Review of Palaeobotany and Palynology, Volume 259, 2018, Pages 207-222,
https://doi.org/10.1016/j.revpalbo.2018.10.002.

HIGH-RESOLUTION (SUB-DECADAL) POLLEN ANALYSIS OF VARVED SEDIMENTS FROM LAKE MONTCORTÈS (SOUTH-CENTRAL PRE-PYRENEES): A FINE-TUNED RECORD OF LANDSCAPE DYNAMICS AND HUMAN IMPACT DURING THE LAST 500 YEARS.

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Keywords: Retting; *Cannabis*; human impact; historical data; varves; palaeoecology

ABSTRACT

A high-resolution (6 years/sample) palaeoenvironmental reconstruction using pollen, charcoal and non-pollen palynomorphs was carried out on annually laminated sediments of Lake Montcortès (South-Central Pre-Pyrenean flank). The results were combined with historical data to better understand landscape evolution and human interaction during the last 500 years. Our results show that human activities (cropping, livestock breeding and hemp cultivation and retting) have been the most important factors responsible for vegetation changes with highest intensity between 1530 and 1900 CE. By means of a sub-decadal study we have been able to evaluate short-lasting events at local and regional scales related to climate (heavy rainfall events and, high-land forest fluctuations) or to historical and well-dated and documented socio-economic events (i.e., crop promotions (hemp) or land abandonment-population emigration). The temporal extent (400 years) and continuity of *Cannabis* pollen peaks have been confirmed, and new evidence of water quality changes, likely as a consequence of hemp retting practices between the mid 17th to late 19th century, are provided. This is the first high-resolution palaeoenvironmental study carried out in a varved lake on the Iberian Peninsula so far. With these data we hope to contribute to filling the gap in high-resolution palaeoenvironmental data.

Keywords: Retting; *Cannabis*; human impact; historical data; varves; multiproxy palaeoecology

1. INTRODUCTION

Lake and peatlandssediments are natural archives that store information on limnological, biological, geochemical and anthropogenic processes occurring in the water body and in the catchment area (Smol et al., 2002; Veski et al., 2005). Understanding the process that leads to the recent evolution of landscapes and discerning between natural and anthropogenic causes is a challenging question that can best be empirically addressed with palaeoecological data. Changes in the spatial structure of a landscape result from natural process such as climate variability and/or soil development combined with human activity driven by socio-economic and cultural factors (Veski et al., 2005). Thus, to fully understand the changes and their drivers, it is necessary to combine data from different sources and disciplines such as archaeology, documentary sources, ecology, palaeoclimatology and palaeoenvironmental data, although such a task may not be easy. For instance, the lack of enough spatial and temporal resolution of the different data sources sometimes does not permit to obtain a complete and accurate image of the past (Jones et al., 2009; Rull et al., 2014; Sadori et al., 2015; Contreas et al., 2018). Archaeology, palaeoclimatology and palaeoenvironmental science often strive to achieve regional and long-term relevance, resulting in a coarse resolution of multi-decadal to multi-millennial scales (Rull et al., 2014; Contreras et al., 2018). In contrast, ecological, and historical data provide more constrained spatial and temporal resolutions (sub-decadal/annual/seasonal) (Rull et al., 2014; Contreras et al., 2018). In palaeoecology, a solution for this issue is to work with varved sediments that allow annual to seasonal time-resolutions or with sediment records with very high sediment accumulation rates (Veski et al., 2005; Ojala et al., 2012; Rull 2014).

Within the sedimentary archive, the last millennium is especially interesting for studying landscape and human environment interactions due to the availability of good quality and well preserved historical records (Dearing 2013; Zolitschka et al., 2015) and because it has been a key period of the development of modern vegetation types and the formation of cultural landscapes (Rull et al., 2011; Wacnik et al., 2016). Furthermore, significant climatic variations occurred in relatively short periods of time (Medieval Climatic Anomaly, Little Ice Age, and the onset of Global Warming) that might drive short-lasting vegetation disturbances only be detectable by -resolution analyses (Wacnik et al., 2016).

Several high-resolution studies from lake sediments and some from varved records are already available for Europe using both physicochemical and biological proxies. Most of them are focused on palaeoclimate and are aimed to perform quantitative reconstructions (some examples: Feurdian et al., 2008 (pollen); Trachsel et al.,2010 (biogenic silica and chironomids); Lotter et al., 2012 (chironomid and pollen); de Jong et al.,2013 (chrysophyte stomatocyst). Palaeoenvironmental high-resolution studies are less frequent but equally important as they are the only available tool to evaluate past biodiversity losses or to identify past key periods that can help to set conservation targets and to visualize realistic future scenarios (Ekblom and Gillson, 2017).

For the Iberian Peninsula, a considerable number of pollen records are already available. They are mainly performed at a low resolution and cover several millennia, although some exceptions at moderate resolution and covering the last millennium exist (i.e., Riera et al., 2004; Morellón et al., 2009; Ejarque et al., 2009; Rull et al., 2011¸ Garcés-Pastor et al., 2016). The available pollen records from the Pyrenean range mostly belong to high altitude lakes and peatlands. High altitude mountain areas have traditionally been viewed as pristine environments with low human population density where more severe climatic conditions might hamper human occupation. But, for the case of the Pyrenees and Pre-Pyrenees, it has been demonstrated that substantial human pressure and considerable exploitation of natural resources have taken place since the Mesolithic: farming, mining, logging and fire impact (Gassiot and Jiménez 2006; Palet et al 2007, Sancho and Planas 2009 Ejarque et al., 2010; Bal et al., 2011; Cunill et al., 2013; Corella et al., 2013,). Therefore, lower altitudes on the Pyrenean - montane stage (ranging from 800 to 1600 m a.s.l)- which are very favorable for human occupation and consequently sensitive to be higher human impacted, arise as an interesting area to study human occupation history and human-landscape evolution relationships.

Lake Montcortès, which is located in the pre-Pyrenean range (1026 m a.s.l.) is a very suitable place to reconstruct past human-environment relationships. The exceptional scientific value of this lake is due to its strategic location and to the varved nature of its sediments that are ideal for performing high-resolution studies with accurate time control (Corella et al., 2011, 2012). This feature, which is uncommon among Iberian lakes, supports several studies which have demonstrated the potential to reconstruct the ecological dynamics of the lake communities and vegetation dynamics related to climate and human activities at a sub-centennial scale (Scussolini et al., 2011; Rull et al., 2011; Rull and Vegas-Vilarrúbia et al., 2015; Montoya et al., 2018). Reconstructions of past climate and past shifts in oxygenation regime at annual and sub-decadal resolutions have also been performed in this lake (Corella et al., 2014; 2016 and Vegas-Vilarrúbia et al., 2018). Moreover, modern sedimentary analogue studies and a detailed floristic inventory of lake surroundings have been published recently, both, are very useful tools that helped to interpret the sediment record (Mercadé et al., 2015; Rull et al., 2017; Trapote et al., 2018). Among the key results found, the Lake Montcortès pollen record contains large amounts of hemp (*Cannabis sp*.) (Rull et al., 2011). Historically, *Cannabis* has been a fundamental plant for the development of human societies then, the identification of *Cannabis* pollen is a very useful tool to track and identify human activities and their impacts (van Zant et al., 1979; Mercuri et al., 2015, Peglar 1993).

Here, we present for the first time in the Iberian Peninsula, a high-resolution and continuous palynological reconstruction (6 years/sample on average) carried out in a Pre-Pyrenean varved lake. We perform a multiproxy reconstruction using pollen, charcoal, non-pollen palynomorphs (NPPs) and historical documents for the last 500 years adding unique high-resolution palaeoenvironmental and palaeoecological studies covering modern period. Our main aim is to erform a detailed, and accurate palaeoenvironmental reconstruction to investigate vegetation history, land-use and human impact around Lake Montcortès at the highest detail achieved so far. This study provides new data on historical land-use and management and on the potential use of Lake for hemp retting. Data covering the last century and therefore, the climatic instrumental record, is presented for the first time. Our data, together with the varved nature of the Lake Montcortès record and the already available palaeoenvironmental information for the lake Montcortès, combined with historical and paleoecological data available for the Pyrenees have made possible to perform a thorough picture at local and regional scales of human-vegetation interactions around the lake.The data obtained with this work may contribute to develop and test computational models of interactions between climate, landscape evolution and land-use as well as to constrain and decrease the uncertainties in future environmental projections (Dearing 2006; Hegerl et al., 2006; Dearing et al., 2013).

1.1. Study area

Lake Montcortès (42° 19’ N; 0° 59’ E and 1027 m a.s.l) is a small karstic lake situated on the south-central pre-Pyrenees in the Pallars region (Fig.1). It was formed by karstic processes of dissolution and collapse on Triassic evaporates. The lake’s catchment is small and is emplaced in Oligocene carbonate conglomerates, Triassic limestones, marls and evaporites (Rosell, 1994). The lake is fed manly by groundwater and lake level is controlled by an outlet stream located along the northern shore and water evaporation (Corella et al., 2016). It has a maximum water depth of 30 m. According to the nearest meteorological station, total annual mean precipitation is 669 mm, with February being the driest month and May being the wettest. Annual average air temperature is 12.8°C, with maximum and minimum mean temperatures of 23.3°C (July) and 2.9°C (January) respectively (reference period 1961–1990). Lake alternating meromictic and holomictic conditions as has been demonstrated by Trapote et al. (2018) and Vegas-Vilarrúbia et al. (2018), remaining stratified most of the year and mixing during winter. It is an oligotrophic lake with very low nutrient content particularly for phosphorous, well buffered waters and maximum phytoplankton productivity occurring during late summer and early autumn (see Trapote et al. (2018) for more detail).

The lake lies near the altitudinal boundary corresponding to the sub-montane belt, which in the Pyrenees is situated around 800-1000 m a.s.l. elevation, depending on local conditions (Vigo and Ninot 1987). Three major forest formations occur at the lake region reflecting this boundary condition: 1) Evergreen oak forest dominated by *Quercus rotundifolia* L. (representative of the Mediterranean lowlands)*;* 2) Deciduous oak forest dominated by *Q. pubescens* L. and *Q. pyrenaica* L. (representative of the middle montane belt with higher precipitation); and 3) Conifer forest of *Pinus nigra* L. at lower and southern regions (probably secondary replacing the deciduous oak forest) and *Pinus sylvestris* L. at higher elevations (making the transition between Sub-montane and Montane belt) (Folch, 1981; Rull et al., 2011; Mercadé et al., 2014) (Fig. 1A). The lake is surrounded by a dense littoral vegetation belt dominated by *Phagmites, Cladium mariscus* L. and *Typha* and, to a lesser extent, represented by *Juncus and Scirpus* (Mercadé et al., 2013). Hay meadows, pastures (mostly for cattle and horses) and cereal crops are the most important rural anthropic habitats around the lake. Besides farming, since 1970's the most important human activity around the lake and in the area is rural tourism.

