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ORIGINAL PAPER

Vegetation changes in the southern Pyrenean flank during the last millennium in relation to climate and human activities: the Montcortès lacustrine record

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Abstract We report vegetation changes of the last millennium inferred from palynological analysis of a sediment core from Lake Montcortès, situated at ~1,000 m elevation in the southern pre-Pyrenean flank. The record begins in the Middle Ages (~AD 800) and ends around AD1920, with an average resolution of ~30 years. The reconstructed vegetation sequence is complex and shows the influence of both climate and humans in shaping the landscape. Pre-feudal times were characterized by the presence of well-developed conifer forests, which were intensely burned at the beginning of feudal times (AD 1000) and were replaced by cereal (rye) and hemp cultivation, as well as meadows and pastures. In the thirteenth century, a relatively short period of warming, likely corresponding to the Medieval Warm Period, was inferred from the presence of a low Mediterranean scrub community that is today restricted to <800 m elevation. This community disappeared during Little Ice Age cooling in the fifteenth century, coinciding with a decline in human activities around the lake. Forest recovery began around AD 1500, at the beginning of the Modern period, coinciding with wetter climate. Forests, however, declined again during the seventeenth century, coinciding with maximum olive and hemp cultivation. This situation was reversed in post-Modern times (nineteenth century), characterized by an intense agricultural crisis and a significant decline in population that favored forest re-expansion. Correlations with nearby Estanya Lake, situated about 350 m below, provide a regional picture of environmental change. Besides some climate forcing evident in both sequences, human activities seem to have been the main drivers of landscape and vegetation change in the southern Pyrenean flank, in agreement with conclusions from other studies in high-mountain environments.

Keywords Palynology · Climatic change · Human forcing · Historical records · Last millennium · Pyrenees

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Introduction

Paleoecological study of mountain ecosystems is useful to document the effects of climate warming and predict potential future consequences of such temperature increase. A key issue in these investigations is the need to disentangle the influence of natural climatic variations from human disturbance on observed ecological shifts. One strategy is to compare ecological changes that occurred before human settlement (e.g., during glacial or postglacial times) with those of the last few millennia, when human activities intensely transformed mountain landscapes and ecology. Another approach is to develop multiproxy studies that include independent proxies for climatic, ecological and anthropic processes, and compare results. Given the available paleoecological information for the Pyrenean range and its recent human history, the region provides a suitable setting to apply both approaches. On the one hand, the Pyrenees have been recognized as an important glacial refuge from which European forests expanded during post-glacial and Holocene warming (Jalut et al. 1992; Montserrat 1992; Brewer et al. 2002; Terhürne-Berson et al. 2004; González-Sampériz et al. 2004, 2005; Leroy and Arpe 2007; Benito et al. 2008; Magri 2008). On the other hand, this range has a history of ~7,000 years of human settlement and landscape utilization (Marsan and Utrilla 1996; Galop 2001), with particularly intense land use in the last millennium (Esteban 2003; Miras et al. 2007).

Long-term ecological changes are often reconstructed by pollen analysis, one of the best indicators of vegetation and climate change (Birks and Birks 1980). In the Pyrenees, the northern slope has been studied palynologically both extensively and intensively (Jalut et al. 1992; Reille and Lowe 1993 and Visset et al. 1996), but such detailed study has not occurred on the southern slope, though studies by Montserrat (1992), González-Sampériz et al. (2006) and Miras et al. (2007), among others, are worthy of mention. Studies covering the last millennium in detail are also scarce, but have increased recently (Galop 2001; Riera et al. 2004, 2006; Morellón et al. 2009b; Ejarque et al. 2009; Pèlachs et al. 2009a, b), and an understanding of the recent paleoecological history is starting to emerge. This paper reports pollen analysis of recent sediments from Lake Montcortès (1,027 m elevation), covering vegetation changes that occurred during the last millennium. We compare our results to those from neighboring Lake Estanya (670 m elevation), covering the same period (Riera et al. 2004, 2006; Morellón et al. 2009b). Paleoclimatic trends are inferred from multiple climate proxies (sedimentology, mineralogy, geochemistry and physical properties) of the laminated Montcortès sediments (Corella et al. 2010). Potential influence of human activities on recorded ecological changes is derived from relatively detailed historical records from the area (Esteban 2003; Riera et al. 2004; Marugan and Rapalino 2005). Lake Montcortès sediments are an excellent target for high-resolution studies because they accumulated rapidly and are varved, yielding excellent time control (Corella et al. 2010). These are ideal conditions for studying changes during the last millennia and disentangling the effects of natural environmental changes from the impacts of human activities in shaping present-day landscapes.

Study area

Geography and climate

Lake Montcortès is situated on the southern flank of the Central Pyrenees, in the Pallars region, at 42° 19′ N–0° 59′ E and 1,027 m altitude (Fig. 1). The lake lies in karstic terrain characterized by Triassic limestones, marls and evaporites (Keuper and Muscheskalk facies), and Oligocene carbonatic conglomerates (Rosell 1994; Gutiérrez et al. 2008). The catchment is small and the lake is fed mainly by groundwater, with intermittent small creeks and scattered springs. The main water losses are due to evaporation and a small seasonal outlet at the north end. The lake is roughly circular, with a diameter

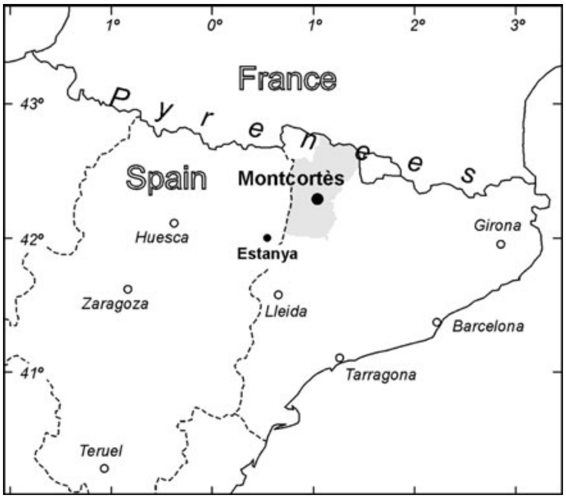

Fig. 1 Location map of Lakes Montcortès and Estanya. The Pallars region is highlighted (*grey* area)

between 400 and 500 m and a maximum water depth of 30 m near the center (Camps et al. 1976; Modamio et al. 1988). The annual average temperature is 10.6°C, ranging from 1.9°C in January to 20.3°C in July. Total annual precipitation is 860 mm, with March is the driest month (46.6 mm) and May is the wettest month (99.2 mm) (Corella et al. 2010).

