollen taxa which display a significant increase at this time (Fig. 2). Though *Fagus* may be affected at that time by human activities, the decorrelation between *Fagus* signal and the anthropogenic vegetation changes reinforce the interpretation of *Fagus* as a good climate indicator until this approximate date. However, after 1100 cal BP *Fagus* proportions increasingly drop. Human impact on forest taxa should be too strong and *Fagus* can no longer be used as an aridity proxy.

6.7. Cultivated plants record

The first evidence of *Cerealia*-type pollen recorded in the Palavas pollen sequence at 4400 cal BP (Fig. 2) is congruent with the Embouchac pollen record, attesting to cereal cultivation in the vicinity of the lagoon shores by Neolithic populations (Puertas, 1999) (Fig 1). Later, during the Middle Ages (Fig. 2), the maximum of *Cerealia*-type pollen correlates with the strong anthropogenic impact associated with the cereal fields planted along the Mosson and Lez rivers flowing into the lagoon (Fig. 1) (Durand, 2003).

In the archeologial record, evidence for grape cultivation occurs from the Iron Age and accounts for the presence of *Vitis* pollen after 2500 cal BP (Alonso et al., 2007, 2008). Earlier, *Vitis* pollen grains may originate from wild grapes naturally growing in this area (Ali et al., 2008). Moreover archeobotanical studies demonstrate that Neolithic and Bronze Age populations were gathering wild grapes and thus may have favored this taxon near the lagoon (Alonso et al., 2007, 2008; Chabal and Terral, 2007).

Before Classical Antiquity, it is assumed that the few *Olea* pollen grains found at Palavas (Fig. 2) refer to wild olive trees probably present in narrow thermomediterranean coastal areas. The later continuous record of *Olea* since Classical Antiquity (Fig. 2) is probably related to its introduction and cultivation by the Romans in southern France (Leveau, 2003). However at Palavas, low proportions of *Olea* are recorded throughout the first millennium AD. Indeed, various archeological archives attest to limited cultivation of olives in this area during the Roman period (Alonso et al 2008, Leveau 2003). Historical studies demonstrate that olive cultivation developed later in Languedoc, during the High Middle Ages (Leveau 2003) in agreement with our pollen data (Fig. 2).

During the medieval period, simultaneous increases in *Juglans* and *Castanea* with *Olea* (Fig. 2) suggests an expansion of tree cultivation and corroborates the major influence of human activities on the environment in the Palavas region around 1000 AD.

6.8. Reforestation during the last century

At the beginning of the 20th century , the major reforestation with evergreen *Quercus* and *Pinus* recorded at Palavas is consistent with land registry data which indicate that forest cover increased from 80 000 to 190 000 ha between 1900 and 2000 AD in the French department of Hérault (Koerner et al., 2000). This change corresponds to the well-known industrial revolution, which resulted in migration of rural populations towards cities, and to widespread land abandonment. The mechanization of farming at the beginning of the 20th century amplified the abandonment of land unsuitable for modern agriculture, which was consequently recolonized by the forest.

6.9. The deciduous forest replacement

During the 20^{th} century reforestation, *Pinus* and evergreen *Quercus* proportions rise while deciduous *Quercus* proportions remain stable (Pal-VIII in Fig 2 and Fig 3). The expansion of evergreen *Quercus* and *Pinus* forest has no equivalent in the past. Indeed at the end of the 9th century, after one hundred years of reforestation the dominant taxon was still deciduous *Quercus*.

Differences between the reforestation dynamic of the 20^{th} century compared to that of the 9^{th} century might be related to the Late Holocene aridification. During the last one thousand years, the enhanced dryness could have favored *Pinus* and evergreen *Quercus*. However, ecological studies in southern France demonstrate that in the near future *Quercus pubescens*, the present deciduous species in this area, could replace *Quercus* ilex and *Pinus halepensis* in many places (Bacilieri et al., 1993). Indeed, *Pinus halepensis* is a pioneer species of Mediterranean ecological successions that will typically be replaced by *Q. ilex*. Furthermore, it is known that *Q. ilex* inhibits the germination of its own seeds and not those of *Q. pubescens* (Barbero et al., 1990; Bran et al., 1990; Bacilieri et al., 1993; Li and Romane, 1997). Such processes of auto-allelopathy enable the replacement of *Q. ilex* by Q. pubescens. Vegetation surveys over several decades show that without any human disturbances the proportions of *Quercus pubescens* in the vegetation increase (Barbero et al., 1990).

Therefore the *Pinus* and evergreen *Quercus* expansion is more likely related with enhanced anthropogenic impact on forests. Indeed *P. halepensis* was widely planted (Barbero et al., 1988) and coppicing was widespread in southern France during the first half of the 20^{th} century (Ducrey, 1988; Barbero et al., 1990; Koerner et al., 2000). As a consequence of coppicing, *Quercus pubescens* has been supplanted by *Q. ilex* as the deciduous oak is less efficient for resprouting and thus less resilient to high frequency disturbances such as forest harvesting compared to the evergreen oak (Barbero et al., 1990). Similar situations where the present Mediterranean vegetation is strongly shaped by recent human activities more than climatic factors are also recorded in Italy (Henne et al., 2015).

7. Conclusion

Based on the Palavas pollen record, vegetation changes highlighted during the last 4600 cal BP are interpreted in terms of climate and/or human influence and indicate:

A clear aridification trend from 4600 cal BP to the present-day expressed through the range contraction toward the north in *Fagus* and *Abies*.

Three short arid events which interrupt the general trend at 4600-4300 cal BP, 2800-2400 cal BP and 1300-1100 cal BP. These events coincide in time with rapid climatic events that occurred during the late Holocene. The closeness in time of arid events with high storm activity periods within the Bond windows, suggests a two phases pattern with a humid phase followed by an arid one.