2. METHODS

2.1. Coring and age modelling

In July 2013, a 114 cm long sediment core named MONT-0713-G05 was retrieved from the deepest distal lake basin (~30 m water depth) using a UWITEC 60 mm diameter gravity corer. It was kept at the lake shore during 3 days to allow consolidation and then transported to the core repository at the Institute of Earth Sciences Jaume Almera (Spanish Research Council). In previous studies, Corella et al., (2011, 2014) built an age-depth model for the last six centuries, which is based on independent varve counting and ^{210}Pb and ^{14}C radiometric dating. Varve counting was performed on a composite sequence obtained from cores MON12-3A-1G and MON12-2A-1G and by double counting in 14 overlapping thin sections. Less than 1% of varves were interpolated using annual sedimentation rates from well-preserved adjacent varve sections. Further details of this age-depth model are provided in Corella et al., (2014). Stratigraphic correlation between core MON12-3A-1G and MONT-0713-G05 was obtained based on a detailed inspection of sedimentary structures, varve thickness patterns and characteristic features seen in specific varves that allowed the identification of 96 marker horizons (i.e., flood layers and/or distinct sub-layering in calcite layers).

2.2. Core sampling, pollen, charcoal and non-pollen palynomorphs (NPPs)

The varved part of MONT-0713-G05 was sampled continuously every 0.5 mm using a syringe to obtain volumetric samples, which was the highest resolution possible that allowed us to obtain enough sedimentary material for pollen analysis. Turbidites were avoided following the sampling procedure described in Corella et al. (2017) since these sediment-laden layers represent allochtonous material eroded from the lake catchment and deposited within hours/days (Corella et al., 2015). A set of 96 samples were processed using standard palynological methods (Moore et al., 1991; Bennet and Willis, 2001), including KOH, HCl, HF digestions and acetolysis. Two *Lycopodium* tablets (batch n° 483216; 18,583 spores/tablet) were added to each sample before chemical processing. Residues were suspended in liquid glycerine and microscopic slides were mounted in the same medium. Pollen was identified according to Moore et al. (1991) and Reille (1992, 1995, 1998) and following previous Montcortès studies (Rull et al., 2011; Rull and Vegas-Vilarrúbia 2014, 2015). All samples were counted until diversity saturation (Rull, 1987) with a minimum of 300 pollen grains excluding *Cannabis-type pollen*, which was superabundant in some samples (40 - 85% respect to the total terrestrial pollen sum). Algal remains were also identified and counted to genus level. Charcoal particles were counted and classified into two groups based on size: charcoal I (< 100 µm) as indicator of regional fires and charcoal II (between 100-500 µm) as indicator of more local fires (Whitlock and Larson 2001). Fungal spores were identified following van van Geel and Aptroot (2006), van Geel et al. (2011), and López-Vila et al. (2014). The pollen sum included all pollen types except those from aquatic and semi-aquatic taxa: Cyperaceae, *Myriophyllum, Scirpus, Potamogeton and Typha-Sparganium*, hereafter referred as *Typha* according to local vegetation surveys (Mercadé et al., 2013) . Pollen and spores below 3% of the pollen sum were not shown in the pollen diagram. Pollen accumulation rates (PAR) and charcoal influx in cm $^{-2}$ yr $^{-1}$ were calculated. Diagrams were plotted and zoned using the software Psimpoll 4.27 (Bennet 2002) and the method of optimal splitting by information content (OSIC) (Bennett, 1996) considering only pollen types. Percentages for NPPs (algal remains and fungi spores) were referred to the pollen sum. Pollen groups were defined according to the present day vegetation types as previously presented for Montcortès in Rull et al. (2011) and Mercadé et al. (2013). Table 1 presents each group and the corresponding taxa included in it for the sediment record presented in this work.

Table 1. Pollen groups according to the present day vegetation types, based on Rull et al., 2011

Vegetation type	**Pollen taxa**
Conifer forest	*Pinus, Abies*

Evergreen oak forest	*Quercus*- evergreen-type
Decidious oak forest	*Cornus, Carpinus, Fagus, Fraxinus, Tilia, Betula, Quercus* deciduous- type
Riverine forest	*Alnus, Populus, Salix, Ulmus*
Shrubs	*Buxus, Erica*-type, *Ilex aquifolium, Juniperus/Cupressus, Phillyrea, Pistacia*
Low shrubs	*Ephedra, Hedysarum, Helianthemum*
Meadows/ pastures	*Plantago,* Poaceae (others)
Cultivated trees	*Corylus, Juglans, Olea, Prunus*
Herbaceous crops	Cerealia (others), *Secale, Cannabis*-type
Ruderal/weeds	*Artemisia, Centaurea, Chenopodium, Echium, Rumex, Urtica*-type
Other	Apiaceae, Asteraceae (others), Asteraceae (fenestrate), *Campanula, Euphorbia, Castanea, Cerastium, Galium, Morus, Potentilla, Sanguisorba minior, Thymus, Veronica*-type*, Scabiosa, Sedum*-type
Aquatic plants	*Alisma, Claudium, Thypa*, Cyperaceae (others), *Mentha-type Myriophyllum, Scirpus, Potamogeton, Ranunculus*

3. RESULTS & INTERPRETATION

3.1. Age model

The three different lithostratigraphic units previously defined in Corella et al (2014) were also clearly identified in core MON-0713-G05 (Fig.2) (unit 1, 0-15 cm , 2013-1902 CE; unit 2, 15-59 cm, 1901-1844 CE; unit 3, 59-100 cm 1844-1423 CE). Several marker horizons have also been detected and correlated between cores (Fig. 2). Sedimentation rates (SR) in cores MON12-3A-1G and MON-0713-G05 display similar values except for unit 2, where SR were 26% higher in core MONT-0713-G05 than in core MON12-3A-1G due to the thicker detrital layers deposited during the 19th century.

3.2. Vegetation and landscape changes

Results are expressed in both percentage –for pollen and NPPs- (Fig.3 and 4) and PAR (Fig.5). The interpretation, in terms of vegetation shifts, is based on the percentage diagram (including *Cannabis* as a component of the regional landscape), with reference to PAR values to follow the behavior of the more significant taxa and/or vegetation groups. A summary pollen diagram excluding *Cannabis* has been added to assess vegetation changes in zones where hemp pollen attain more than 40% of relative abundance and therefore pollen signal could have been adulterated. Vegetation classification and interpretation of pollen spectra follow previous palynological studies: Cañellas-Boltà et al. (2009), Mercadé et al. (2013); Rull and Vegas-Vilarrúbia (2015) and Rull et al. (2011, 2017). This section is concerned only with vegetation dynamics and the potential processes involved that can be directly inferred from the evidence obtained in this work (pollen, charcoal, algae, and fungi spores). Other aspects needing additional independent evidence, such as the potential influence of climatic shifts, historical events or comparisons with previous works and similar regional reconstructions, are addressed in the discussion.

Overall, the percentage diagram (Fig.3) is dominated by conifers (*Pinus*), evergreen and deciduous oaks (*Quercus*) and herbaceous crops, notably the *Cannabis*-type (thereafter *Cannabis*). These pollen types show significant abundance changes, especially at the base and the top of the diagram. Some autochthonous and cultivated trees (*Betula, Olea*), *Juniperus/Cupressus* type (likely corresponding to *Juniperus communis* L., which is abundant in the present vegetation), herbs (mainly Poaceae, *Plantago* and *Artemisia*) and aquatic taxa (*Typha,* Cyperaceae other than *Scirpus*) are also well represented and exhibit meaningful shifts throughout the diagram. The sequence has been subdivided into six significant pollen zones, named MC1 to MC6, which are described as follows.

Zone MC1: 100.5 – 95.5 cm, 1423-1481 CE (58 years; 11 samples; average resolution: 5.2 years/sampling interval)

This zone is dominated by trees -notably evergreen *Quercus*, the main representative taxon of the evergreen oak forests- and herbs, mainly *Artemisia* and Poaceae (others), belonging to the ruderal/weeds and the meadows/pastures groups, respectively (Fig. 3). These two herbaceous groups attain up to 50% of the pollen assemblage in this zone. Other trees (*Pinus*, deciduous *Quercus* and *Olea*), shrubs (*Juniperus*) and herbs (*Plantago*) show intermediate values. Among minor components, *Betula*, *Corylus*, *Fagus* and *Alnus* are below 10% but they attain their maximum abundances as compared to other zones. Trees such as *Quercus* (evergreen), *Pinus* and *Olea* experience an increasing trend while some of the main herbaceous pollen types, notably *Artemisia* and *Plantago*, decrease towards the top of the zone. Aquatic taxa are at their minimum values, with a slight decrease in *Typha*, which almost disappears at the end of the zone. PAR values are very low, showing an increasing trend in all vegetation types except low shrubs, herbaceous crops and aquatic plants (Fig. 5). Charcoal I (indicative of regional fires) reaches its lowest values spiked by a conspicuous peak near the base of the zone (99.5 cm; 1434 CE), whereas charcoal II (indicative of fires occurring in a more local scale) is present only in the form of two small peaks. Among algal remains, *Botryococcus* is the most abundant, showing an increasing trend towards the top of the zone that coincides with a small *Tetraedron* peak, which was almost absent before (Fig. 4). *Cosmarium* and *Pseudoschizaea* are present only as small and scattered peaks. The most abundant fungal spores are *Sporormiella* and *Glomus*, always below 10% and showing a similar trend between them.

During the time interval represented by this zone (1420 to 1490 CE), the landscape of the Montcortès catchment and its surroundings was characterized by the presence of forests, mostly evergreen oak forests, meadows, pastures and herbaceous crops, with the corresponding ruderal plants and weeds. This was not a static landscape state as oak forests were expanding at the expense of the rest of vegetation types, especially ruderal plants and weeds. Fire incidence was very low, except for a distinct burning event around 1434 CE. The presence of *Sporormiella*, a coprophilous fungi living in the dung of herbivorous animals, suggests the presence of livestock around the lake (van Geel and Aptroot, 2006). The occurrence of *Glomus* indicates that erosion of catchment soils was ongoing (Anderson et al., 1984). *Pseudoschizaea,* that also has been used as indicator of soil erosion (van Geel et al., 1989, 2003), might be indicative of cattle trampling around the lake (Ruiz-Zapata et al., 2006) The whole picture suggests a humanized landscape where anthropogenic impact was declining and wild oak forests were in expansion. *Olea* is a low-elevation tree but its pollen can be easily transported long-distance and to higher elevations than the parent plant (Cañellas-Boltà et al., 2009; Bell and Fletcher 2016); hence, its peak at the end this zone could be due to causes related with events occurring at the adjacent lowlands, which will be discussed later.

Zone MC2: 95-89cm, 1490-1536 CE (46 years; 9 samples; average resolution: 5.1 years/sampling interval)

This zone is dominated by arboreal taxa from both conifer forests (*Pinus*) and evergreen oak forests (*Quercus*), reaching overall abundances above 60% at the middle of the zone, with a decline to almost 45% at the top (Fig.3). Shrubs do not change but herbs of the meadows/pastures and ruderal/weeds groups (mainly *Plantago* and *Artemisia*) significantly decrease, as compared to zone MC1. The peak of arboreal pollen is due to the increase of *Pinus*, as other trees from other evergreen and deciduous forests either decrease (evergreen *Quercus*, *Betula*, *Alnus*, *Corylus*) or remain at values similar to zone MC1 (deciduous *Quercus*, *Fagus*). Concerning cultivated plants, *Cannabis* (hemp) is insignificant at the base of the zone but progressively increase to ~20% at the top. *Secale* (rye) also experiences a slight increase, whereas *Olea* (olive tree) decrease with respect to the former zone. No remarkable shifts are observed in aquatics. PAR values (Fig.5) experience a general increase but declined to minimal values at the top of the zone. Charcoal I undergoes an abrupt increase at the base to progressively decrease through the top, whereas charcoal II do not change with respect to the former zone (Fig.3). Regarding algae, *Botryococcus* continue to increase and *Tetraedron* almost disappear, whereas other types do not experience significant changes, except *Cosmarium*, which is much less frequent. Fungal spores (*Sporormiella*, *Glomus* and *Chaetomium*) undergo a general increase (Fig.4).