Vegetation

The lake lies near the altitudinal boundary between the Mediterranean lowlands and the Middle Montane belt, which in the Pyrenees is situated around 800–1,000 m elevation, depending on local conditions (Vigo 2008). Three major forest formations occur around the lake, reflecting this boundary condition (Fig. 2). Evergreen oak forests dominated by *Quercus rotundifolia* are representative of the Mediterranean lowlands, while deciduous oak forests dominated by *Quercus pubescens* represent the Middle Montane belt, with higher total annual precipitation. Conifer forests of *Pinus nigra* subsp. *salzmanii* are mostly secondary, and colonize or eventually replace the degraded deciduous oak forests

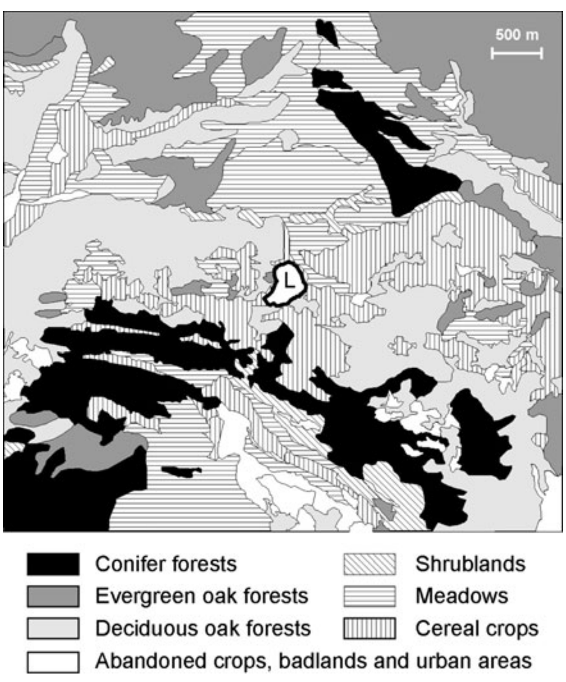

Fig. 2 Vegetation map according to the classification of Carreras et al. (2005–2006), using the CORINE system (CBM 1991). L, Lake Montcortès

(Folch 1981). Carreras et al. (2005–2006), using the CORINE system (CBM 1991), distinguished twelve vegetation types in the catchment (Fig. 2, Table 1). Around the lake shore, there is a belt of littoral vegetation dominated by *Juncus*, *Scirpus*, *Phragmites*, *Typha* and *Sparganium* (Camps et al. 1976).

Historical background

A summary history of the Pallars region is presented in Fig. 3. The beginning of the Medieval Period was marked by defeat of the Roman Empire by the Visigoths (around AD 400), who dominated until the early eighth century. The region was then under the dominance of Muslims until about AD 800, when the Carolingians became established. The last millennium is divided into three main periods (Esteban 2003; Marugan and Rapalino 2005): Medieval Ages (eighth to fifteenth centuries), Modern Ages (sixteenth to eighteenth centuries) and Post-modern Ages (nineteenth century onwards). Until the tenth century, the southern Pyrenean flank was a poor and overpopulated region, due to pressure from the northward Muslim expansion. The land was divided into small properties ruled by autonomous landholders. Forest clearance by fire was a common practice to prepare the terrains for shifting cultivation, the main economic activity at the time. After AD 1000, the individual properties were confiscated by the nobility and the church, thus establishing the feudal system, which endured until the end of the Middle Ages. Fire and shifting cultivation were replaced by more permanent land exploitation. The increase in cattle, mainly sheep, led to deforestation and the development of meadows and pastures. The common crops were cereals (wheat, barley and oat), olives and vineyards. The last two, however, were restricted to the southern lowlands (<1,000 m elevation), due to climate constraints. Toward the end of the Medieval Period, depopulation of the Pallars region was caused by wars, epidemics and Little Ice Age cooling (Marugan and Oliver 2005).

Feudalism collapsed and was replaced by the monarchy around AD 1500 (Modern Ages). This led to the return of a private property system, but this time land owners were rich families and an oligarchic system was established. The Pallars region became a marquisate and was newly populated by immigrants from the north, what is now France. Agriculture and cattle raising expanded and diversified. There was increased animal

Table 1 Vegetation types in the Montcortés lake area, following Carreras et al. (2005–2006) and using the CORINE system (CBM 1991)

CORINE units	Vegetation types	Main components	Environmental observations	Climate
Unit 42v	Submontane conifer forests	*Pinus nigra* subsp. *salzmanii*, poorly developed understory	Diverse substrates	Moderately wet
Unit 45f	Evergreen oak forests	*Quercus rotundifolia*, well developed understory with abundant sclerophylous shrubs (*Quercus coccifera, Rhamnus alaternus, Rhamnus saxatilis, Prunus spinosa, Buxus sempervirens, Lonicera etrusca*). Herbaceous stratum with nemoral (shadow-adapted) species: *Rubia peregrina, Teucrium chamaedrys, Asparagus acutifolius* and *Brachypodium retusum*	Well exposed sites of lowland plains, hills and slopes	Continental Mediterranean
Unit 41 k	Deciduous oak forests	*Quercus pubescens*, sometimes with *Pinus sylvestris* or, less frequently, *Fagus sylvatica* or *Tilia cordata.* Other trees: *Quercus cerrioides, Quercus subpyrenaica, Acer monspessulanum, Acer opalus* subsp. *opalus;* Shrubs: *Buxus sempervirens, Coronilla emerus, Amelanchier ovalis, Colutea arborescens, Cytisophyllum sessilifolium, Viburnum lantana;* Herbs: *Primula veris* subsp. *columnae, Hepatica nobilis, Brachypodium phoenicoides, Campanula persicifolia*	Well exposed warm slopes, submontane stage, up to 1,500 m a.s.l., calcareous substrates	Submediterranean or mountain Mediterranean
Unit 24a	Non-forested river margins	Pioneer plants frequent. Trees: *Salix* spp.; Shrubs: *Myricaria germanica;* Herbs: *Mentha longifolia, Juncus* spp., *Saponaria officinalis, Polygonum* spp., *Bidens* spp., *Xanthium italicum, Agrostis stolonifera, Polypogon viridis, Paspalum distinctum, Andryala ragusina, Glaucium flavum*	Azonal vegetation type due to natural or anthropic causes, present from the lowlands to the subalpine zone	
Unit 31q	Shrubland	*Amelanchier ovalis, Buxus sempervirens* and *Rhamnus saxatilis*. Up to 2 m high, with an irregular herbaceous stratum of heliophyllous plants. Other shrubs: *Coronilla emerus, Ligustrum vulgare, Cytisophyllum sessilifolium*; Herbs: *Tanacetum corymbosum, Viola alba, Teucrium chamaedrys, Carex halleriana*	Well exposed rocky slopes, on calcareous terrains. Secondary colonizer where the forest has been removed	Submediterranean
Unit 32 ab	Shrubland	*Arctostaphylos uva-ursi*, with some emergent shrubs (*Buxus*) or trees (*Pinus, Quercus*). Other shrubs: *Juniperus communis, Amelanchier ovalis*; Herbs: *Primula veris* subsp. *columnae, Lavandula angustifolia* subsp. *pyrenaica, Hepatica nobilis, Cruciata glabra, Carex humilis, Avenula pratensis* subsp. *iberica*	Deforested areas and forest clearings on calcareous soils	Submediterranean