Oscillations of evergreen *Quercus* representation and arboreal pollen proportions mainly correlated with human history. Firstly farming activities favored evergreen *Quercus* since the Neolithic, gradually changing the forest composition. Secondly three deforestation episodes are depicted 1) from the Bronze Age to the end of the Iron Age, 2) at the transition between Classical Antiquity and Middle-Ages and 3) during the 9th century. Between the two first episodes, Classical Antiquity is characterized by a major reforestation related to the concentration of rural activities and populations in plains leading to forest recovery in the mountains. At the beginning of the 20th century, a new reforestation occurred due to farming mechanization. Evergreen *Quercus* and *Pinus* expansion is related to coppicing and the increase in fire frequency.

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Bibliography

Ali, A. A., Roiron, P., Chabal, L., Ambert, P., Gasco, J., André, J. and Terral, J.-F.: Holocene hydrological and vegetation changes in southern France inferred by the study of an alluvial travertine system (Saint-Guilhem-le-Désert, Hérault), Comptes Rendus Geoscience, 340(6), 356–366, doi:10.1016/j.crte.2008.02.001, 2008.

Aloïsi, J.-C., Monaco, A., Planchais, N., Thommeret, J. and Thommeret, Y.: The Holocene transgression in the Golfe du Lion, southwestern France: paleogeographic and paleobotanical evolution, Géographie physique et Quaternaire, 32(2), 145–162, 1978.

Alonso, N., Buxó, R. and Rovira, N.: Recherches sur l'alimentation végétale et l'agriculture du site de Lattes-Port Ariane: étude des semences et fruits, Lattara, 20, 219–249, 2007.

Alonso, N., Buxó, R. and Rovira, N.: Archéobotanique des semences et des fruits de Lattara: bilan des recherches, La ville portuaire de Lattara (Lattes, Hérault) et son territoire: nouveaux acquis, nouvelles questions. Gallia, 65, 1–8, 2008.

Bacilieri, R., Bouchet, M. A., Bran, D., Grandjanny, M., Maistre, M., Perret, P. t and Romane, F.: Germination and regeneration mechanisms in Mediterranean degenerate forests, Journal of Vegetation Science, 4(2), 241–246, 1993.

Barbero, M., Bonin, G., Loisel, R. and Quézel, P.: Changes and disturbances of forest ecosystems caused by human activities in the western part of the Mediterranean basin, Plant Ecology, 87(2), 151–173, 1990.

De Beaulieu, J.-L., Miras, Y., Andrieu-Ponel, V. and Guiter, F.: Vegetation dynamics in north-western Mediterranean regions: instability of the Mediterranean bioclimate, Plant Biosystems-An International Journal Dealing with all Aspects of Plant Biology, 139(2), 114–126, 2005.

Bennett, K. D.: PSIMPOLL: a quickBASIC program that generates PostScript page description files of pollen diagrams, INQUA Commission for the study of the Holocene: working group on data handling methods newsletter, 8, 11–12, 1992.

Berglund, B. and Ralska-Jasiewiczowa, M.: Pollen analysis and pollen diagrams, Handbook of Holocene palaeoecology and palaeohydrology, 455, 484, 1986.

Blaauw, M.: Methods and code for "classical"age-modelling of radiocarbon sequences, Quaternary Geochronology, 5(5), 512–518, 2010.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M. N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I. and Bonani, G.: Persistent solar influence on North Atlantic climate during the Holocene, Science, 294(5549), 2130–2136, 2001.

Bran, D., Lobreaux, O., Maistre, M., Perret, P. and Romane, F.: Germination of Quercus ilex and Q. pubescens in a Q. ilex coppice, Vegetatio, 87(1), 45–50, 1990.

Britton, C., Chabal, L., Pagès, G. and Schneider, L.: Approche interdisciplinaire d'un bois méditerranéen entre la fin de l'antiquité et la fin du Moyen Âge, Saugras et Aniane, Valène et Montpellier, Médiévales. Langues, Textes, Histoire, (53), 65–80, 2007.

Broström, A., Nielsen, A. B., Gaillard, M.-J., Hjelle, K., Mazier, F., Binney, H., Bunting, J., Fyfe, R., Meltsov, V. and Poska, A.: Pollen productivity estimates of key European plant taxa for quantitative reconstruction of past vegetation: a review, Vegetation history and archaeobotany, 17(5), 461–478, 2008.

Cacho, I., Grimalt, J. O., Canals, M., Sbaffi, L., Shackleton, N. J., Schönfeld, J. and Zahn, R.: Variability of the western Mediterranean Sea surface temperature during the last 25,000 years and its connection with the Northern Hemisphere climatic changes, Paleoceanography, 16(1), 40–52, 2001.

Carrión, J. S.: Patterns and processes of Late Quaternary environmental change in a montane region of southwestern Europe, Quaternary Science Reviews, 21(18), 2047–2066, 2002.

Carrión, J. S., Sánchez-Gómez, P., Mota, J. F., Yll, R. and Chaín, C.: Holocene vegetation dynamics, fire and grazing in the Sierra de Gádor, southern Spain, The Holocene, 13(6), 839–849, 2003.

Cavero, J. and Chabal, L.: Paléogéographie, dynamique forestière et peuplement d’un milieu lagunaire. L’étang de l’Or (Hérault) à la fin de la Préhistoire, Quaternaire. Revue de l’Association française pour l’étude du Quaternaire, 21(1), 13–26, 2010.

Chabal, L.: Étude anthracologique de Lattes Port Ariane: forêts littorales en Bas Languedoc depuis le Néolithique moyen, I. Daveau (éd.), Port Ariane (Lattes, Hérault), construction deltaïque et utilisation d’une zone humide lors des six derniers millénaires. Lattara, 20, 183–198, 2007.

Chabal, L. and Terral, J.-F.: Le bois de vigne de Port Ariane: étude de racines de vigne alto-médiévales, Lattara, 20, 1–7, 2007.

Combourieu Nebout, N., Peyron, O., Dormoy, I., Desprat, S., Beaudouin, C., Kotthoff, U. and Marret, F.: Rapid climatic variability in the west Mediterranean during the last 25 000 years from high resolution pollen data, Climate of the Past, 5(3), 503–521, 2009.