Between 1490 and 1540 CE, evergreen and deciduous forests around the lake retracted and herbaceous crops, mainly hemp, and to a lower extend rye, expanded. The increase of *Glomus* indicates enhanced erosion, likely due to forest cover reduction, and the higher abundance of coprophilous fungi compared to former zone suggests grazing intensification. This, together with the sudden increase of charcoal, is compatible with an intensification of human impact both on the catchment area and at regional scale probably by using slash-and-burn practices for forest clearance and the enhancement of arable lands. The decline of *Artemisia* and *Plantago*, indicators of grazing, suggests the decline of pastoral activity, in which case, coprophilous fungi would indicate the presence of domestic animals associated with agriculture and/or transport activities. Pine forests are characteristic of higher elevations; therefore, their expansion would be independent of increased human activity around the lake, and will be discussed later.

Zone MC-3: 88.5-76.5 cm 1547-1717 CE (170 years; 25 samples; average resolution: 6.8 years/sampling interval)

This zone is characterized by a sharp increase of *Cannabis*, attaining values of almost 40%, and a general decrease of trees, including *Pinus*, with the exception of *Olea*, whose percentages remain stable. PAR values show that this is not a percentage artefact, as tree pollen –as well as most pollen types- actually decrease whereas *Cannabis* increase, with respect to the former zones (Fig. 5). Shrubs also stay unchanged. The most significant herbs, including those cultivated, also show rather stable percentages with only minor variations. Aquatic plants (*Typha* and Cyperaceae) experience a general increase at about the middle of the zone (84 cm; 1643 CE), coinciding with the appearance of *Scirpus* and a general increase of PAR values (Figs. 3 and 5). Charcoal I increase about the middle of the zone (ca 1643 CE, 84 cm) and peak at on the top, coinciding with the increasing trend in aquatic plants (Fig.3). Among algae, *Botryococcus* stabilizes in values attained at the end of the former zone but sharply peaks towards the end of this zone, coinciding with a remarkable increase of *Pediastrum*, which is very scarce earlier. *Cosmarium* is absent in this zone and for the rest of the sequence. In this zone, fungi spores experienced a general decline (Fig.4).

Between 1540 and 1720 CE, a dramatic shift occurred in the Montcortès landscape due to the general forest retraction and the onset of intensive and/or extensive hemp cultivation. Other crops (olive trees and cereals) remained in a situation similar to former times. Pastoral practices, might experience a slightly decrease as indicated by the modest reduction *of Poaceae* and coprophilous fungi although *Artemisia* remained similar to the former zone. It seems that most agricultural activity was centered on hemp. Within this general scenario, the aquatic ecosystem (aquatic plants and the algal remains) changed around the middle of the zone (ca 1643 CE) probably indicating changes in lake water quality.

Zone MC-4: 76-44 cm; 1723-1874 CE (151 years; 32 samples; average resolution: 4.7 years/sampling interval)

The most distinguishing traits of this zone are the acme of *Cannabis*, reaching values of 60% to 80%, and the reduction of all trees and shrubs with no exception even Cannabis pollen is excluded of the pollen sum (Fig. 3). PAR values show that tree pollen do not decrease and their lower percentages are due to the comparatively higher rates of *Cannabis* increase (Fig. 5). Cereal crops, including *Secale*, slightly increase and the ruderal/weeds group remains unchanged. Some herbs that are scarce or sporadic in former zones appear more constantly and with slightly higher values in this zone. This is the case of *Urtica*-type and *Galium*. Charcoal I slightly declines and peaks near the top. Charcoal II increases its frequency and abundance, as compared to former zones. Regarding aquatic plants *Typha* and *Scirpus* attain their maximum percentages in this zone and decrease towards the top (Fig.3). *Potamogeton*, almost absent in former zones, starts to be present in a continuous fashion but with low values. Among algae, *Botryococcus* declines and *Pediastrum* increases. *Tetraedron*, almost absent in the former zone, reappears in the form of two peaks, at the base and nearly the top of the zone. Concerning fungal spores, *Sporormiella* and *Glomus* show similar values to the former zone including two peaks and *Chaetomium* exhibitS a similar trend but only relate to/in regards to the upper peak (Fig.4). A peculiar feature of these zones is an interval located in its uppermost part (61 to 45 cm; 1838-1869 CE), where *Cannabis* pollen, as well as some algae (*Tetraedron*) and fungi spores (*Sporormiella*), show large and sharp peaks coinciding with a conspicuous charcoal acme (Fig. 3 and 4). This feature is also evident in PAR values of almost all pollen groups, except for the conifer forest (Fig.5).

Contrary to zone MC3, in this time interval (1720-1880 CE), the increase in *Cannabis* pollen, suggesting its cultivation around the lake, was not paralleled by forest reduction. If hemp was actually cultivated this did not occurred at the expense of forests or other vegetation types, as none of them seem to have reduced their cover (see PAR values). Therefore, the increase of *Cannabis* suggests an extra source for this pollen (likely hemp retting), which might have increased pollen release to the sediments. It cannot be ignored that a proportion of this significant *Cannabis* pollen increment can also indicate increases on cultivation at local and also at regional scale attending the great distances that *Cannabis* pollen can travel away from parental plant (Cabezudo et al., 1997; Giner et al., 2002).Increases in aquatic plants and algal remains suggest that the limnlogical shifts initiated in the former zone (1640 CE) were maintained, possibly exacerbated. Lake-level changes cannot be dismissed as increases in aquatic plants could be related with increases of the flooded area. Independent data (i.e. geochemical data) able to record lake-level changes, would be necessary support this interpretation. Relative high values of charcoal I and increases in charcoal II (indicatives of more regional and local fires respectively) together with increases in cereal crops and nitrophilous plants (such as *Urtica*-type and *Galium)* support human impact intensificationon the area.This seems to be the phase of maximum anthropogenic influence, not only on the catchment and regional landscape but also on the aquatic ecosystem.

Zone MC-5: 15-3cm 1886-1971 CE (85 years; 13 samples; 6.5 years/sampling interval)

This zone is characterized by the rapid decrease of *Cannabis* and a general increase of trees (up to 60%, as in zone MC2) and shrubs, notably *Juniperus*. *Fagus* is an exception as its pollen is almost absent (Fig.3). PAR values confirm that tree and shrub pollen is generally increasing and *Cannabis* pollen almost disappears (Fig.5). Notably, *Quercus* (deciduous) and *Olea* attain their maximum values in this zone. *Secale* and the ruderals/weeds group (especially *Urtica* and *Galium*) also decline while other cereals remain stable but decreased at the end of the zone. Charcoal I decreases notably and charcoal II almost vanishes in this zone (Fig.3). Aquatic plants remain with values similar to former zones, except *Typha*, which is significantly reduced from this zone onwards. Regarding algae, *Botryococcus* sharply increases, peaking at the middle of the zone, whereas *Pediastrum* significantly declines and *Tetraedron* almost disappears (Fig.4). Fungal spores, with *Sporormiella* as the most abundant type, initiate a decreasing trend, almost disappearing at the top of the zone (Fig.4).

The results indicate that, between 1880 and 1970 CE, the *Cannabis* industry (i.e., cultivation and retting) was virtually non-existent around Lake Montcortès and forests recovered the same importance of former times, as for example, between 1490 and 1540 CE. In general, it could be stated that the landscape and the aquatic ecosystem returned to conditions similar to those observed on MC-1 before the *Cannabis* peak, with enhanced forest cover, less fire incidence and a similar trophic state of the lake. The conspicuous increase of *Olea* suggests that its cultivation in the adjacent lowlands increased.

Zone MC6: 2.5-0 cm; 1978-2013 CE (35 years; 6 samples; average resolution 5.8 years/sampling interval)

This zone is defined by a new increase of *Cannabis* to values of 20-30% and some trees, chiefly *Pinus* (attaining its maximum values throughout the diagram) and *Quercus* (deciduous), reaching values similar to zones MC1 and MC2. Other trees and shrubs decline, as is the case of *Quercus* (deciduous), *Betula*, *Corylus*, *Olea* and *Juniperus*. Herbaceous crops and ruderals/weeds attain their minimum values and aquatic plants remain stable with respect to the former zone, except for *Scirpus* and *Potamogeton* that disappear towards the top. PAR values show a general increase of all vegetation types except low shrubs (Fig.5). Charcoal also shows values similar to zone MC5 (Fig.3). *Botryococcus* attains its maximum in this zone, whereas *Pediastrum* and *Tetraedron* remain at lower values. Fungal spores are very scarce, almost absent (Fig.4).

During the time interval represented in this zone, conifer forests and evergreen oak forests expanded and deciduous forests receded. The significant increase in *Cannabis* contrasts with the general decline of farming and grazing activity, which requires explanation. Data from other disciplines are needed for a sound interpretation of this zone. Fortunately, historical documentation is abundant for this time period, but this will be addressed in the discussion.

4. DISCUSSION

Figure 6 shows a comparison between a previous pollen study carried out in Lake Montcortès (Rull et al., 2011) and the present study. With this contribution, we have notably enhanced the average time resolution from 52 *to* 6 years/sampling interval which means an improvement from 9 to 79 samples for the overlapping time period. Additionally, we have analysed the recent vegetation history corresponding to 20th and 21st centuries for the first time in Lake Montcortès. The multiproxy study of the sediment record (pollen, charcoal and NPPs), the continuity between samples and the high temporal resolution covering the last 500 years have provided new insights about vegetation and the environmental history of the lake Montcortès catchment that were previously unnoticed. These new data allowed us to perform more precise comparisons with the available historical records and to disentangle local from regional events. Correlations with other sequences at local and regional scales are not easy to perform because of the lack of high resolution reconstructions covering the same period. Nevertheless, some similarities are found. Figure 7 shows a summary of the main findings of the present work and comparison with other studies developed in Lake Montcortès. Due to the variable human pressure on the landscape, discussion has been organised according to different degrees of anthropogenic impact.

4.1 Moderate human pressure (Pollen zones MC-1 and MC-2; from ~ 1423 to ~ 1536 CE)

Our record begins in the 15th century when pollen percentages suggest a humanized landscape where anthropogenic activity was progressively declining. This decline can be appreciated by forest increases at expense of pastures, meadows and ruderal taxa (Fig. 3). The end of the 14th century was a turbulent socio-economic moment for all of the Western Europe devastated by the "black death" epidemic. In Catalonia (Spain) and the Pallars region (where Montcortès is located) (Fig. 1), this moment was especially severe due to the Catalan Civil War, the contemporary framer rebellion (1462-1472 CE) and the Pallars War (1481-1487 CE). As a consequence, the population decreased and emigrated to the lowlands (see Rull and Vegas-Vilarrúbia 2015) and literature therein for more detail). This is consistent with the Lake Montcortès pollen record that showed evergreen oak forest increases and pine forest expansions in the higher-mountain areas, likely as a result of field abandonment. *Olea* expansion during this period was also in concordance (Fig. 3). Olive is a lowland crop, probably promoted due to lowland emigration. Its expansion, together with cereal cultivation, was recorded during the same period in other lowland lakes at that time (Estanya lake; 670 m a.s.l (Riera et al., 2004)) and in high-mountain records (Garcés-Pastor et al., 2016; Ejarque et al., 2009 2010; Pérez-Sanz et al., 2011) owing to its high pollen dispersion capacity (Cañellas-Boltà et al., 2009; Bell and Fletcher 2016).