Table 1 continued

CORINE units	Vegetation types	Main components	Environmental observations	Climate
Unit 34n	Meadows	*Aphyllanthes monspelliensis.* Shrubs: *Salvia lavandulifolia, Santolina chamaecyparissus, Ononis natrix, Teurcium polium, Genista scorpius, Helianthemum italicum, Euphorbia nicaeensis, Thymus vulgaris;* Herbs: *Avenula pratensis* subsp. *iberica, Koeleria vallesiana, Brachypodium phoenicoides, Leuzea conifera, Linum narbonense, Carduncellus monspeliensium, Catananchae caerulea, Asphodelus cerasiferus, Asperula cynanchica*	Light pastures from 1,000 to 1,400 m a.s.l., on calcareous, generally unstable terrains	Mediterranean to Submediterranean
Unit 38b	Mowing meadows	*Arrhenaterum elatius*. Other herbs: *Trisetum flavescens, Trifolium pratense, Dactylis glomerata, Rhinanthus mediterraneus, Gentiana lutea, Plantago lanceolata, Lotus corniculatus, Daucus carota, Rumex acetosa*	Plains and gentle slopes with deep and eutrophic soils	Submediterranean
Unit 82a	Extensive herbaceous crops	Cereals, rarely forages, with abundant weeds. Herbs: *Hordeum sp., Avena sativa, Triticum* sp., *Secale cereale, Medicago sativa*; Weeds: *Lolium rigidum, Papaver rhoeas, Bromus* sp., *Polygonum aviculare*	Open valleys and gentle slopes, on clayey deep soils	Mediterranean
Unit 87a	Abandoned crops	Pasture-like terrains colonized by shrubs and ruderal species like *Inula viscosa* and *Oryzopsis miliacea*	Lowlands to medium elevations, on a wide range of soils	Wide range of climate conditions
Unit 61f	Badlands	Devoid of vegetation or with few scattered plants like *Achnatherum calamagrostis, Brachypodium phoenicoides, Erucastrum nasturtifolium, Tussilago farfara, Genista scorpius, Thymus vulgaris* or *Lithospermum fruticosum*	Highly eroded terrains, generally on steep slopes	
Unit 86a	Urban areas	Diverse ruderal and cultivated flora		

husbandry and use of animals in agriculture for plowing and fertilizing. Forests were exploited mainly for wood. Other common activities were mining, hunting and fishing. At the end of the Modern period, commerce became important (Bringué 2005).

The post-modern period began with the nascent capitalist society typical of the nineteenth century, characterized by the centralization of the production system and development of routes for commercial interchange. The Pallars region, however, remained an isolated and self-sufficient subsistence economy during the nineteenth cenury. At the beginning of the twentieth century, the general agricultural crisis caused renewed depopulation in the region, but development of a widespread hydroelectric power program soon promoted socio-economic revival. The Spanish Civil War (AD 1936–1939) again interrupted modernization, but a second hydroelectric program and new mining efforts revitalized the economy. Between 1960 and 1980, industrialization caused a global crisis manifested in the massive emigration from rural to urban areas. Today, the main economic activities of the Pallars region are tourism and related services (Farràs 2005).

Materials and methods

In April 2004, four sediment cores were obtained from the deepest part (~30 m water depth) of Montcortés

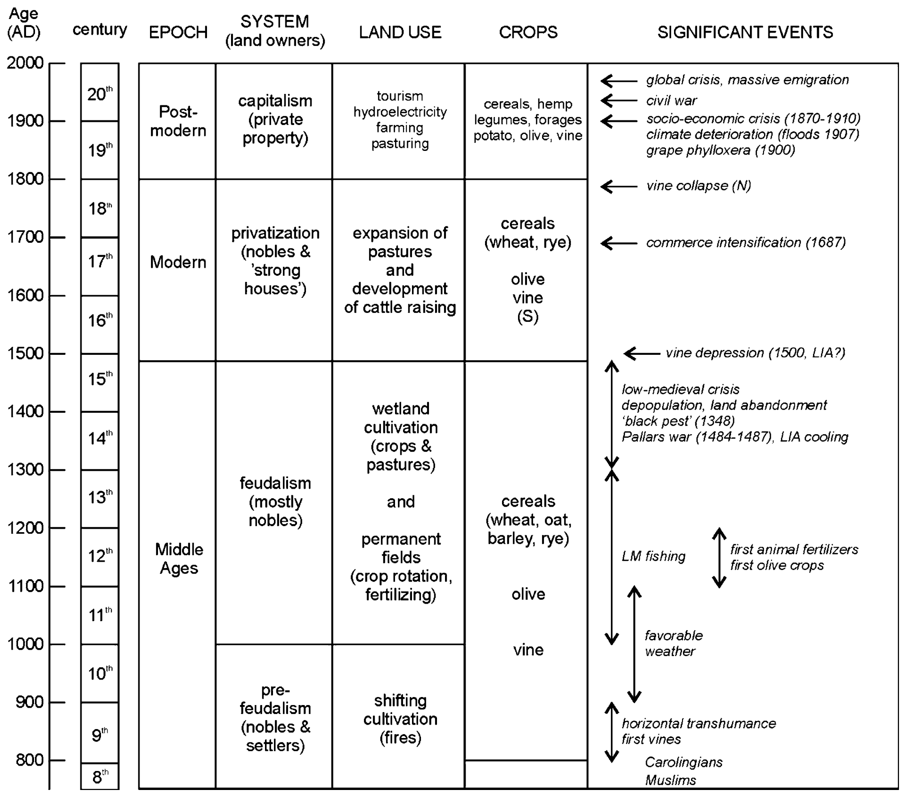

Fig. 3 Schematic account of the main historical periods and events in the Pallars region, especially those related to economic models and land use. Summary after Esteban (2003), Marugan and Oliver (2005), Bringué (2005), and Farràs (2005). LM, Lake Montcortès; N, North; S, South

Lake along a NW–SE transect, using the Kullenberg corer and platform from the Limnological Research Centre (LRC), University of Minnesota, Minneapolis. All the cores were split and imaged. Their physical properties were measured with a Geotek core logger (Corella et al. 2010). Core MON-04-1A-1 K, 6.69 m long, was selected for palynological analysis and sampled every 10 cm. In this paper, we report results from the upper 3.60 m, roughly corresponding to the last millennium. Chronology was taken from the age-depth model of Corella et al. (2010), based on radiocarbon dating of macroremains and bulk sediment samples. The average resolution of this pollen record is around 33 years per sample interval, but ranges between about 14 and 59 years.