Combourieu-Nebout, N., Peyron, O., Bout-Roumazeilles, V., Goring, S., Dormoy, I., Joannin, S., Sadori, L., Siani, G. and Magny, M.: Holocene vegetation and climate changes in the central Mediterranean inferred from a high-resolution marine pollen record (Adriatic Sea), Climate of the Past, 9(5), 2023–2042, 2013.

Debret, M., Bout-Roumazeilles, V., Grousset, F., Desmet, M., McManus, J. F., Massei, N., Sebag, D., Petit, J.-R., Copard, Y. and Trentesaux, A.: The origin of the 1500-year climate cycles in Holocene North-Atlantic records, Climate of the Past Discussions, 3(2), 679–692, 2007.

Delhon, C. and Thiébault, S.: The migration of beech (Fagus sylvatica L.) up the Rhone: the Mediterranean history of a “mountain” species, Vegetation History and Archaeobotany, 14(2), 119–132, 2005.

Desprat, S., Combourieu-Nebout, N., Essallami, L., Sicre, M.-A., Dormoy, I., Peyron, O., Siani, G., Bout Roumazeilles, V. and Turon, J. L.: Deglacial and Holocene vegetation and climatic changes in the southern Central Mediterranean from a direct land-sea correlation, Climate of the Past, 9(2), 767–787, 2013.

Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P. and Von Grafenstein, U.: Intense storm activity during the Little Ice Age on the French Mediterranean coast, Palaeogeography, Palaeoclimatology, Palaeoecology, 299(1), 289–297, 2011.

Ducrey, M.: Sylviculture des taillis de Chêne vert pratiques traditionnelles et problématique des recherches récentes, 1988.

Durand, A.: Les paysages médiévaux du Languedoc: Xe-XIIe siècles, Presses Univ. du Mirail., 2003.

Faegri, K. and Iversen, J.: Textbook of pollen analysis (4th edn by Faegri, K., Kaland, PE & Krzywinski, K.), Wiley, Chichester., 1989.

Field, C. B., Barros, V. R., Mastrandrea, M. D., Mach, K. J., Abdrabo, M.-K., Adger, N., Anokhin, Y. A., Anisimov, O. A., Arent, D. J. and Barnett, J.: Summary for policymakers, Climate change 2014: impacts, adaptation, and vulnerability. Part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change, 1–32, 2014.

Figueiral, I., Jung, C., Martin, S., Tardy, C., Compan, M., Pallier, C., Pomaredes, H. and Fabre, L.: La perception des paysages et des agro-systèmes antiques de la moyenne vallée de l'Hérault. Apports des biomarqueurs à l'archéologie préventive, in La perception des paysages et des agro-systèmes antiques de la moyenne vallée de l'Hérault. Apports des biomarqueurs à l'archéologie préventive, pp. 415–430, APDCA., 2010.

Fletcher, W. J. and Zielhofer, C.: Fragility of Western Mediterranean landscapes during Holocene Rapid Climate Changes, CATENA, 103(0), 16–29, doi:10.1016/j.catena.2011.05.001, 2013.

Fletcher, W. J., Boski, T. and Moura, D.: Palynological evidence for environmental and climatic change in the lower Guadiana valley, Portugal, during the last 13 000 years, The Holocene, 17(4), 481–494, 2007.

Frigola, J., Moreno, A., Cacho, I., Canals, M., Sierro, F. J., Flores, J. A., Grimalt, J. O., Hodell, D. A. and Curtis, J. H.: Holocene climate variability in the western Mediterranean region from a deepwater sediment record, Paleoceanography, 22(2), doi:10.1029/2006PA001307, 2007.

Gasco, J.: L'âge du Bronze dans le sud de la France, in La France préhistorique, un essai d'histoire., 2010.

Giraudi, C.: The Apennine glaciations in Italy, Quaternary glaciations—extent and chronology, part I: Europe. Developments in quaternary science, 2, 215–224, 2004.

Giraudi, C.: Middle to Late Holocene glacial variations, periglacial processes and alluvial sedimentation on the higher Apennine massifs (Italy), Quaternary Research, 64(2), 176–184, 2005.

Giraudi, C., Magny, M., Zanchetta, G. and Drysdale, R. N.: The Holocene climatic evolution of Mediterranean Italy: A review of the continental geological data, The Holocene, 21(1), 105–115, 2011.

Henne, P. D., Elkin, C., Franke, J., Colombaroli, D., Calò, C., La Mantia, T., Pasta, S., Conedera, M., Dermody, O. and Tinner, W.: Reviving extinct Mediterranean forest communities may improve ecosystem potential in a warmer future, Frontiers in Ecology and the Environment, 13(7), 356–362, 2015.

Hughen, K. A., Baillie, M. G., Bard, E., Beck, J. W., Bertrand, C. J., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B. and Damon, P. E.: Marine04 marine radiocarbon age calibration, 0-26 cal kyr BP, 2004.

Jallot, L.: La fin du Néolithique dans la moitié sud de la France, in La France préhistorique, un essai d'histoire., 2010.

Jallot, L.: Frontières, stabilités, emprunts et dynamique géoculturelle en Languedoc méditerranéen au Néolithique final (3400-2300 av. J.C.), in Actes des _èmes Rencontres Méridionales de Préhistoire Récente, pp. 87–119., 2011.

Jalut, G.: Analyse pollinique de sédiments holocènes de l'étang de Capestang (Hérault), Temps et espace dans le bassin de l'Aude du Néolithique à l'Age du Fer, 293–302, 1995.

Jalut, G., Amat, A. E., Bonnet, L., Gauquelin, T. and Fontugne, M.: Holocene climatic changes in the Western Mediterranean, from south-east France to south-east Spain, Palaeogeography, Palaeoclimatology, Palaeoecology, 160(3), 255–290, 2000.