However, human activity was still ongoing around Lake Montcortès, which is indicated by the continuous presence of coprophilous fungi and soil erosion indicators (Fig. 4). As recorded in historical records, the movement of large amounts of livestock through the Pyrenees was a regular practice. Farmers tried to keep livestock moving to avoid them being stolen due to poverty, famine and social instability (Bringué, 2005). Lake Montcortès, which is located on the way to the North, was likely used as a water source and rest area for livestock on the journey to the high-mountain areas, where livestock was hidden during social instability periods. Later on, from 16th century onwards, Lake Moncortès was likely used as a rest area for transhumance livestock. Lake level increases might also took place giving rise to marshy environments, as *Pseudoschizaea* is often related with humid environments (Scott, 1992), and *Cosmarium* has been related to lake level changes and increased turbidity (Reynolds, 2006; Casco et al., 2009). These conditions were probably promoted by cattle trampling near the lake shore. This is also in agreement with the lake level rises recorded for the same period in the nearby karstic Lake Estanya (Riera et al., 2004; Morellón et al., 2011). However, no changes in aquatic taxa such Cyperaceae, *Typha* or submerged vegetation were recorded in the Lake Montcortès sequence at that time.

4.2. Intensification of human related activities: *Cannabis* pollen peak and water quality changes (Pollen zones MC-3 and MC-4; from ~1547 to ~1874 CE)

At the end of the 16th century, oak and riverine forests started to decrease locally, charcoal notably increased and herbaceous crops (hemp and cereals) expanded, meanwhile pine forest increased between 1490 to 1524 CE (Fig. 3). The recovery of the human population after the crisis was fast due to immigration from France (Bringué, 2005; Rull et al., 2011, 2015). The conifer forest expanded, which contrasts with the progressive decrease of oak and riverine forest around Lake Montcortès. The conifer forest expansion that took place in lake Montcortès record has been obserbed in other Pyrenean records (Ejarque et al 2009, Ejarque et al 2012) and it is in agreement with a period of farming decrease recorded in the Pyrenean high-mountain areas between 1430 to 1530 CE (Ejarque 2009). This was one of the colder phases of the Little Ice Age recorded nearby (Mateo and Gómez, 2004), which could have determined unfavourable for human life in the area (Ejarque et al., 2009; Mazier et al., 2009). The farming declining episode recorded in the Pyrenean high-mountain areas seem to have affected Lake Montcortès catchment where the riverine and oak forest decreased and anthropogenic activities persisted probably because its lower mountain elevation (González-Sampériz et al., 2017). Actually, during the Litle Ice Age (from ˜14th to 19th centuries), and even during its colder (Fig.7) phases and when droughts and floods occurred (Corella et al., 2014; 2011, Morellón et al., 2012; Oliva et al.2017), intense human impact is recorded from 1550 to 1900 CE in the Montcortès record (Fig. 3 and 4). Increases in hemp, cereals, ruderal and nitrophilous taxa are the main vegetation changes recorded in the Montcortès pollen record from approximately 1500 to 1900 CE (Fig. 3). Charcoal also increased while forest retreated. This period was marked by a diversification and intensification in the exploitation of natural resources in the Pyrenees (crops, cattle and forest exploitation) (Reventós 2004; Bringué 2005). Forest, mainly pines, oak and beech, were used to obtain coal to feed a rising and increasing demand for iron Industry (iron forges) and for domestic use (Madoz, 1845-1850; Pèlachs et al 2009; Ferrer Alòs, 2017). The Lake Montcortès pollen record showed the diversification of land uses in concordance with historical sources that documented slash-and-burn agriculture practices to obtain fields for cropping and cattle from 1500 to 1700 CE (Bringué, 2005; Ferrer Alòs, 2017). The consistent presence of coprophilous fungi and soil erosion indicators (*Glomus*) confirm the presence of livestock around Lake Montcortès (Fig. 4). Transhumance practices and iron forge activities were also very important activities between 1550 to 1700 CE and caused the intensification of forest exploitation to obtain fields for grazing and charcoal to fuel iron industry activities (Pèlachs et al., 2009; Ejarque et al 2009). A rising intensity of charcoal production was recorded near Montcortès, in the Vallfarrera Valley (Pèlachs et al., 2009), coinciding with increases in the charcoal influx in the Lake Montcortès record.

The high hemp pollen percentages and the dramatic increase from 1720 to 1880 CE in the Montcortès record is coincident with one of the most important socio-economic and political moments throughout the Iberian Peninsula. Since the European discovery of America in 1492, the Spanish Royal Navy intensified its activity and hemp became a highly demanded product, mostly for supplying rigging and sails, and became strategic for commercial purposes (Díaz-Ordoñez, 2016). In this context, hemp cultivation was mandatory in Spain (for more detail, see Riera et al., 2004; Rull and Vegas-Vilarrúbia, 2014 and the literature therein). Catalonia was the second most important region for hemp production in Spain, just behind Valencia, and the one that produced the highest quality hemp fibres of the Iberian Peninsula (Sanz, 1995; Raventós, 2004). Lleida (Lerida) province (the present administrative limit where the Pallars region and Montcortès are located) (Fig. 1), was an important area for hemp production and fibre manufacturing (Ferrer and Alòs, 2017). The detailed proxy -data obtained and the historical data reviewed in the present work attest that the Pallars was a renowned region for hemp production. Inhabitants of the area were well-known by their specialized skills in hemp manufacturing and by the diversity of peculiar tools for hemp manipulation characteristic of the region (Violant I Simorra 1934). This is the case of la Pobleta de Bellví at less than 6 km from Lake Montcortès, where inhabitants were highly appreciated by their outstanding skills for hemp combing (Violant I Simorra 1934). This can explain the implication of Lake Montcortès in hemp related activities.

Two main shifts can be observed in the hemp pollen curve coinciding with pollen zones MC-3 and MC-4 where percentages of 30% and more than 40% are the trend, respectively, and hemp peaked twice in 1838 and 1867 CE. The question of whether these percentages are due to hemp cultivation around Lake Montcortès or the lake was used for hemp retting has been raised in former low resolution studies (30-50 years/sampling interval, in average) (Rull et al., 2011; Rull and Vegas-Vilarrúbia, 2014). The present study presents more independent data (proxies and historical data sources), and higher resolution data required to address fully the question. Water changes are recorded in Lake Montcortès from the mid 17th century onwards. Cyperaceae, and more notably *Typha,* increased coinciding with the increases of hemp pollen that overcome the threshold of more or less constant frequencies of 30% that lasted ~200 years. At the same time, *Pediastrum* increased notably and *Tetraedron* peaked in 1838 CE, coinciding with one of the maximum hemp values (~63%). Increases in Cyperaceae and *Typha* have been related to fluctuations in water levels but also with water nutrient enrichment. *Typha* species thrives in areas of high nutrient input (i.e., nitrogen and phosphorous) mainly because of their fast growth rates and ability to take up nutrients rapidly (Newman et al., 1996; Miao and Sklar, 1998). The notable increase in *Pediastrum* 1680 to 1850 CE and *Tetraedon* peak that coincided with hemp maxima might also be related with eutrophication processes as it has been observed in other similar lakes with hemp retting (Riera et al., 2006). Furthermore, increases in both types of algal remains might be an indicator of the differential growth response to different nutrient species supply. *Tetraedron* spp. grow better in the presence of phosphorous compounds, whereas *Pediastrum* spp. responds more effectively in exploiting nitrogen sources (Berman et al., 1991; Berman and Chava, 1999). The process of hemp water retting pollutes water bodies and induces significant changes in water quality, eutrophication and oxygen depletion (Anderson, 1995; Paridah et al., 2011; Clerke and Merlin, 2013). Therefore, the changes recorded in the aquatic communities in Lake Montcortès might be a response to disturbances produced by the hemp retting process. Other proposed proxies that can provide additional arguments to corroborate retting in a water body are lithological changes (increases on sedimentation rates, detrital material or shore reworked sediments) (Cox et al., 2001), plant fibres and seeds (that indicate the physical presence of the plant in the water body) (Clarke and Merlin, 2013), diatoms and cyanobacteria (responding to water quality changes) (Lotter, 2001; Bradshaw et al., 2006; Miras et al 2015), biomarkers (unique to *Cannabis* plants, i.e., Cannabinol) (Lavrieux et al., 2013) and the presence of *Potamogeton* (Bradshaw et al., 1981; Riera et al., 2004, 2006). This latter case is fulfilled for Lake Montcortès as *Potamogeton* is absent in the former zones until the *Cannabis* acme, when appeared (Fig. 3). *Potamogeton* species grow well in eutrophic and mesotrophic waters and seem to be a good competitor regarding other submerged taxa in turbid waters (Sidorkewicj et al., 1996; Ven den Berg et al., 1999). This is in concordance with Vegas-Vilarrúbia et al., (2018), who, by analysing sedimentary pigments and physicochemical parameters of the sediment record, inferred anoxic water conditions, increased nutrient supply and turbidity during this period in Lake Montcortès. Despite the notable increase of hemp and cereals crops in MC-4, forest and/or other vegetation types did not decrease as might be expected (Fig. 5). This fact reinforces the idea of hemp retting as an extra source of *Cannabis* pollen into the lake. Another explanation for this surprising hemp pollen increase lies in the episode of cultivation intensification that took place during this period (from 18th century to the first half 19th century) due to technical advances and enhancement on irrigation techniques that made it possible to increase land productivity by obtaining more than one harvest per year (commonly two) (Sanz, 1995; Reventós, 2004). Cultivation intensification has also been recorded in other Pyrenean lakes and peatlands (Riera et al. 2004; Ejarque et al., 2009, 2010; González-Sampériz et al., 2017), but their lower resolution prevents detailed comparisons with Lake Montcortès and precise assessments of eventual time offsets and/or regional trends. Decreases in smaller charcoal influx (charcoal I) are also consistent with forest recovery observed in PAR values during this period (1700-1880 CE) although the frequency of bigger charcoal particles (type II) increased. These increases could be related to some agrarian techniques applied on fields surrounding Lake Montcortès as a consequence of production intensification. To maintain the intense productivity, farmers needed to fertilize the field to assure soil properties suitable for cropping. The most well-known and used method consisted of spreading manure in the fields, but it was too expensive, and depending on the crop type, the cost of manuring was higher than the profit of the corresponding harvest. Alternatively, farmers burned vegetal biomass mixed with soil to later spread and fertilize the field. Curiously, hemp was one on the most commonly used biomass sources for burning mixed with other vegetation types (Reventós 2004). With technical advances and cropping intensification, it was possible to keep harvested products in extra stock and feed animals at home. Consequently, transhumance practices were notably reduced (Reventós 2004). The reduction of transhumance and the increase of field productivity also helped to make forest recovery possible nearby Lake Montcortès.