Pollen samples consisted of ~3–5 g of sediment, which were processed using standard palynological methods, including NaOH, HCl and HF digestions and density gradient centrifugation, without acetolysis (Bennett and Willis 2001). Two *Lycopodium* tablets (batch n° 483216; 18,583 spores/tablet) were added to each sample before chemical processing. Residues were suspended in glycerine and slides were mounted with glycerine jelly. Pollen and pteridophyte spores were identified and counted until diversity saturation (Rull 1987), obtaining total counts between 289 and 873 (average 427). Algae remains were also identified to the genus level and counted. Fungal spores and charcoal particles >5 µm were counted as groups. The percentage diagram was based on the pollen sum (ΣP), which included all pollen types except those from aquatic plants (Cyperaceae, *Cladium*, *Myriophyllum*, *Pinguicula*, *Potamogeton*, *Ranunculus*, *Typha/Sparganium*-type and *Utricularia*), ranging from 266 to 866 (average 421) counts. Pollen and spore types below 0.1% of the ΣP were not represented, these are: *Acer*, *Androsace*, *Asphodelus albus/ramosus*-t, *Centaurea*, *Convolvulus*, *Cornus*, *Cupressus*, *Draba*-t, *Echium*, *Gentiana*, *Geranium*, *Linum*, *Myriophyllum*, *Paronychia*-t, *Pedicularis*, *Pinguicula*, *Polygonum aviculare*-t, *Populus*, *Potamogeton*, *Prunus avium*-t, *Ranunculus*, *Rhamnus*, *Sideritis*, *Tilia*, *Utricularia*, *Valeriana*, *Huperzia*, *Isoëtes* and *Lycopodium cernuum*. Zonation was performed using the Optimum Splitting by Information Content (OSIC) and the broken-stick methods (Bennett 1996), considering only pollen types. Pollen groups (Table 2) were defined

Table 2 Pollen groups according to the present-day vegetation types, as defined by Carreras et al. (2005–2006), with additional information from Muenscher (1980), Folch (1981), Vigo (1983, 1996, 2008), de Bolòs et al. (1990), and de Bolòs (2001)

Vegetation groups	Pollen taxa
Conifer forests	*Pinus, Abies*
Evergreen oak forests	*Quercus*-evergreen type
Deciduous oak forests	*Quercus*-deciduous type, *Tilia, Acer, Betula, Cornus, Corylus, Fagus*
Riverine forests	*Alnus, Populus, Salix, Ulmus*
Cultivated trees	*Cupressus, Juglans, Olea, Prunus avium*-type
Shrubs from both shrublands and the understory of light oak forests	*Buxus*, Ericaceae, *Juniperus, Phillyrea, Rhamnus*
Low scrubs	*Rosmarinus*-type, *Hedysarum*-type, *Heliantehmum, Ephedra*
Meadows and/or pastures	*Asphodelus albus/ramosus*-type, *Linum, Plantago,* Poaceae, *Sideritis, Pedicularis*
Herbaceous Crops	*Cannabis*-type, *Triticum/Avena*-type, other Fabaceae, *Secale*
Ruderal plants and/or weeds	*Artemisia, Centaurea, Chenopodium*-type, *Convolvulus, Echium, Polygonum aviculare*-type, *Rumex*
Aquatic plants	*Cladium,* other Cyperaceae, *Myriophyllum, Pinguicula, Potamogeton, Typha/Sparganium, Utricularia*
Others or taxa occurring in several vegetation types or with insufficient taxonomic resolution	*Ambrosia*-type, *Androsace, Apiaceae*, Asteraceae, *Bupleurum*-type, Psilate tricolporate (~*Castanea*), *Cerastium*-type, *Draba*-type, *Gentiana*-type, *Geranium, Paronychia*-type, *Ranunculus*, *Sanguisorba minor*-type, *Valeriana*

according to the present-day vegetation types. Percentages for non-pollen palynomorphs or NPP (algae, fungi, etc.) were referred to the pollen sum.

Results

The pollen diagram is dominated, alternatively, by trees and herbs, while shrubs are relatively scarce (Fig. 4). Among trees, the more abundant are *Pinus* and *Quercus* (evergreen) followed by *Olea*, whereas the dominant herbs are Poaceae (others), *Plantago*, *Cannabis*-type and *Artemisia*. Cyperaceae dominate the aquatic assemblage, in which *Typha/Sparganium* is important only in the upper part. Fern spores are comparatively scarce, in general. Total pollen and charcoal particles have their maxima near the base. The dominant vegetation types are conifer forests at the beginning, meadows/pastures in the middle, and herbaceous crops at the end. Oak forests show a progressive increase towards the top, while ruderal plants and weeds decline from the base to the top (Fig. 5). The following pollen zones were identified:

Zone M-1 (360–325 cm, 1,172–1,000 cal BP, AD 778–950, 4 samples, 45 years/sampling interval)

This zone is dominated by *Pinus*, followed by *Quercus* (evergreen) and Poaceae (others), which show a decreasing trend toward the top. *Cannabis*-type, *Artemisia* and psilate monoletes, however, increase toward the top. These patterns coincide with an increase in charcoal concentration. Conifer forests are the dominant vegetation type (Figs. 4, 5). Meadows/pastures are important at the base, but they decline around the middle, where herbaceous crops and ruderal/weeds start to increase. *Pseudoschizaea* has its maximum and *Botryococcus* is poorly represented (Fig. 6). Fungi are also at maximum values and increasing. Among them, *Glomus* is well represented. The data suggest an initial pine woodland landscape around AD 800 that was progressively reduced by fires and replaced by crops and associated elements. i.e., ruderal plants and weeds. The abundance of *Pseudoschizaea* and the scarcity of planktonic algae is consistent with low lake levels or marshy environments, indicative of dry climates (Scott 1992; Carrión 2002, Carrión et al. 2004, 2007). The presence of *Glomus* has been interpreted