Jalut, G., Dedoubat, J. J., Fontugne, M. and Otto, T.: Holocene circum-Mediterranean vegetation changes: climate forcing and human impact, Quaternary international, 200(1), 4–18, 2009.

Janin, T.: L'âge du fer dans le sud de la France, in La France préhistorique, un essai d'histoire, pp. 461–486., 2010.

Jiménez-Espejo, F. J., García-Alix, A., Jiménez-Moreno, G., Rodrigo-Gámiz, M., Anderson, R. S., Rodríguez-Tovar, F. J., Martínez-Ruiz, F., Giralt, S., Huertas, A. D. and Pardo-Igúzquiza, E.: Saharan aeolian input and effective humidity variations over western Europe during the Holocene from a high altitude record, Chemical Geology, 374, 1–12, 2014.

Jiménez-Moreno, G., Rodríguez-Ramírez, A., Pérez-Asensio, J. N., Carrión, J. S., López-Sáez, J. A., Villarías-Robles, J. J., Celestino-Pérez, S., Cerrillo-Cuenca, E., León, Á. and Contreras, C.: Impact of late-Holocene aridification trend, climate variability and geodynamic control on the environment from a coastal area in SW Spain, The Holocene, 25(4), 607–617, 2015.

Jorda, C., Chabal, L. and Blanchemanche, P.: Lattara entre terres et eaux, Gallia, 65, 1–230, 2008.

Kaplan, M.: Le Moyen Âge, IV'-X siècles, Paris, Bréal., 1994.

Koerner, W., Cinotti, B., Jussy, J.-H. and Benoît, M.: Evolution des surfaces boisées en France depuis le début du XIXe siècle: identification et localisation des boisements des territoires agricoles abandonnés, Revue forestière française, 52(3), 249–270, 2000.

Kotthoff, U., Müller, U. C., Pross, J., Schmiedl, G., Lawson, I. T., van de Schootbrugge, B. and Schulz, H.: Lateglacial and Holocene vegetation dynamics in the Aegean region: an integrated view based on pollen data from marine and terrestrial archives, The Holocene, 18(7), 1019–1032, 2008.

Leveau, P.: L'oléiculture en Gaule Narbonnaise: données archéologiques et paléoenvironnemtales. Présentation-Interprétation, Revue archéologique de Picardie, 1(1), 299–308, 2003.

Li, J. and Romane, F. J.: Effects of germination inhibition on the dynamics of Quercus ilex stands, Journal of Vegetation Science, 8(2), 287–294, 1997.

Magny, M.: Holocene climate variability as reflected by mid-European lake-level fluctuations and its probable impact on prehistoric human settlements, Quaternary International, 113(1), 65–79, 2004.

Magny, M.: Orbital, ice-sheet, and possible solar forcing of Holocene lake-level fluctuations in west-central Europe: a comment on Bleicher, The Holocene, 23(8), 1202–1212, 2013.

Magny, M., Miramont, C. and Sivan, O.: Assessment of the impact of climate and anthropogenic factors on Holocene Mediterranean vegetation in Europe on the basis of palaeohydrological records, Palaeogeography, Palaeoclimatology, Palaeoecology, 186(1), 47–59, 2002.

Magny, M., Joannin, S., Galop, D., Vannière, B., Haas, J. N., Bassetti, M., Bellintani, P., Scandolari, R. and Desmet, M.: Holocene palaeohydrological changes in the northern Mediterranean borderlands as reflected by the lake-level record of Lake Ledro, northeastern Italy, Quaternary Research, 77(3), 382–396, 2012.

Magny, M., Combourieu-Nebout, N., De Beaulieu, J. L., Bout-Roumazeilles, V., Colombaroli, D., Desprat, S., Francke, A., Joannin, S., Peyron, O. and Revel, M.: North-south palaeohydrological contrasts in the central Mediterranean during the Holocene: tentative synthesis and working hypotheses, Climate of the Past Discussions, 9, 2013.

Marchal, O., Cacho, I., Stocker, T. F., Grimalt, J. O., Calvo, E., Martrat, B., Shackleton, N., Vautravers, M., Cortijo, E. and van Kreveld, S.: Apparent long-term cooling of the sea surface in the northeast Atlantic and Mediterranean during the Holocene, Quaternary Science Reviews, 21(4), 455–483, 2002.

Naughton, F., Goñi, M. S., Kageyama, M., Bard, E., Duprat, J., Cortijo, E., Desprat, S., Malaizé, B., Joly, C. and Rostek, F.: Wet to dry climatic trend in north-western Iberia within Heinrich events, Earth and Planetary Science Letters, 284(3), 329–342, 2009.

Nissen, K. M., Leckebusch, G. C., Pinto, J. G., Renggli, D., Ulbrich, S. and Ulbrich, U.: Cyclones causing wind storms in the Mediterranean: characteristics, trends and links to large-scale patterns, Natural Hazards and Earth System Science, 10(7), 1379–1391, 2010.

Ouzoulias, P.: La géographie de la villa dans les Gaules romaines : quelques observations., in Actes du colloque international AGER IX, pp. 253–268., 2013.

Pérez-Obiol, R., Jalut, G., Julià, R., Pèlachs, A., Iriarte, M. J., Otto, T. and Hernández-Beloqui, B.: Mid-Holocene vegetation and climatic history of the Iberian Peninsula, The Holocene, 21(1), 75–93, 2011.

Planchais, N.: Palynologie lagunaire de l'étang de Mauguio. Paléoenvironnement végétal et évolution anthropique, Pollen et spores, 1, 93–118, 1982.

Planchais, N.: Impact de l'homme lors du remplissage de l'estuaire du Lez (Palavas, Hérault) mis en évidence par l'analyse pollinique, Pollen et spores, 29(1), 73–88, 1987.

Puertas, O.: Palynologie dans le delta du Lez: contribution à l'histoire du paysage de Lattes, Association pour la recherche archéologique en Languedoc oriental., 1998.