From 1850 to 1870 CE (pollen zone MC-4), a saw-tooth trend is mostly recorded by the hemp pollen curve (exceeding 80%) but also by other taxa and charcoal and fungal spores. Such trends are much more evident looking at PAR values (Fig. 5). The saw-tooth trend is recorded at the same time that extreme precipitation events were observed in the Lake Montcortès record (Corella et al., 2014, 2016). The clastic microfacies resulted from the increased runoff during flood events that took place at the sub-decadal scale and were cross-correlated with documented extreme floods occurred in most rivers in the NE Iberian Peninsula (see Corella et al., 2014, 2016 for more detail) (Fig. 7). The increased input of external detrital material from the watershed is clearly recorded in pollen sedimentation rates and other terrestrial proxies (charcoal and fungi). The only vegetation type that did not record the saw–tooth trend was the conifer forest, which mostly comes from high-mountain areas, giving a weak signal resulting from the watershed weathering. Therefore, the high-resolution obtained for the pollen record, in this case, gives us information about sub-decadal scale periods of runoff increases from the immediate surroundings of Lake Montcortès.

4.3. Low human pressure: field abandonment (Pollen zones MC-5 and MC-6; from ~ 1875 to ~ 2013)

The notable decrease in *Cannabis* pollen, as well as the decrease of other human presence indicators during 20th century in lake Montcortès record, indicates the decrease in human pressure intensity: *Secale, Urtica*-type decreases and the near disappearance of coprophilous fungi at the end of the century together with the considerable reduction of fire and forest recovery indicate the reduction of agro-pastoral activities and field abandonment. The dramatic and sharp hemp reduction occurred during the 20th century coincided with the dismantlement of the Spanish Royal Navy and also with important socio-political changes in the country. The need for materials for rigging, sails, clothes or trading was sharply reduced. Moreover, the appearance of new fibres (synthetic fibres and imported cotton from USA, Brazil, Mexico, Syria and Turkey) provoked almost the total disappearance of hemp fibre used for clothing in Spain (Simó, 1985). The only crop that seemed to increase during the 20th century was olive, but it could be an artefact of pollen percentages since increases in *Olea* at that moment were not recorded in PAR values (Cultivated trees) (Fig. 5). A remarkable human population increase took place from 1860 onwards in the Pyrenees, which provoked a crisis at the end of the 19th century due to the lack of enough resources to maintain the increasing population. This situation forced the population to emigrate to industrialized areas (Guiardo, 2011; Farràs, 2005). Agro-pastoral activities in the Pyrenees were reduced to fewer and richer houses that were able to adapt to a high demanding market and change to a more intensive production model. The economic activities in the area changed with the advent of capitalism and the most important economic activity in the Pyrenees was the implantation and exploitation of hydroelectric power stations (Rotés 2011). Furthermore, the Spanish Civil War (1936-1939 CE) interrupted industrialization and socio-economic activities. It was not until the 1950s when the country again started with socio-economic recovery and modernization (Guirado 2011). This can be appreciated in the Montcortès record with the declining of human indicators. Aquatic plants and algal remains also experienced changes during this period. *Typha* and *Botryococcus* (a low nitrogen and phosphorous tolerant alga (Reynolds 2006)) were reduced. This is coherent with a declining human pressure scenario. It seems that Lake Montcortès returned to similar states prior to *Cannabis* pollen maxima, likely more oligotrophic conditions that lasted until present day (Trapote et al., 2018).

From the 1970s onwards, forest continued to expand around Lake Montcortès. Coprophilous fungi disappeared, and hemp was the only cultivated plant increasing its percentages. Currently, there is no hemp cultivation known close to Lake Montcortès and, according to local people, the lake has not been used for hemp retting during the last decades. Since 1992, Montcortès is considered a site of natural heritage and it is protected by means of different administrative measures (Gentcat 2006; Xarxanatura 2000). The hemp maxima during the 21st century in Lake Montcortès is recorded from the mid to late 1990s. At the beginning of the 1970s, a renewed interest in hemp, mainly as a source for paper pulp manufacturing, took place in Spain (Gorchs and Lloveras, 2003) The European Union started to economically support hemp cultivation from the late 1980s. In the middle 1990s, EU hemp subsidy amounts reached their maxima and farmers have since been interested in growing hemp for its economic benefits (Gorchs and Lloveras, 2003; Karus, 2004). Consequently, in just a couple of decades, areas of hemp cultivation expanded again and reached their climax in Spain around 1998 (Karus 2004), coinciding with maximum hemp production in Catalonia (Gorchs and Lloveras, 2003). From the 2000s onwards, EU hemp cultivation subsidy amounts were notably reduced, and therefore, hemp production became less economically profitable and cultivation was reduced. Currently, hemp is still used for clothing, animal feeding, oil (seeds), pulp paper, building materials and water treatment (hemp dust) among other uses (Gorchs and lloveras 2003; Clarke and Merlín 2013). The abrupt hemp peak observed during the 21st century lasted less than 20 years after almost a century of very low hemp pollen frequencies, then, decreased again until the present. The presence of this peak is related to a very specific and short-term duration historical event that can only be detected by means of high-resolution observations.

Despite a notable hemp reduction at the beginning of the 2000s, at present, Lake Montcortès still records significant amounts of hemp pollen. It was observed by Rull et al., (2017), who carried out a two year study of seasonal sediment trapping in Lake Montcortès from 2013 to 2015 CE. *Cannabis* pollen was continually recorded in the trapped material during the whole studied period at about 5% of total abundance and greatly increased during fall seasons when reached 40%. The current presence of hemp pollen in Lake Montcortès can be explained by its great air dispersion. Hemp pollen can travel far away from the parent plant (i.e., from North Africa to southern Spain, as found by Cabezudo et al., 1997; Giner et al., 2002). The mentioned trap study also found that hemp pollen was positively correlated with wind velocity supporting this idea. Another explanation could be due to an involve increasing cultivation near Lake Montcortès, as currently, there is a growing interest on hemp cultivation to recover natural and environmental friendly fibres. Moreover, the pre-Pyrenean areas have been identified as suitable for hemp cultivation due its humidity and because hemp has been reintroduced as a rotation crop together with wheat (Gorchs et al., 2006). During the trapping study period, no hemp retting was carried out in Lake Montcortès and inhabitants of the area had no notions about the effect of hemp fields on the surroundings.

5. CONCLUSIONS

We have evaluated a 500 year-long varve record from Lake Montcortès at the highest resolution achieved so far for a varved lake in the Iberian Peninsula. We have notably improved our knowledge of the recent history of Lake Montcortès and its surroundings in several terms. We have improved the temporal resolution (~6 years /sampling interval) and improved the historical and palaeoecological precision, as well as the spatial scope, with the new studied time interval (20th and 21st centuries). By means of a multiproxy analysis of biological indicators combined with independent evidence from historical sources and comparison with previous studies carried out in Lake Montcortès, we have reconstructed human-landscape dynamics in detail. The present work also helped to answer some questions that arose with former studies and to go deeply into one of the most streaking features of the Montcortès pollen record: the outstanding hemp pollen percentages . We shed more light on potential consequences of human impact on the aquatic system derived from hemp retting practices.

Human activity around the lake during the last 500 years has had a greater influence on vegetation community changes than climatic factors, and only increases in the frequency of flood events could have been inferred from the studied record from the mid to the end of the 19th century. Cropping, livestock breeding, and hemp related activities have been the most important factors responsible for landscape modulation. Even during harsher climate conditions (LIA), human activities remained significant in the area. The high-resolution study provided enough data to evaluate short-lasting events at local and regional resolutions that otherwise would not be possible to identify as related to climate (sub-decadal frequency of floods and high-land forest recovery) or to historical and socio-economic events (i.e., crop promotions (hemp) or land abandonment).

The temporal extent of the *Cannabis* pollen peak (400 years) and its temporal continuity have been confirmed. The revision of new historical sources available combined with pollen and NPP indicators from Lake Montcortès provided further and detailed evidence of the local use of hemp, implying cultivation and manufacturing, as well as potential effects of retting hemp in the lake, on the aquatic communities between the mid 17th to late 19th centuries, which was not possible to confirm in previous studies at lower resolution. Further investigations using aquatic proxies at high-resolution are necessary in this sense to better assess the eutrophication degree and water community disturbance. Geochemical analyses of sedimentary cannabinol or other hemp specific biomarker would unequivocally confirm the use of Lake Montcortès for hemp retting.

More work is needed to take advantage of the great scientific potential of the Montcortès sediment record, and also to exploit the unusual and very valuable availability of modern sedimentary pollen analogues as a tool to better interpreting the fossil signal Studies that include and combine lake and modern analogue monitoring with high-resolution palaeoenvironmental reconstructions in varved sediments are very scarce, but it opens a range of possibilities to exploit the potential of palaeodata contained in the sediment record, i.e. it is possible to assess the yearly flux of pollen sediment rates and define rates of palaeoenvironmental changes at decadal and even at sub-decadal scales (Birks and Birks, 2006)

The present study is the first that combines all of the explained above advantages for a varved lake in the Iberian Peninsula and the Mediterranean region. The value of the data obtained in this study lies in the potential to be used to calibrate and validate future model scenarios, perform quantitative climatic or environmental reconstructions and use it as a tool to apply in the conservation and restoration of cultural landscapes. Further work should focus on improving sampling techniques to obtain higher temporal resolution for biological proxies and to obtain modern analogues for the variety of potential environmental and climatic proxies.

6. ACKNOWLEDGEMENTS

This work was funded by the Ministry of Economy, Industry and Competitiveness (project MONT-500; reference CGL2012-33665 with an associated pre-doctoral research grant (FPI; BES-2013-065846); PI: Teresa Vegas-Vilarrúbia). We would like to thanks people that participated and helped during fieldwork: Elisabet Safont, Núria Cañellas-Voltà, Teresa Buchaca, Joan Gomà. The authors are grateful to the Council of Baix Pallars and the Cultural Association Lo Vent do Port for their continuous support, and to the Busseing Pallars Company for their implication and maintenance of field devices. Fieldwork permits were provided by the Territorial Service of the department of Agriculture, Livestock, Fishing and Natural Environment of Catalonia. We wish to thank to Dr. Carrión and the two reviewers, Dr. W. Fletcher and Dr. A: Ejarque, the comments and suggestions provided that helped to improve the manuscript

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8. **FIGURE CAPTIONS**

Figure 1 A) Location of Catalonia (squared area) and Lake Montcortès (yellow point). B) Catalonia map with its provinces and Pallars region (green shaded areas): Numbers refer to two different administrative boundaries within the Pallars region: 1- Pallars Sobirà (Montcortès location) and 2- Pallars Jussà. C) Vegetation map modified from Rull et al., 2015.

Figure 2. Age–depth model for the sediment cores MONT07-13-G05 (present study) and MONT12-3A-1G (Corella et al., 2014) based on varve counting for the last 500 years. Core correlation of the main sedimentary units and marker horizons are also shown.

Figure 3. Percentage sporomorph diagram including the total pollen sum (%)Elements included in the pollen sum: CF, conifer forests; EOF, evergreen oak forests; DOF, deciduous oak forests; RF, riverine forests; CT, cultivated trees; S, shrublands; M/P, meadows/pastures; HC, herbaceous crops; R/W, ruderal/weeds.