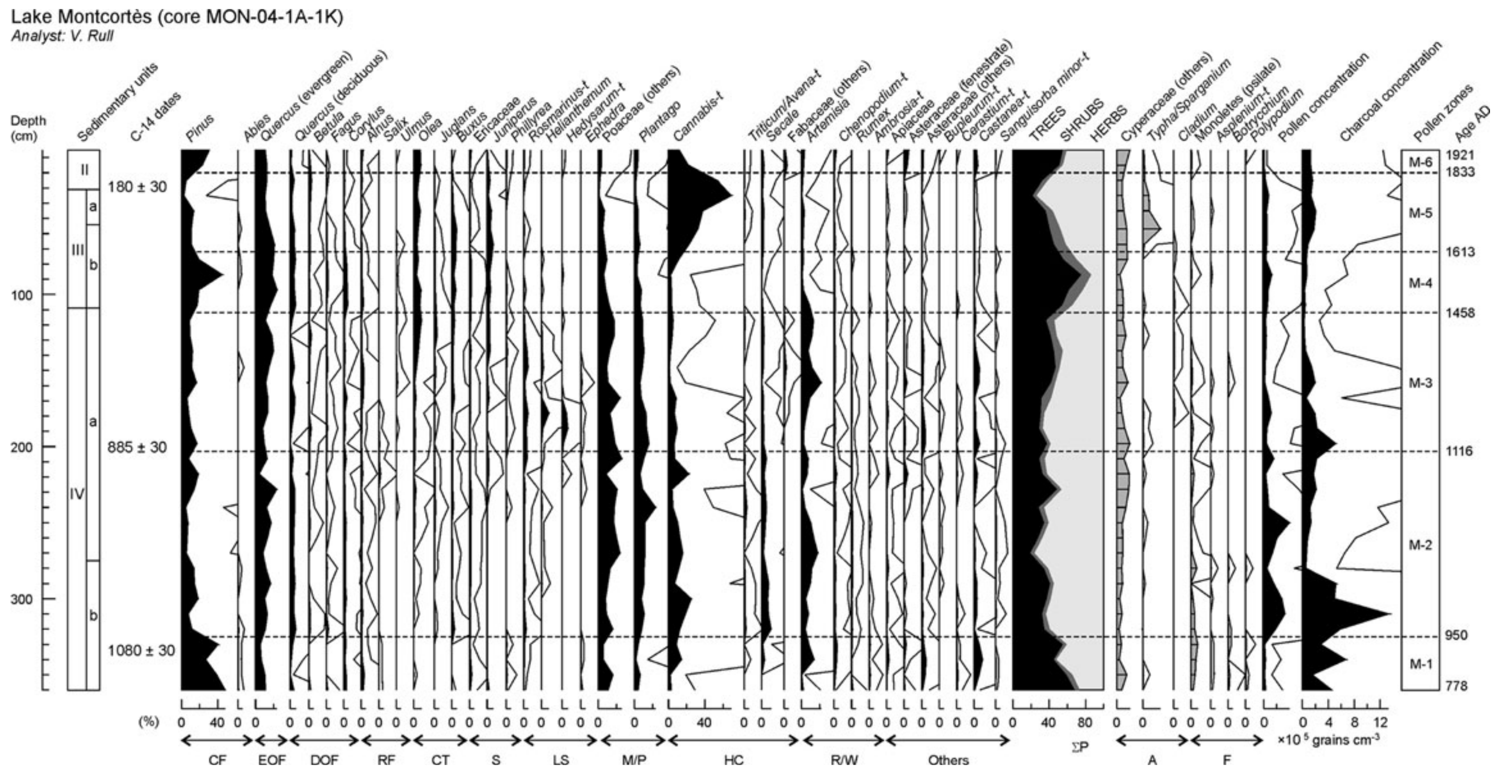

Fig. 4 Percentage sporomorph diagram, including the total pollen and charcoal influx. Elements included in the pollen sum: CF, conifer forests; EOF, evergreen oak forests; DOF, deciduous oak forests; RF, riverine forests; CT, cultivated trees; S, shrublands; MS, Low Mediterranean scrubs; M/P, meadows/pastures; HC, herbaceous crops; R/W, ruderal/weeds. Elements outside the pollen sum: A, aquatic plants; F, ferns. Zonation was made using the Optimum Splitting by Information Content (*OSIC*) and the broken stick methods (Bennett 1996). Solid lines indicate 10× exaggeration

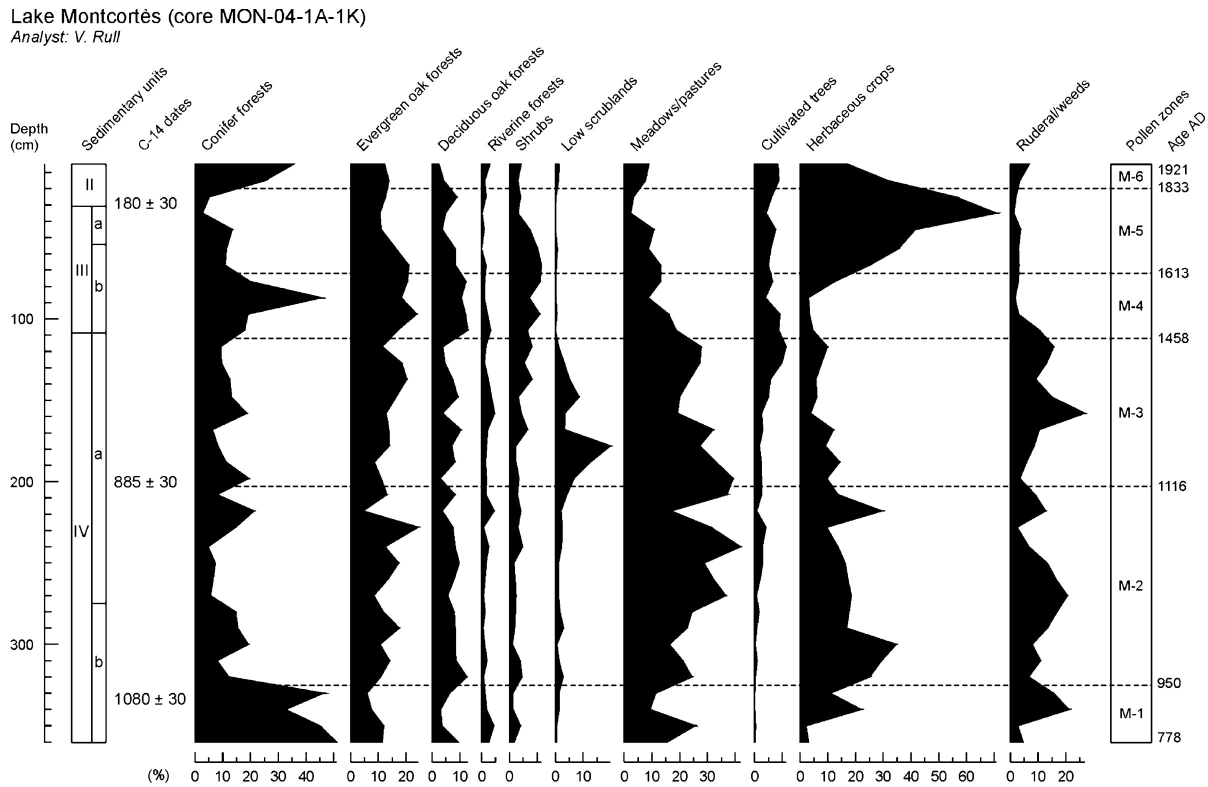

Fig. 5 Percentage pollen diagram grouped by vegetation types, according to Carreras et al. (2005–2006), with additional information from Muenscher (1980), Folch (1981), Vigo (1983, 1996, 2008), de Bolòs et al. (1990), and de Bolòs (2001). The zonation is based on the percentage diagram (Fig. 3)