Puertas, O.: Premiers indices polliniques de néolithisation dans la plaine littorale de Montpellier (Hérault, France), Bulletin de la Société préhistorique française, 96(1), 15–20, 1999.

Punt, W.: The Northwest European Pollen Flora (NEPF) Vol I (1976), Vol II (1980), Vol III (1981), Vol IV (1984) Vol V (1988), Vol VI (1991), Vol VII (1996), Elsevier, Amsterdam., 1976.

Quezel, P.: La région méditerranéenne française et ses essences forestières, signification écologique dans le contexte circum-méditerranéen, Forêt Méd, 1(1), 7–18, 1979.

Reille, M.: Pollen et Spores d'Europe et d'Afric du Nort, Mar-seille: Laboratoire de Botanique historique et Palynologie, 520p, 1992.

Reille, M. and Pons, A.: The ecological significance of sclerophyllous oak forests in the western part of the Mediterranean basin: a note on pollen analytical data, in Quercus ilex L. ecosystems: function, dynamics and management, pp. 13–17, Springer., 1992.

Reimer, P. J., Baillie, M. G., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk, R. C., Buck, C. E., Burr, G. S. and Edwards, R. L.: IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP, 2009.

Roberts, N., Jones, M. D., Benkaddour, A., Eastwood, W. J., Filippi, M. L., Frogley, M. R., Lamb, H. F., Leng, M. J., Reed, J. M. and Stein, M.: Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis, Quaternary Science Reviews, 27(25), 2426–2441, 2008.

Roberts, N., Eastwood, W. J., Kuzucuoğlu, C., Fiorentino, G. and Caracuta, V.: Climatic, vegetation and cultural change in the eastern Mediterranean during the mid-Holocene environmental transition, The Holocene, 21(1), 147–162, 2011.

Sabatier, P. and Dezileau, L.: Archives sédimentaires dans les lagunes du Golfe d’Aigues-Mortes. Estimation de l’aléa de tempête depuis 2000 ans, Quaternaire. Revue de l’Association française pour l’étude du Quaternaire, 21(1), 5–11, 2010.

Sabatier, P., Dezileau, L., Colin, C., Briqueu, L., Bouchette, F., Martinez, P., Siani, G., Raynal, O. and Von Grafenstein, U.: 7000years of paleostorm activity in the NW Mediterranean Sea in response to Holocene climate events, Quaternary Research, 77(1), 1–11, 2012.

Sadori, L., Jahns, S. and Peyron, O.: Mid-Holocene vegetation history of the central Mediterranean, The Holocene, 21(1), 117–129, 2011.

Sadori, L., Giardini, M., Gliozzi, E., Mazzini, I., Sulpizio, R., van Welden, A. and Zanchetta, G.: Vegetation, climate and environmental history of the last 4500 years at lake Shkodra (Albania/Montenegro), The Holocene, 25(3), 435–444, 2014.

Schmiedl, G., Kuhnt, T., Ehrmann, W., Emeis, K.-C., Hamann, Y., Kotthoff, U., Dulski, P. and Pross, J.: Climatic forcing of eastern Mediterranean deep-water formation and benthic ecosystems during the past 22 000 years, Quaternary Science Reviews, 29(23), 3006–3020, 2010.

Schneider, L.: Aux marges méditerranéennes de la Gaule mérovingienne. Les cadres politiques et ecclésiastiques de l’ancienne Narbonnaise Iere entre Antiquité et Moyen Age (Ve-IXe siècles), L’espace du diocèse. Genèse d’un terrioire dans l’occident médiéval (Ve-XIIIe siècle), 69–95, 2008.

Schneider, L., Fauduet, I. and Odenhardt-Donvez, I.: Structures du peuplement et formes de l’habitat dans les campagnes du sud-est de la France de l’Antiquité au Moyen Âge (IVe-VIIIe s.): essai de synthèse, Gallia, 64(1), 11–56, 2007.

Sorrel, P., Tessier, B., Demory, F., Delsinne, N. and Mouazé, D.: Evidence for millennial-scale climatic events in the sedimentary infilling of a macrotidal estuarine system, the Seine estuary (NW France), Quaternary Science Reviews, 28(5), 499–516, 2009.

Stockmarr, J.: Tablets with spores used in absolute pollen analysis, Pollen et spores, 1971.

Sugita, S.: A model of pollen source area for an entire lake surface, Quaternary research, 39(2), 239–244, 1993.

Tinner, W., van Leeuwen, J. F., Colombaroli, D., Vescovi, E., Van der Knaap, W. O., Henne, P. D., Pasta, S., D'Angelo, S. and La Mantia, T.: Holocene environmental and climatic changes at Gorgo Basso, a coastal lake in southern Sicily, Italy, Quaternary Science Reviews, 28(15), 1498–1510, 2009.

Triat-Laval, H.: Contribution pollenanalytique à l'histoire tardi-& postglaciaire de la végétation de la Basse Vallée du Rhône, Université d'Aix-Marseille III., 1978.

Trouet, V., Scourse, J. D. and Raible, C. C.: North Atlantic storminess and Atlantic Meridional Overturning Circulation during the last Millennium: Reconciling contradictory proxy records of NAO variability, Global and Planetary Change, 84, 48–55, 2012.

Vaquer, J.: Le Néolithique moyen en France, cultures et intéractions (4600-3500 av. J.C.), in La France préhistorique, un essai d'histoire., 2010.

Zazo, C., Mercier, N., Silva, P. G., Dabrio, C. J., Goy, J. L., Roquero, E., Soler, V., Borja, F., Lario, J. and Polo, D.: Landscape evolution and geodynamic controls in the Gulf of Cadiz (Huelva coast, SW Spain) during the Late Quaternary, Geomorphology, 68(3), 269–290, 2005.