Elements outside the pollen sum: aquatic plants. An additional pollen sum diagram excluding *Cannabis* pollen is also shown Charcoal curves are expressed in fluxes for two categories of particle size. The horizontal lines correspond to statistically significant pollen zones (Bennett, 1996). Solid lines indicate (x10) exaggeration.

Figure 4. Percentage diagram for non-pollen palynomorphs (NPP) with respect to the pollen sum. The scales of *Tetraedron* and *Botryococcus* have been reduced for more clarity. NPP nomenclature based on the original publications (van Geel 1978; van Geel et al., 1981; 1989; 2003; Montoya et al., 2010; Bakkerand van Smeerdijk 1982) Solid lines indicate (x10) exaggeration. Zonation as in Fig.3.

Figure 5. Pollen Accumulation Rates (PAR) diagram grouped by the vegetation groups detailed in Table 1. Solid lines indicate (x10) exaggeration. Zonation as in Fig.3.

Figure 6. Comparison between the palynological results obtained in Rull et al. (2011) and the present work. Grey colored correspond to shared time interval. Red colored correspond to new time interval presented in this work. Note horizontal lines as indicators of sampling resolution.

Figure 7. Summary figure including the main findings of this study compared with previous studies of Lake Montcortès(Corella et al., 2014; Vegas-Vilarrúbia 2018), historical data referring to main historical events (Díaz-Ordoñez, 2016; Rotés 2011; Reventós 2004; Bringué 2005; Pérez-Sanz et al., 2011; Simó 1985; Rotés 2011; Gorchs and Lloveras, 2003; Karus, 2004) and climatic data (Oliva et al.2017 ; Morellón et al 2012, Mateo and Gómez 2004).

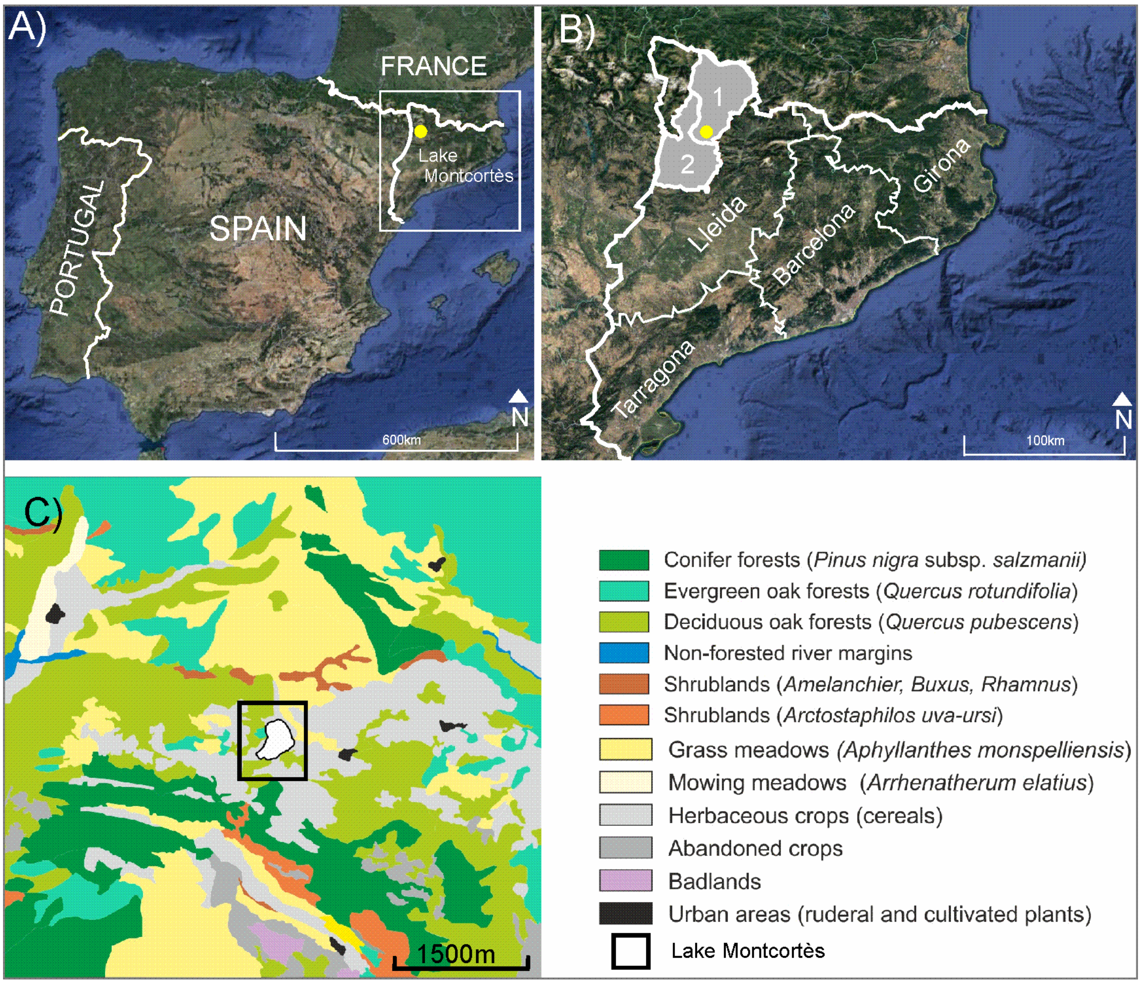
A)
FRANCE
Lake
Montcortès
SPAIN
PORTUGAL
N
600km
B)
1
2
Lleida
Barcelona
Girona
Tarragona
N
100km
C)
1500m
Conifer forests (*Pinus nigra* subsp. *salzmanii)*
Evergreen oak forests (*Quercus rotundifolia*)
Deciduous oak forests (*Quercus pubescens*)
Non-forested river margins
Shrublands (*Amelanchier, Buxus, Rhamnus*)
Shrublands (*Arctostaphilos uva-ursi*)
Grass meadows *(Aphyllanthes monspelliensis*)
Mowing meadows (*Arrhenatherum elatius*)
Herbaceous crops (cereals)
Abandoned crops
Badlands
Urban areas (ruderal and cultivated plants)
Lake Montcortès

Fig.1

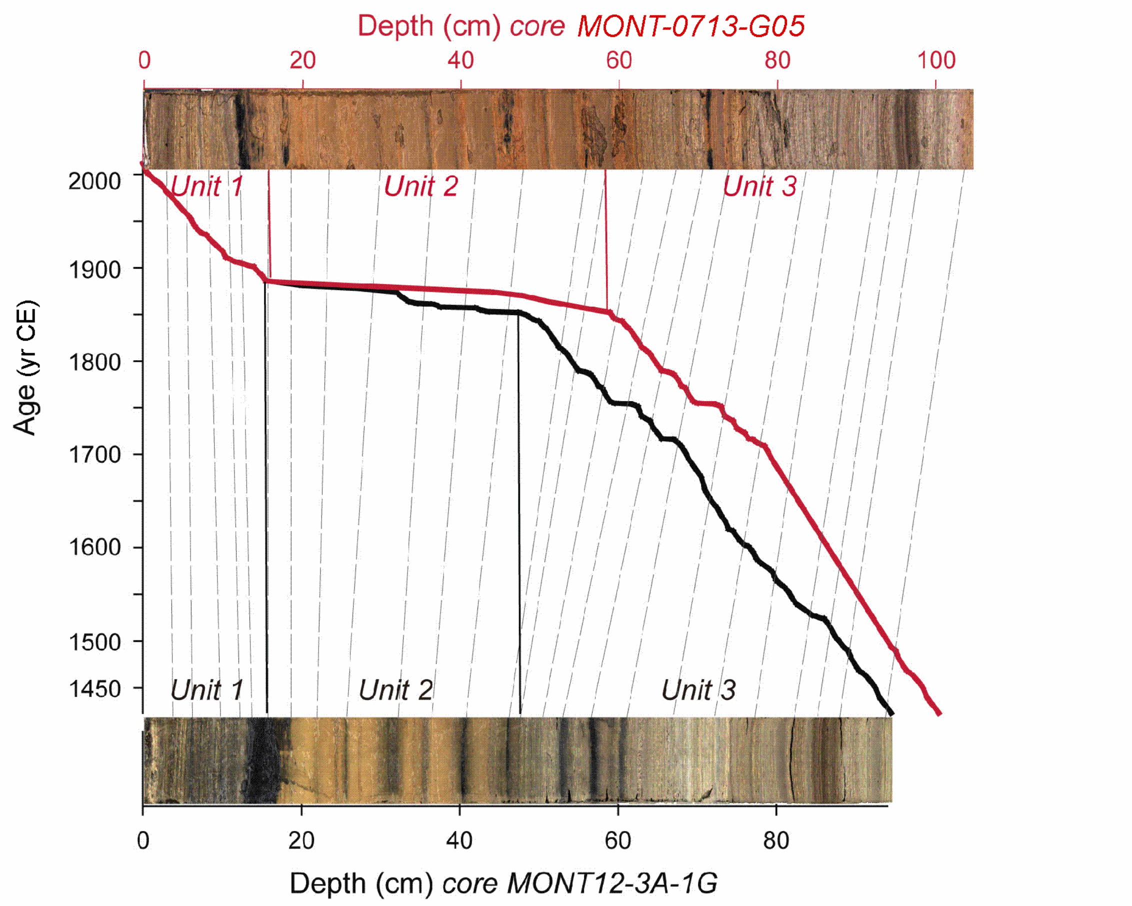
Depth (cm) core MONT-0713-G05
0
20
40
60
80
100
Unit 1
Unit 2
Unit 3
Age (yr CE)
2000
1900
1800
1700
1600
1500
1450
Unit 1
Unit 2
Unit 3
0
20
40
60
80
Depth (cm) core MONT12-3A-1G