to reflect increased soil erosion (Anderson et al. 1984, van Geel et al. 1989, 2003; Leroy et al. 2009), and is associated with intensification of human activities in the basin (López-Sáez et al. 2009, Argant et al. 2006). *Glomus* is a genus of mycorrhizal fungi commonly associated with forest vegetation. Forest management experiments have shown that mycorrhizal colonization of roots in pine and oak forests is significantly greater if half the forest is removed, compared to uncut and clearcut treatments (Zhou et al. 1997). Therefore, intermediate-impact clearance of *Pinus* forests is suggested for the time interval between *ca.* AD 780 and 940.

Zone M-2 (325–203 cm, 1,000–834 cal BP, AD 950–1116, 12 samples, 14 years/sampling interval)

A dramatic decline in conifer forests, primarily *Pinus*, marks the beginning of this zone (Fig. 4). Oak forests, both evergreen and deciduous, and shrubs increase slightly. The dominance was shared by meadows/pastures, mainly Poaceae and *Plantago*, and herbaceous crops (*Cannabis*-type). They first dominate in the middle of the zone, coinciding with a maximum of ruderals/weeds, with secondary peaks at the beginning and end. Cultivated trees (mostly *Olea*) start to increase in the middle of the zone. These shifts in the pollen assemblage occur at the same time as an abrupt increase in both pollen and charcoal concentrations, which attain their respective maxima. This pollen zone is interpreted to reflect intense land use, mainly cereal cultivation alternating with grazing, as indicated by the increase of meadows and pastures, after an abrupt and severe reduction of conifer forests using fire. Among non-pollen palynomorphs (NPP), *Pseudoschizaea* and *Glomus* decline dramatically, while *Tetraedron* shows a conspicuous peak coinciding with the main charcoal maximum (Figs. 4, 6). The decline in *Glomus* is consistent with a strongly reduced cover of *Pinus* forests (Zhou et al. 1997). The charcoal peak at the

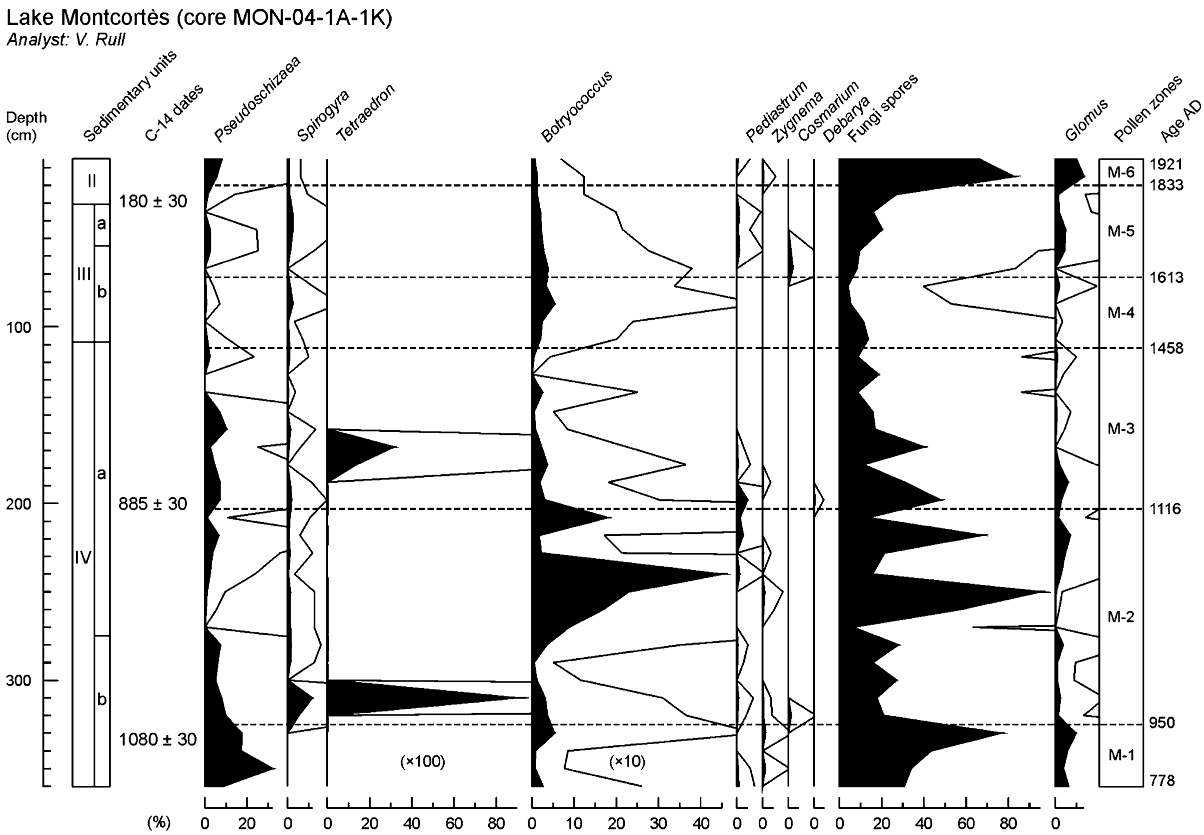

Fig. 6 Percentage diagram for non-pollen palynomorphs (NPP) with respect to the pollen sum. The scales of *Tetraedron* and *Botryococcus* have been reduced for more clarity. Solid lines indicate 10× exaggeration. Zonation as in Fig. 3

beginning of the zone coincides with a peak in *Cannabis*-type and *Secale*, whereas the dramatic charcoal decrease that occurs around 290 cm (~AD 1000) coincides with the increase of meadows/pastures and ruderal/weeds. This suggests that, at that time, the use of fire was linked to herbaceous cropping rather than to pastoralism. The *Tetraedron* peak is indicative of lake fertilization due to increased nutrient release linked to greater organic-rich sediment input.