Table 1. Short description of the PB06/EG08 pollen diagram zonation

Pollen zone	Interval (cm)	Age (yrscal BP)	Age (yrs AD/BC)	Pollen zone signature
Pal-XI	33-0 (EG08)	~ 62/-62	~ 2012/ 1888	*Fagus* (<1%), deciduous *Quercus* (9-11%), sclerophyllous *Quercus* ↑ (from 11 to 21%), *Pinus* ↑ (from 11 to 21%), Ericaceae ↓ (from 5 to 0,5%), *Olea* (3-7%), *Castanea* ↓ (from 5 to 0,5%), Poaceae ↓ (from 8 to 2%), Chenopodiaceae (11-17%)
Pal-X	74-54 (EG08)	~ 202/62	~ 1748/ 1888	*Fagus* (<1%), deciduous *Quercus* (10-13%), sclerophyllous *Quercus* (8-16%), *Pinus* (3-13%), *Olea* (4-10%), *Castanea* ↑ (from 1 to 7%), Ericaceae (1-4%), Poaceae and Chenopodiaceae (7-13%)
Pal-IX	172-120 (PB06)	~ 892/622	~ 1058/ 1328	*Fagus* low (0,5-2,5%), deciduous *Quercus* (14-23%), sclerophyllous *Quercus* (8-15%), *Pinus* ↑ (from 4 to 9%), Ericaceae (1-4%), *Olea* ↑ (from 5 to 12%), Poaceae ↓ (from 16 to 4%), Chenopodiaceae ↓ (from 20 to 10 %)
Pal-VIII	210-172 (PB06)	~ 1192/ 892	~ 758/1058	*Fagus* ↑and ↓(from 1 to 6 % and from 6 to 2%), deciduous *Quercus* ↓(from 30 to 16%), sclerophyllous *Quercus* (8-17%), *Pinus* low (1-6%), *Olea* ↑ (from 1 to 5%), Ericaceae (3-6%) Poaceae ↑ (from 8 to 14%), Chenopodiaceae ↑ (from 5 to 20%)
Pal-VII	220-210 (PB06)	~ 1316/ 1192	~ 634/758	*Fagus* low (2-3%), deciduous *Quercus* ↑ (from 19 to 28%), sclerophyllous *Quercus* (7-12%), *Pinus* low (2-6%), Ericaceae (2-6%), Poaceae (8-10%), Chenopodiaceae (12-14%)
Pal-VI	260-220 (PB06)	~ 2000/ 1316	~ -50/634	*Fagus* ↓ (from 8 to 2%), deciduous *Quercus*↓ (from 30 to 19%), sclerophyllous *Quercus* ↓ (from 20 to 8%), *Pinus* ↓ (from 10 to 4%), *Abies* (<1%), Ericaceae ↑ (from 1 to 8%), Poaceae ↑ (from 3 to 8%), Chenopodiaceae ↑ (from 8 to 11%)
Pal-V	298-260 (PB06)	~ 2434/ 2000	~ -484/-50	*Fagus* ↑ (from 4 to 11%), deciduous *Quercus* (24-35%), sclerophyllous *Quercus* (8-17%), *Pinus* (5-9%), *Abies* (<1%), Chenopodiaceae and Poaceae low (5-10%).
Pal-IV	322-298 (PB06)	~ 2643/ 2434	~ -693/-484	*Fagus* low (2-5%), deciduous *Quercus* very high (35-42 %), sclerophyllous *Quercus* (9-14 %), *Pinus* low (7-4%), *Abies* disappearance (≤ 1%), Poaceae ↑ (from 2 to 6%), Chenopodiaceae (around 6%).
Pal-III	370-322 (PB06)	~ 3038/ 2643	~ -1088/ -693	*Fagus* ↓ (from 11 to 3%), deciduous *Quercus* ↑ (from 25 to 40 %), sclerophyllous *Quercus* (5-9%), *Pinus* (8-13%), *Abies* low (2-3%), Poaceae low (3-7%), Chenopodiaceae (7-12%)
Pal-II	514-370 (PB06)	~ 4350/ 3038	~ -2400/ -1088	*Fagus* high (7-19 %), deciduous *Quercus* high and variable (24-41%), sclerophyllous *Quercus* low (6-14%), *Pinus* (from 14 to 8 %), *Abies* low (1-4%), Poaceae and Chenopodiaceae low (2-9%)
Pal-I	546-514 (PB06)	~ 4694/ 4350	~ -2744/ -2400	*Fagus* low (4-9%), deciduous *Quercus* ↑ (from 25 to 41 %), sclerophyllous *Quercus* low (3-7%), *Pinus* variable (10-22%), *Abies* low (1-3%), Poaceae and Chenopodiaceae low (1-7%)