Fig.2

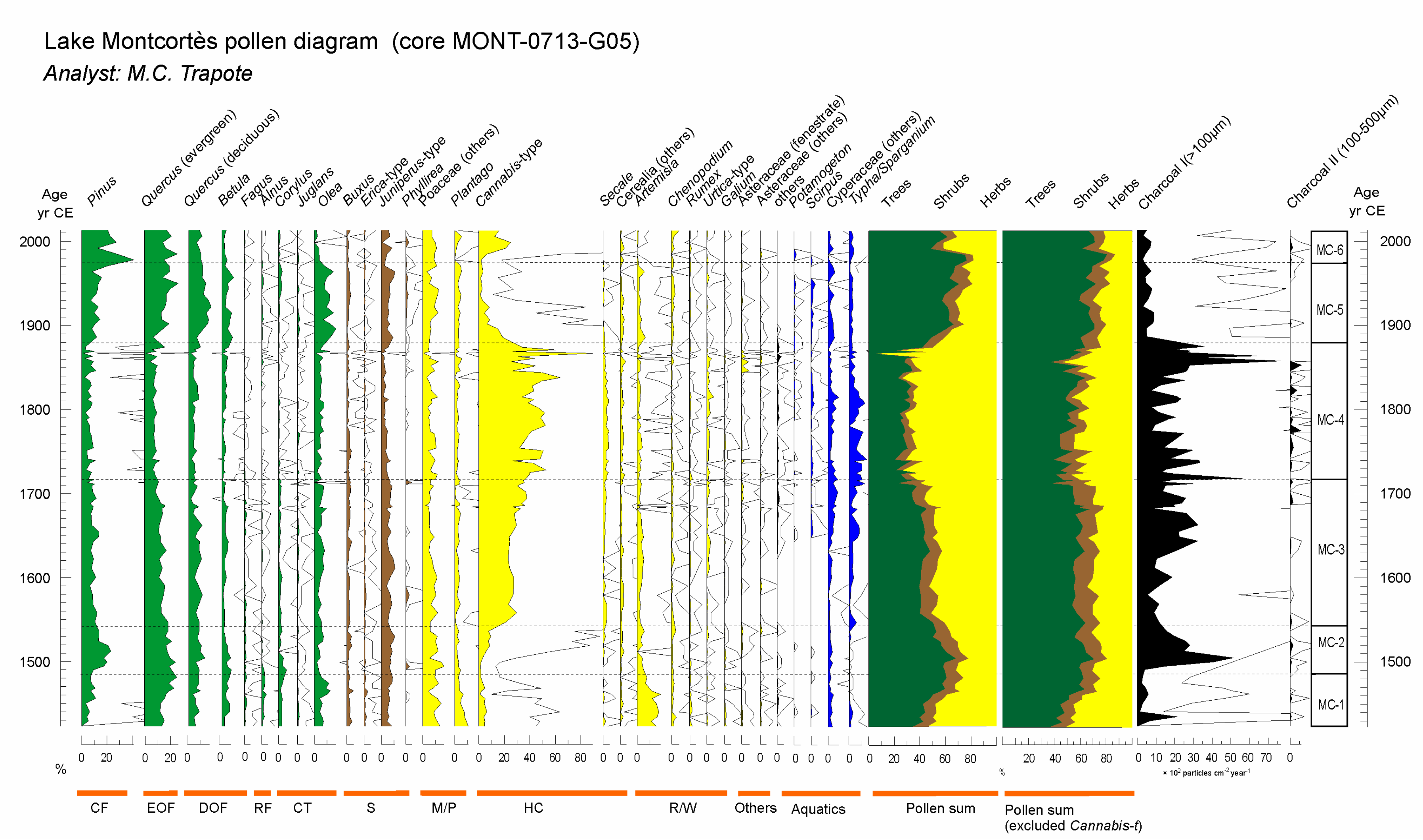
Lake Montcortès pollen diagram (core MONT-0713-G05)
Analyst: M.C. Trapote
Age yr CE
Pinus
Quercus (evergreen)
Quercus (deciduous)
Betula
Fagus
Alnus
Corylus
Juglans
Olea
Buxus
Erica-type
Juniperus-type
Phyllirea
Poaceae (others)
Plantago
Cannabis-type
Secale
Cerealia (others)
Artemisia
Chenopodium
Rumex
Urtica-type
Galium
Asteraceae (fenestrate)
Asteraceae (others)
others
Potamogeton
Scirpus
Cyperaceae (others)
Typha/Sparganium
Trees
Shrubs
Herbs
Trees
Shrubs
Herbs
Charcoal I(>100µm)
Charcoal II (100-500µm)
Age yr CE
2000
1900
1800
1700
1600
1500
MC-6
MC-5
MC-4
MC-3
MC-2
MC-1
%
0 20 0 20 0 0 0 0 0 0 0 0 0 0 0 0 0 20 40 60 80 0 0 0 0 0 0 0 0 0 0 0 0 0 20 40 60 80
% 20 40 60 80
0 10 20 30 40 50 60 70 0
× 10² particles cm⁻² year⁻¹
CF
EOF
DOF
RF
CT
S
M/P
HC
R/W
Others
Aquatics
Pollen sum
Pollen sum (excluded Cannabis-t)

Fig.3

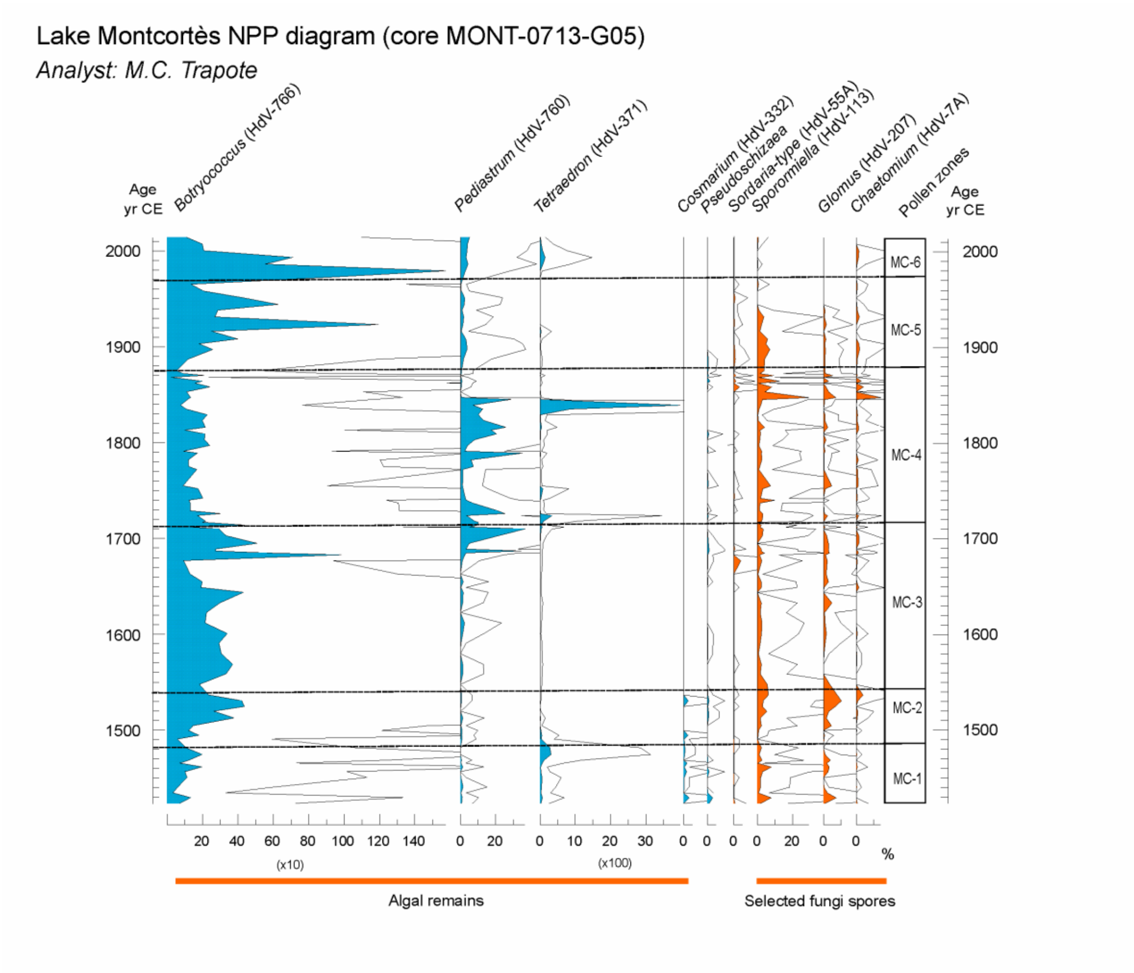
Lake Montcortès NPP diagram (core MONT-0713-G05)
Analyst: M.C. Trapote
Age yr CE
Botryococcus (HdV-766)
Pediastrum (HdV-760)
Tetraedron (HdV-371)
Cosmarium (HdV-332)
Pseudoschizaea
Sordaria-type (HdV-55A)
Sporormiella (HdV-113)
Glomus (HdV-207)
Chaetomium (HdV-7A)
Pollen zones
Age yr CE
2000
1900
1800
1700
1600
1500
MC-6
MC-5
MC-4
MC-3
MC-2
MC-1
20 40 60 80 100 120 140
(x10)
0 20
0 10 20 30
(x100)
0 0 0 0 20 0 0
%
Algal remains
Selected fungi spores

Fig.4

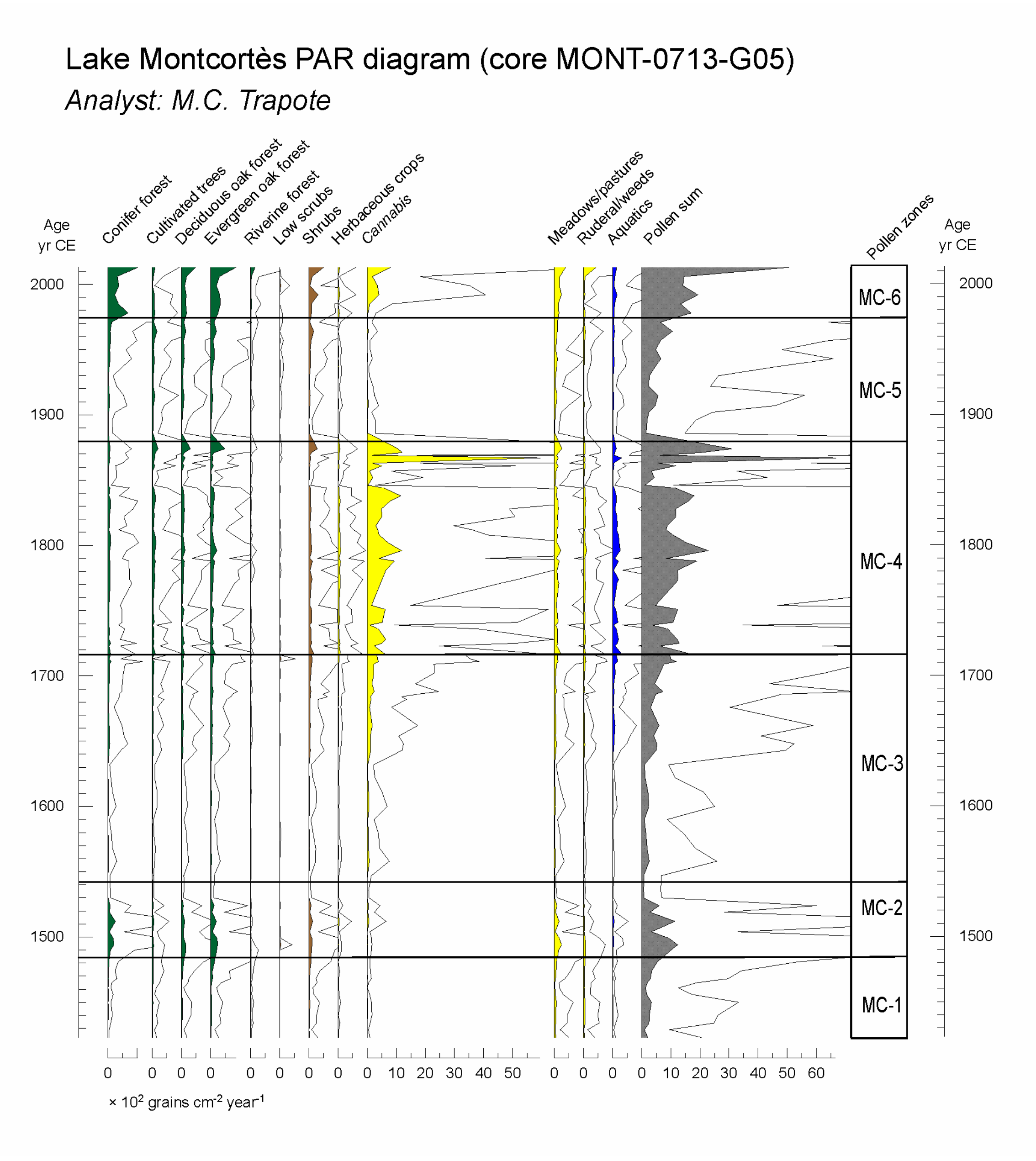
Lake Montcortès PAR diagram (core MONT-0713-G05)
Analyst: M.C. Trapote
Age yr CE
Conifer forest
Cultivated trees
Deciduous oak forest
Evergreen oak forest
Riverine forest
Low scrubs
Shrubs
Herbaceous crops
Cannabis
Meadows/pastures
Ruderal/weeds
Aquatics
Pollen sum
Pollen zones
MC-6
MC-5
MC-4
MC-3
MC-2
MC-1
2000
1900
1800
1700
1600
1500
0 0 0 0 0 0 0 0 0 10 20 30 40 50
0 0 0 0 10 20 30 40 50 60
× 10² grains cm⁻² year⁻¹