Zone M-3 (203–112 cm, 834–494 cal BP, AD 1116–1456, 9 samples, 39 years/sampling interval)

Evegreen and deciduous forests do not show significant changes with respect to zone M-2. The main differences occur in the formerly dominant meadows/pastures and herbaceous crops, which start a consistent decreasing trend, and low scrub (*Rosmarinus*-type, *Helianthemum*, *Hedysarum*-type and *Ephedra*), which peak in the middle of the zone and decrease around 140 cm (~AD 1360). This increase in low scrub occurs shortly after a secondary charcoal peak, which decreases in the middle of the zone and attains minimum values at the end, where cultivated trees (*Olea*) start to increase. Ruderal/weeds show a maximum around the middle of the zone, just after the low scrub peak and before the *Olea* maximum. Total pollen attains its minimal values in this zone. Today, the same low-scrub taxonomic association that characterized this zone corresponds to the *Rosmarinetalia officinalis* order (27.C), a thermophilous community typical of Mediterranean calcareous lowland dry environments below 800 m elevation (de Bolòs 2001). This association is absent today at the elevation of Lake Montcortès, which suggests an upward displacement of this vegetation type by least 200 m due to warming between about AD 1100 and 1350. The small charcoal peak at the beginning of the zone is not followed by an increase of taxa associated with human activities and would therefore support the occurrence of drier climatic conditions, favorable for wild fires. In spite of absence or low incidence of fire, *Pinus* forests did not recover and only evergreen oak forests and shrubs expanded, suggesting drier climates and/or an intensification of seasonality. Also noteworthy is the cessation of cereal and hemp cultivation and the increase of olive crops since about AD 1280.

Zone M-4 (112–72 cm, 494–337 cal BP, AD 1456–1613, 4 samples, 29 years/sampling interval)

The main changes in this zone are the sharp increase of conifer forests, which peak around the middle, and the equally abrupt decline of the meadows/pastures and ruderal/weeds groups (mostly *Artemisia*). Oak forests, especially the deciduous ones, and scrublands also increase. Among cultivated plants, *Olea* shows a slight decrease and cereals are nearly absent, whereas hemp is very low at the beginning, but starts to increase around the middle of the zone, after the *Pinus* peak. There is no significant change in charcoal influx, which is at low values. The general decline of all cultivated elements and others associated with human activities (ruderal/weeds, meadows/pastures) and the low charcoal values indicate the low human pressure between about AD 1480 and 1590, though hemp cultivation seems to restart around AD 1550. The increase in other elements, especially conifer forests and deciduous *Quercus* forests, together with the increase of *Corylus* and the abrupt *Artemisia* decline, suggest a moderate increase in moisture. Low scrub is at minimum values, suggesting colder climates.

Zone M-5 (72–20 cm, 337–117 cal BP, AD 1613–1833, 5 samples, 34 years/sampling interval)

This zone is characterized by the decline of almost all pollen groups, except for the spectacular increase of *Cannabis*-type, which largely dominates the assemblage. This coincides with the increase in charcoal and fungi spores, incuding *Glomus*. The whole picture indicates reinitiation of human activities around the lake since about AD 1630. Fires began again, affecting primarily conifer and oak forests, and cultivation was largely focused on hemp, while *Olea* maintained the importance attained since the end of zone M-3 (AD 1280). The increase of *Typha/Sparganium* and the disappearance of *Cladium* suggest increases in nutrient supply, mainly N and P (Chiang et al. 2000, and literature therein).

Zone M-6 (20–5 cm, 117–29 cal BP, AD 1833–1921, 2 samples, 30 years/sampling interval)

This zone is characterized by a conspicuous change in both the *Pinus* and *Cannabis*-type pollen curves, the other pollen types remaining similar to the former zone. Hemp cultivation declined sharply around AD 1860, and conifer forests reexpanded.

Discussion

Comparison between sedimentological, palynological and historical records

The multiproxy study of the core analyzed here provided a depositional and environmental history for the lake catchment during the last 6,000 years (Corella et al. 2010). The time interval recorded in this study was divided into three main sedimentological phases, represented by lithological units IV, III and II. Sedimentary facies indicate that the lake has been deep and meromictic during the last 1,500 years. During the Medieval epoch, represented by lithologic unit IV (AD 690–1460), the lake had high clastic input. This unit was divided into two subunits (IVa and IVb), with the boundary around AD 1000. Unit IVb is dominated by turbiditic Facies 4, reflecting events of high terrigenous input, while Unit IVa is characterized by the dominance of laminated Facies 1, indicating less sediment delivery to the lake and low bottom bioturbation. Sedimentological unit 4 includes pollen zones M-1 to M-3, and coincides with the Medieval epoch. The boundary between sedimentological units IVb and IVa coincides with the end of the main charcoal peak (Fig. 4) and the disappearance of *Pseudoschizaea* (Fig. 6), indicators of forest fires and increased terrigenous inputs to the lake, respectively. According to the historical records, AD 1000 corresponds to the end of the pre-feudal epoch, when the predominant land use was forest burning and shifting cultivation, and the beginning of feudalism, characterized by more controlled use of fire and more or less permanent land exploitation (Marugan and Oliver 2005). The historical records also report the onset of vineyard and olive cultivation around the same times. In the Lake Montcortès pollen diagram, *Olea* pollen appear consistently at 310 cm (AD 970), but *Vitis* is absent throughout the sequence. A possible explanation is that, during that time, olives and vineyards were cultivated mainly in lowlands below 1,000 m elevation for climatic reasons (Marugan and Oliver 2005), and *Olea* pollen was better dispersed upwards than was pollen of *Vitis*. In support of this interpretation, recent work in a nearby area showed the high upward dispersal efficiency of *Olea* pollen, which was found in surface samples from 800 to >2,600 m elevation, in spite of the absence of the parent plant along the transect (Cañellas-Boltà et al. 2009). Another apparent inconsistency between historical and pollen records is the high amount of hemp pollen in the diagram and the absence of any reference to its cultivation in the Pallars region from the Medieval Ages to the present (Esteban 2003; Marugan and Rapalino 2005). One possibility is that hemp cultivation was restricted to favorable areas and this is not commonly reflected in historical accounts. But it is also possible that these crops were not autochthonous and the lake was used for hemp retting, as occurred in neighboring Lake Estanya during the same epoch (Riera et al. 2004). This, however, is not reported in the writings reviewed so far and more work is still needed with respect to this matter. Among the cereals mentioned in written documents, the better represented in the pollen diagram are wheat (*Triticum*) and rye (*Secale*), but the Poaceae curve probably includes rarer types that are harder to identify with confidence.