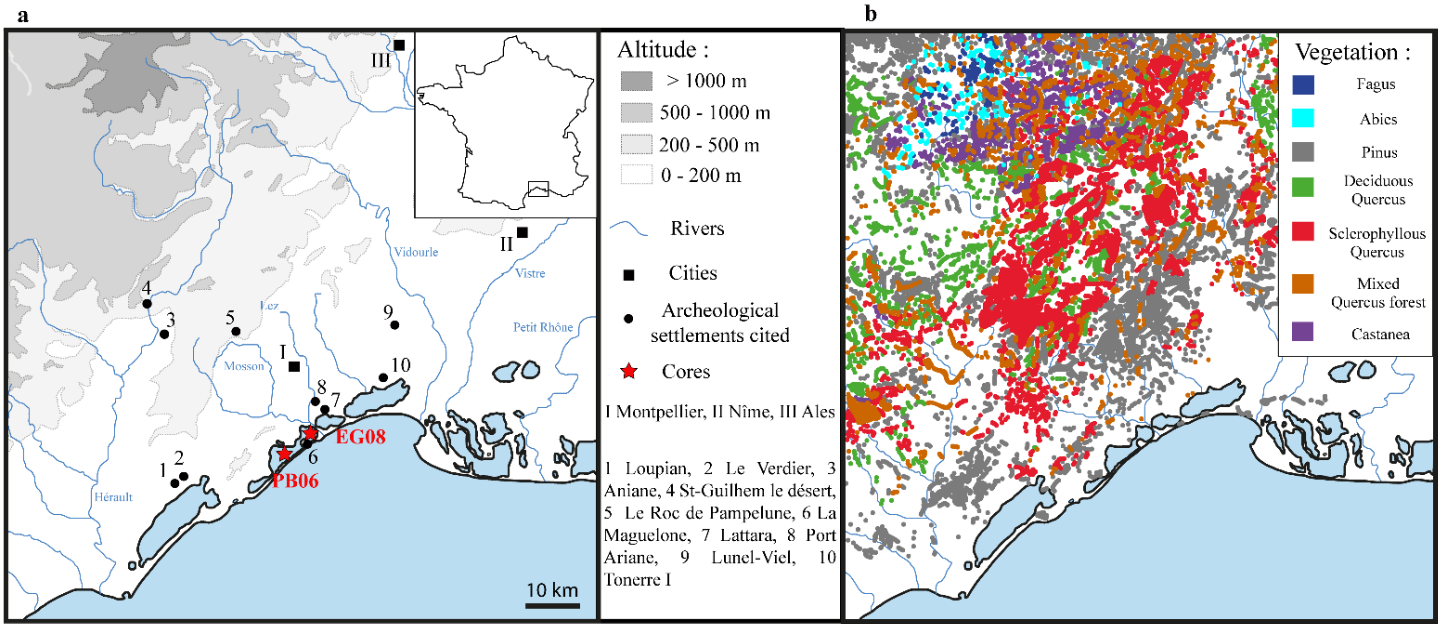


Figure 1. Geographical settings: (a) Studied cores, main cities and rivers, topography and archeological sites mentioned in the articles. (b) Vegetation map showing the distribution of forest types by dominant taxa (data from the National forestry inventory, IFN BD forêt 1).

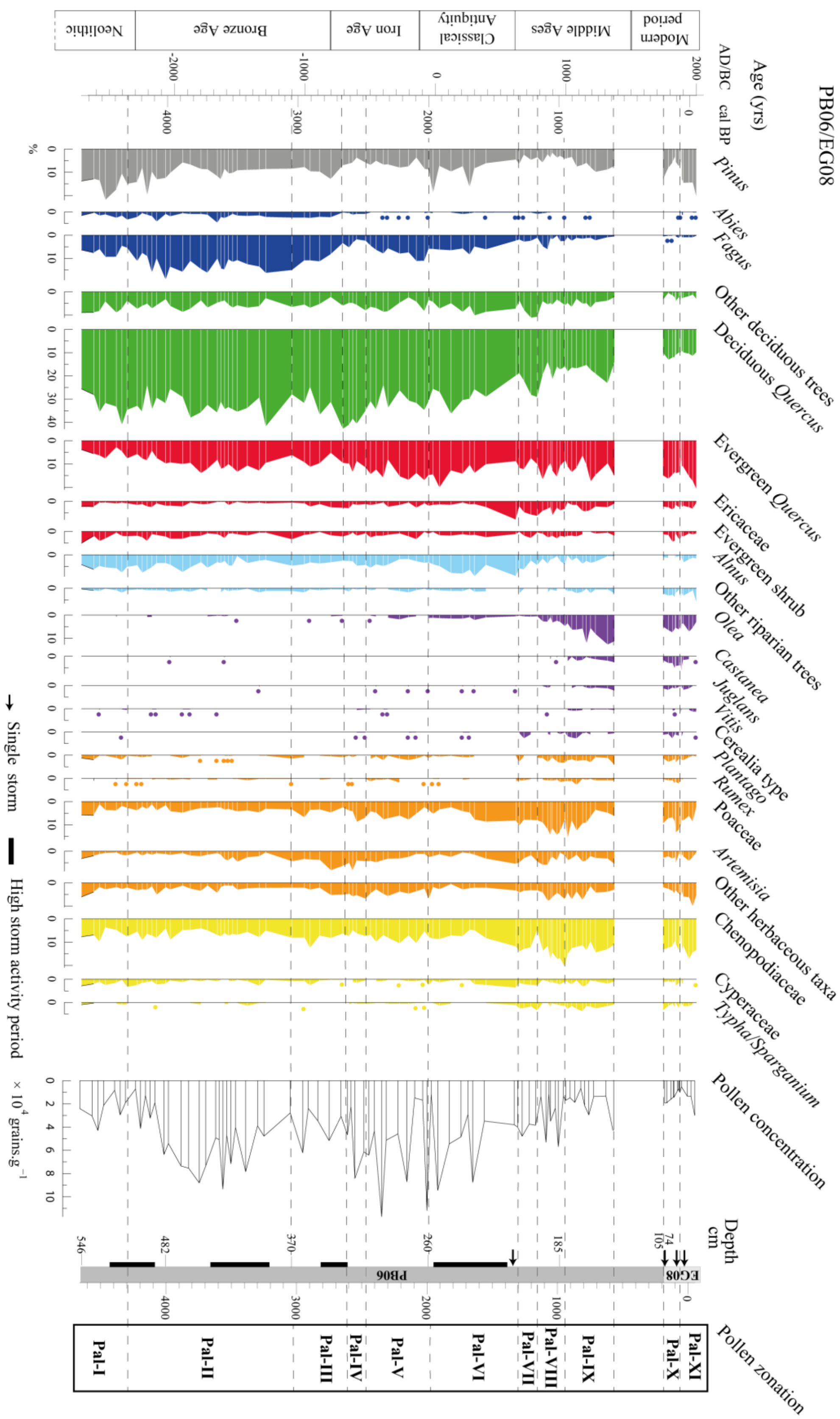
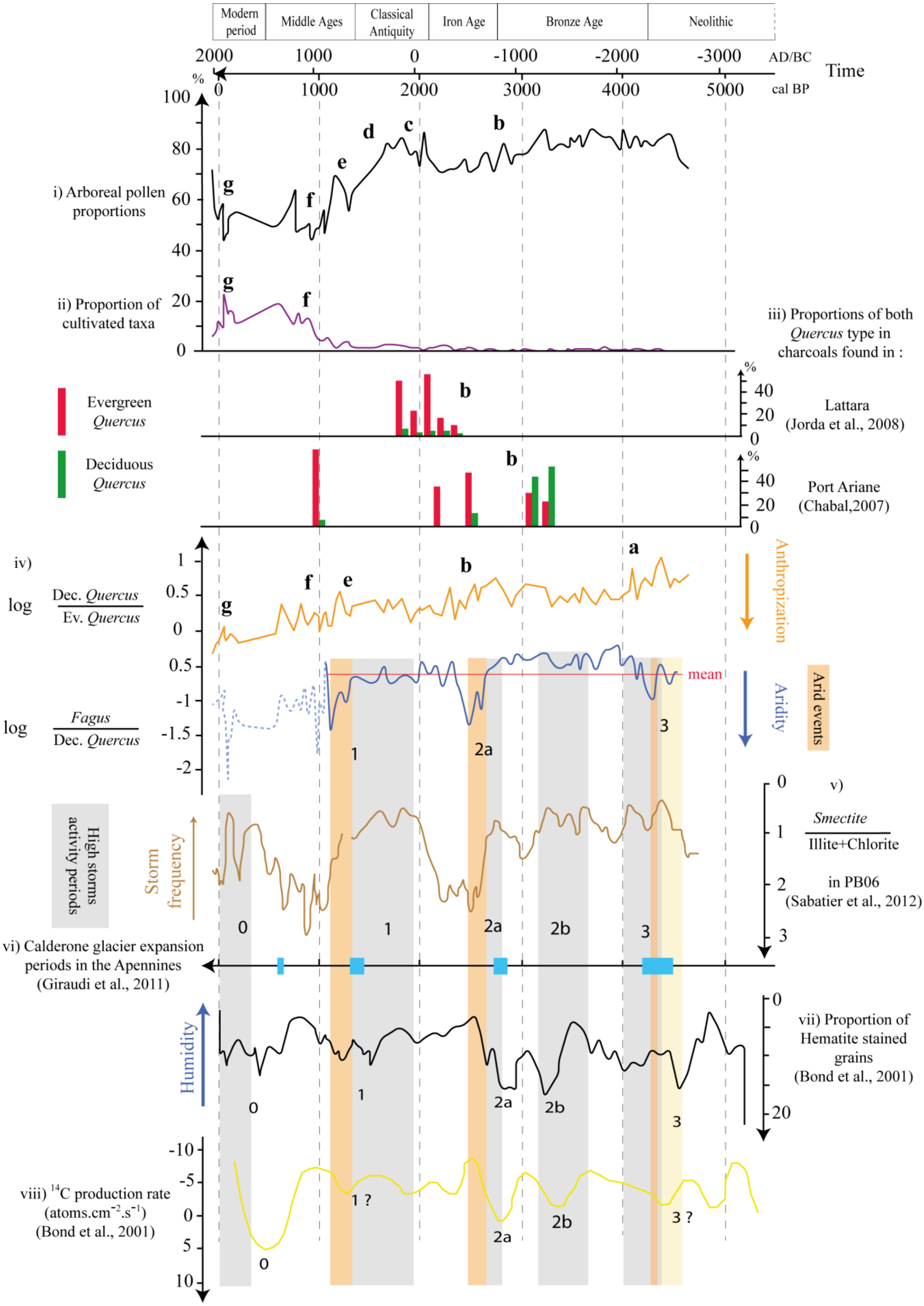