Fig.5

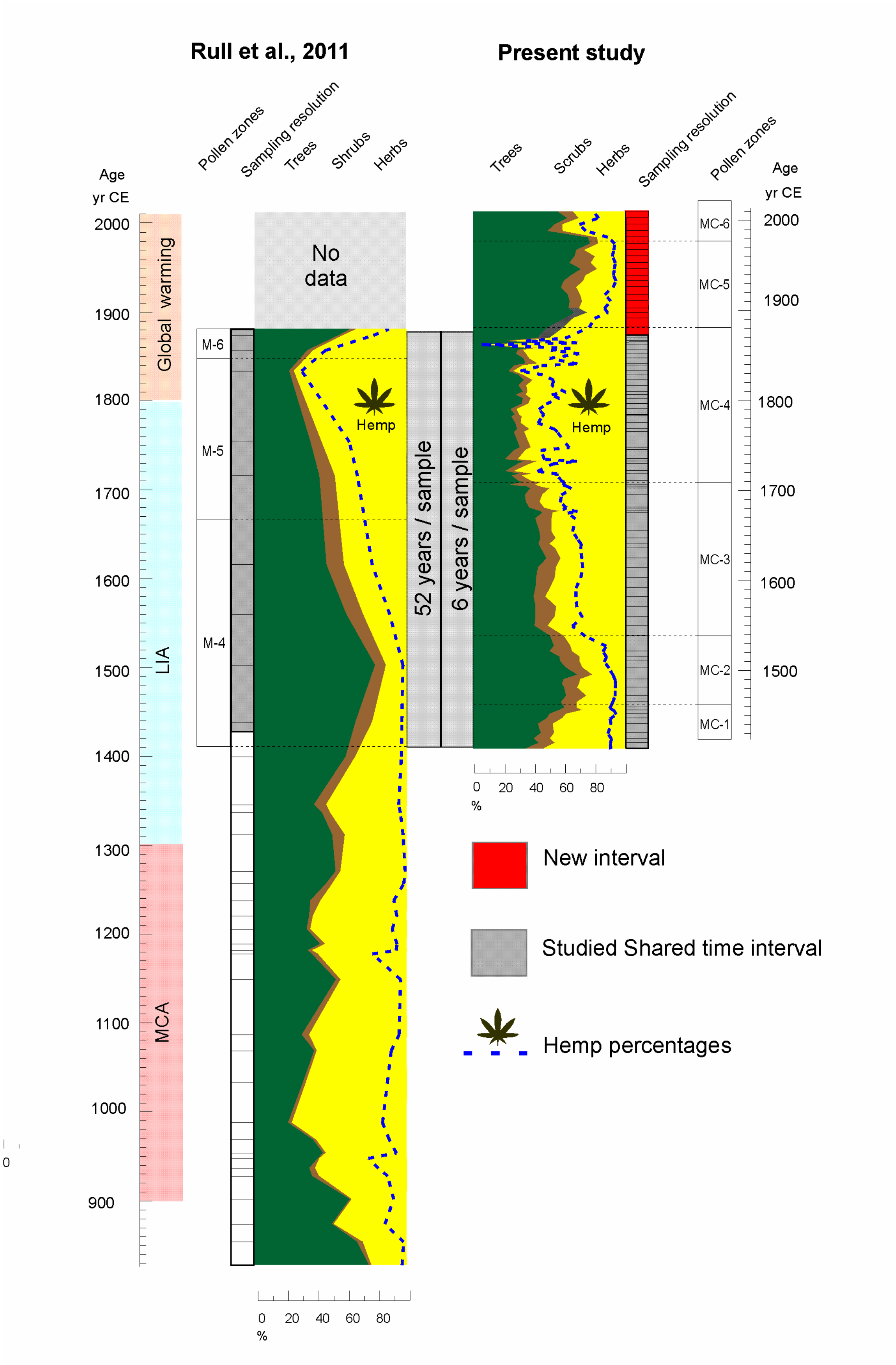
Rull et al., 2011
Present study
Age
yr CE
Pollen zones
Sampling resolution
Trees
Shrubs
Herbs
Scrubs
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
Global warming
LIA
MCA
No data
M-6
M-5
M-4
MC-6
MC-5
MC-4
MC-3
MC-2
MC-1
Hemp
52 years / sample
6 years / sample
0 20 40 60 80
%
New interval
Studied Shared time interval
Hemp percentages

Fig.6

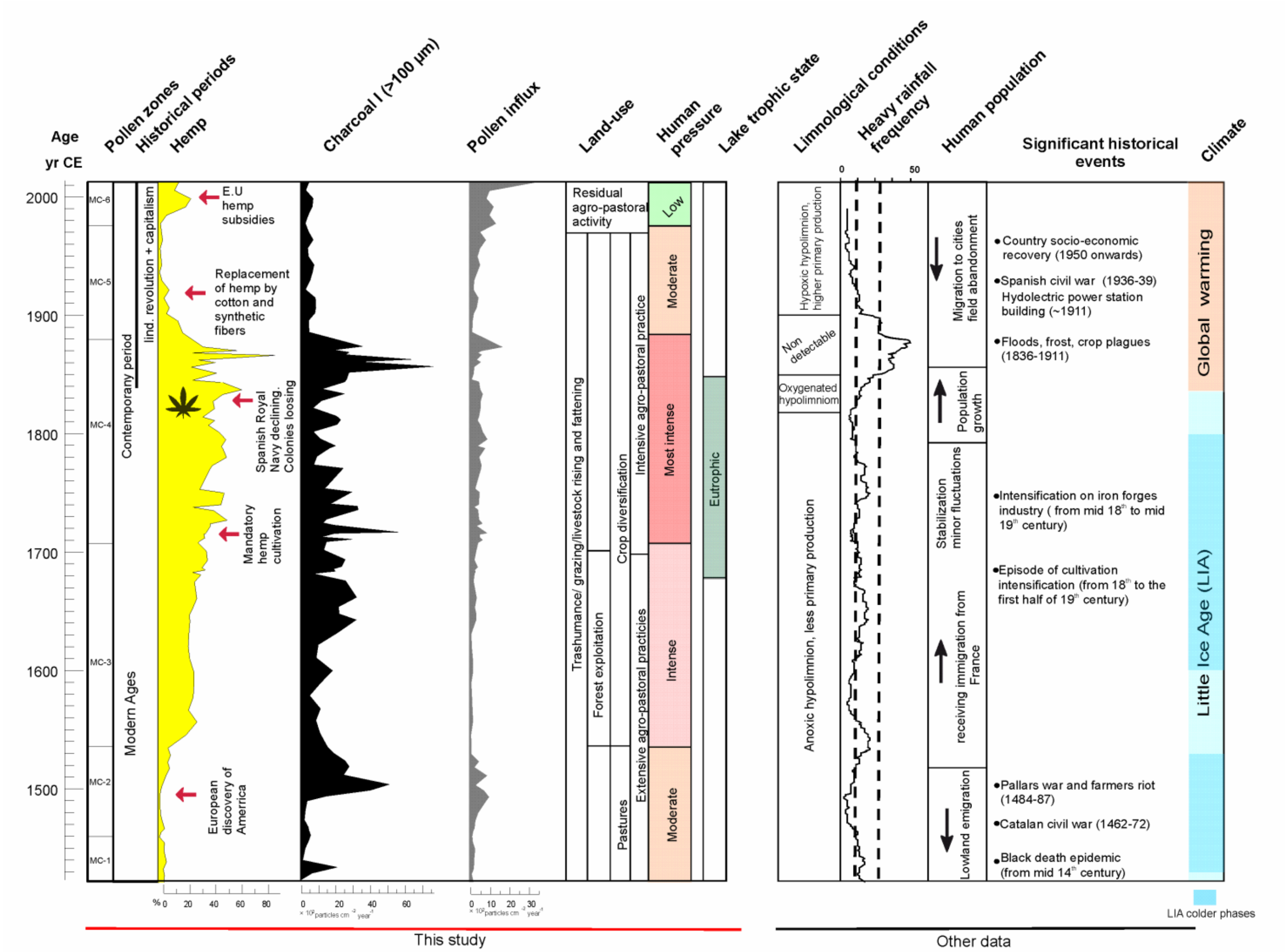
Age
yr CE
Pollen zones
Historical periods
Hemp
Charcoal I (>100 µm)
Pollen influx
Land-use
Human pressure
Lake trophic state
Limnological conditions
Heavy rainfall frequency
Human population
Significant historical events
Climate
2000
1900
1800
1700
1600
1500
MC-6
MC-5
MC-4
MC-3
MC-2
MC-1
Iind. revolution + capitalism
Contemporary period
Modern Ages
E.U hemp subsidies
Replacement of hemp by cotton and synthetic fibers
Spanish Royal Navy declining. Colonies loosing
Mandatory hemp cultivation
European discovery of America
Residual agro-pastoral activity
Trashumance/ grazing/livestock rising and fattening
Forest exploitation
Pastures
Crop diversification
Intensive agro-pastoral practice
Extensive agro-pastoral practicies
Low
Moderate
Most intense
Intense
Moderate
Eutrophic
0
50
Hypoxic hypolimnion, higher primary prduction
Non detectable
Oxygenated hypolimniom
Anoxic hypolimnion, less primary production
Migration to cities field abandonment
Population growth
Stabilization minor fluctuations
receiving immigration from France
Lowland emigration
•Country socio-economic recovery (1950 onwards)
•Spanish civil war (1936-39)
Hydolectric power station building (~1911)
•Floods, frost, crop plagues (1836-1911)
•Intensification on iron forges industry (from mid 18th to mid 19th century)
•Episode of cultivation intensification (from 18th to the first half of 19th century)
•Pallars war and farmers riot (1484-87)
•Catalan civil war (1462-72)
•Black death epidemic (from mid 14th century)
Global warming
Little Ice Age (LIA)
LIA colder phases
% 0 20 40 60 80
0 20 40 60
× 10³particles cm⁻² year⁻¹
0 10 20 30
× 10³particles cm⁻² year⁻¹
This study
Other data

Fig.7