Figure 2. Pollen diagram of the cores PB06 and EG08. Pollen curves are presented in calendar year BP (correspondence between age and depth is presented on the left). On the right of the diagram are represented the pollen zones.



Modern period
Middle Ages
Classical Antiquity
Iron Age
Bronze Age
Neolithic
2000
1000
0
-1000
-2000
-3000
AD/BC
Time
0
1000
2000
3000
4000
5000
cal BP
i) Arboreal pollen proportions
ii) Proportion of cultivated taxa
iii) Proportions of both *Quercus* type in charcoals found in :
Evergreen *Quercus*
Deciduous *Quercus*
Lattara (Jorda et al., 2008)
Port Ariane (Chabal,2007)
iv)
log Dec. *Quercus* / Ev. *Quercus*
log *Fagus* / Dec. *Quercus*
Anthropization
mean
Aridity
Arid events
High storms activity periods
Storm frequency
v) *Smectite* / Illite+Chlorite in PB06 (Sabatier et al., 2012)
vi) Calderone glacier expansion periods in the Apennines (Giraudi et al., 2011)
Humidity
vii) Proportion of Hematite stained grains (Bond et al., 2001)
viii) ^{14}C production rate (atoms.cm^{-2}.s^{-1}) (Bond et al., 2001)

10

Figure 3. Comparison of the pollen data from the core PB06 and EG08 with anthracological and climatic data. Orange shaded bars represent arid events and grey shaded bars represent high storm activity periods. i) Arboreal pollen proportions; ii) Proportion of cultivated taxa; iii) proportions of both *Quercus* type charcoals in Lattara and Port Ariane archeological sites; iv) logarithm of deciduous/evergreen *Quercus* (orange) and *Fagus*/deciduous *Quercus* (blue) ratios, after ~1100 cal BP (10^{th} century) the *Fagus*/deciduous *Quercus* ratio (in dotted light blue) cannot be interpreted in term of climate fluctuations because of the strong human influence; v) Smectite/Illite+Chlorite ratio in the core PB06 (Sabatier et al., 2012); vi) Calderone glacier expansion periods in the Apennines : the width of each blue box represent the estimated time during which the glacier expand (Giraudi et al., 2011); vii) Proportion of hematite stained grains in the cores MC-52/VM29-191 in the north Atlantic (Bond et al., 2001); viii) ^{14}C production rate (Bond et al., 2001).