Pine woodlands were dramatically reduced by AD 950, during pre-feudalism, and did not recover during the whole Medieval epoch, when the landscape was likely a mosaic of predominantly crops and pastures, with smaller pine/oak forest patches. This human-induced vegetation change also coincides with an increase in total pollen concentration, and the dominance of turbidites in the sedimentary sequence, indicating enhanced runoff and siliciclastic inputs to the lake (Corella et al. 2010). The dilution effect of higher sedimentation rates on pollen concentrations, often observed elsewhere (Leroy et al. 2009), was not recorded here. The maximum pollen concentration corresponds to increases in herbaceous crops, meadows/pastures and ruderal/weeds, and could be explained by enhanced pollen production due to the intensification of human activities linked to these vegetation types.

The vegetation changes recorded until around AD 1100 were mainly driven by human activities, thus paleoclimate signals are likely obscured. Historical records indicate a phase of “favorable weather” during the tenth and eleventh centuries (Fig. 3) that favored the expansion of crops and pastures in river margins and wetlands (Esteban 2003; Marugan and Oliver 2005), which is coherent with the interpretation of pollen zone M-2 (Fig. 4). Clearer palynological indications of warming and aridity were found afterwards, between about AD 1100 and 1350, by the presence of low Mediterranean scrub communities in pollen zone M-3. Similar warmer and drier phases have been recorded during the Middle Ages in Lake Estanya and other lakes from the Iberian Peninsula (Morellón et al. 2009a), coinciding with the so-called Medieval Warm Period (MWP) of the Northern Hemisphere (Seager et al. 2007; Mann et al. 2009). The Medieval period ended with cooling, inferred from the decrease in thermophilous low scrub around AD 1400 and its disappearance from the site around AD 1460 (Fig. 5). Between this date and the end of the fifteenth century, the Pallars region was largely depopulated due to wars, epidemics and climate cooling. This cooling is coeval with the onset of the Little Ice Age (LIA) (Mann et al. 2009), which in Europe was a cool and wet phase, also recorded at Lake Estanya and at other lakes on the Iberian Peninsula (Morellón et al. 2009a). As a result, many villages were abandoned and the population concentrated in larger, lowland towns (Marugan and Oliver 2005). This land abandonment is reflected in the pollen diagram by a decline in charcoal and herbaceous crops at the end of zone M-3. Curiously, *Olea*, a lowland element, increases at the same time, attaining its maximum values ($\sim$8%). It might be hypothesized that olive cultivation increased in the lowlands as a result of the population increase.

Lithological Unit III was deposited during the Modern Ages, between AD 1460 and 1770, and is characterized by the predominance of Facies 1, indicating deep, meromictic conditions with high bioproductivity and carbonate precipitation, and reduced terrigenous inputs (Corella et al. 2010). This is consistent with the palynological interpretation of zone M-4 as a period of forest expansion (mainly pines), reduced human activity around the lake (low values of charcoal, crop and ruderal elements), and decreased terrigenous inputs to the lake [low values of *Pseudoschizaea* and fungal spores (Fig. 6)]. Climate was still cool and probably wet, as was common during the LIA, a period characterised by moisture fluctuations, as shown in the nearby Lake Estanya record (Morellón et al. 2009a). In this case, it is likely that climate dominated over human activities with respect to shaping the Montcortès landscape. A similar situation was observed in other regional sequences, such as Taravilla Lake (Moreno et al. 2008), where climate, rather than human action, seems to have been the main cause of hydrological, sedimentological and vegetation changes. Expansion of pastures, documented in historical records after feudalism in the Pyrenees, is not recorded in the Montcortès pollen diagram, suggesting that once more, it occurred primarily in the lowlands. A slight increase in clastic inputs was recorded at AD 1660, coinciding with the return to a phase of forest clearance and farming, as suggested by the decline of forests and the increase of charcoal and hemp pollen.

A significant sedimentological shift occurred at AD 1770, close to the end of the Modern epoch (Fig. 3), when turbiditic sedimentation (Facies 4) appeared again and sedimentation rates increased and remained high until the top of the sequence (Unit II). This coincides with pollen zone M-5, when maximum hemp cultivation and/or retting is observed (Fig. 4), suggesting strong human impact on the lake watershed. Historically, this phase corresponds to the pre-capitalist or pre-industrial period, when subsistence agriculture dominated in the Pallars region due to the area's geographic isolation. In the lowlands, below Lake Montcortès, crops expanded, whereas in the mountains above the lake, cattle raising and forest exploitation were the dominant practices (Bringué 2005). This situation is clearly reflected in the pollen diagram by the reduction of trees, especially *Pinus*, and the increase of herbaceous crops at the end of zone M-5. Once more, the large amount of hemp pollen contrasts with the lack of documentary evidence for its cultivation or the use of the lake for retting. Large amounts of *Cannabis* pollen in zone M-5 favor the second option, but further work is needed to draw a definitive conclusion. Pollen zone M-6 coincides with a subsistence agriculture crisis and significant decline in the population of the Pallars region, coeval with the general European agricultural crisis of the mid-nineteenth century (Farràs 2005). Both climate (floods) and agriculture pests have been invoked to explain this phenomenon. Despite the low number of samples in pollen zone M-6, the decline of herbaceous crops and the forest recovery are evident (Fig. 5) and consistent with historical accounts.

Correlation with the Estanya record: vegetation and land use

When comparing the Lake Montcortès (LM) and Lake Estanya (LE) records, it must be noted that the areas possess different environmental characteristics due to their different altitudes. LE is situated ~50 km SW of LM and is 350 m lower in elevation. Therefore, LM is in the boundary between the Mediterranean lowlands and the Middle Montane belt, within the Submediterranean bioclimatic domain. By contrast, LE is in the Mediterranean lowlands, around the transition between the Submediterranean and the Mediterranean bioclimatic regime (Morellón et al. 2009b; Corella et al. 2010). The climate around LE is continental Mediterranean, with a mean annual temperature of 14°C, ranging from 4 (January) to 24°C (July), and an average annual precipitation of 470 mm, ranging from 18 (July) to 50 mm (October) (Morellón et al. 2009b). At present, the vegetation is a mosaic of shrublands (such as *Buxus, Juniperus,* and *Pistacia*), oak forests (*Q. rotundifolia*), pastures, and barley (*Hordeum*) crops. Littoral vegetation around the lake is dominated by *Tamarix*, *Phragmites*, *Juncus*, *Typha* and *Scirpus* (Ávila et al. 1984). Two pollen records of the last millennium are available for this lake: one from the deepest part, at 20 m water depth (Morellón et al. 2009b) and another from the littoral zone, <1.5 m water depth (Riera et al. 2004). The first covers the last 800 years, whereas the second accounts for the last two millennia, both with a similar average resolution of around 50 years per sampling interval. The main results of these studies and Lake Montcortès, in terms of vegetation and land use, are depicted in Fig. 7 for comparison.

There is an initial phase of apparently undisturbed woodland around both lakes. In Montcortès, these

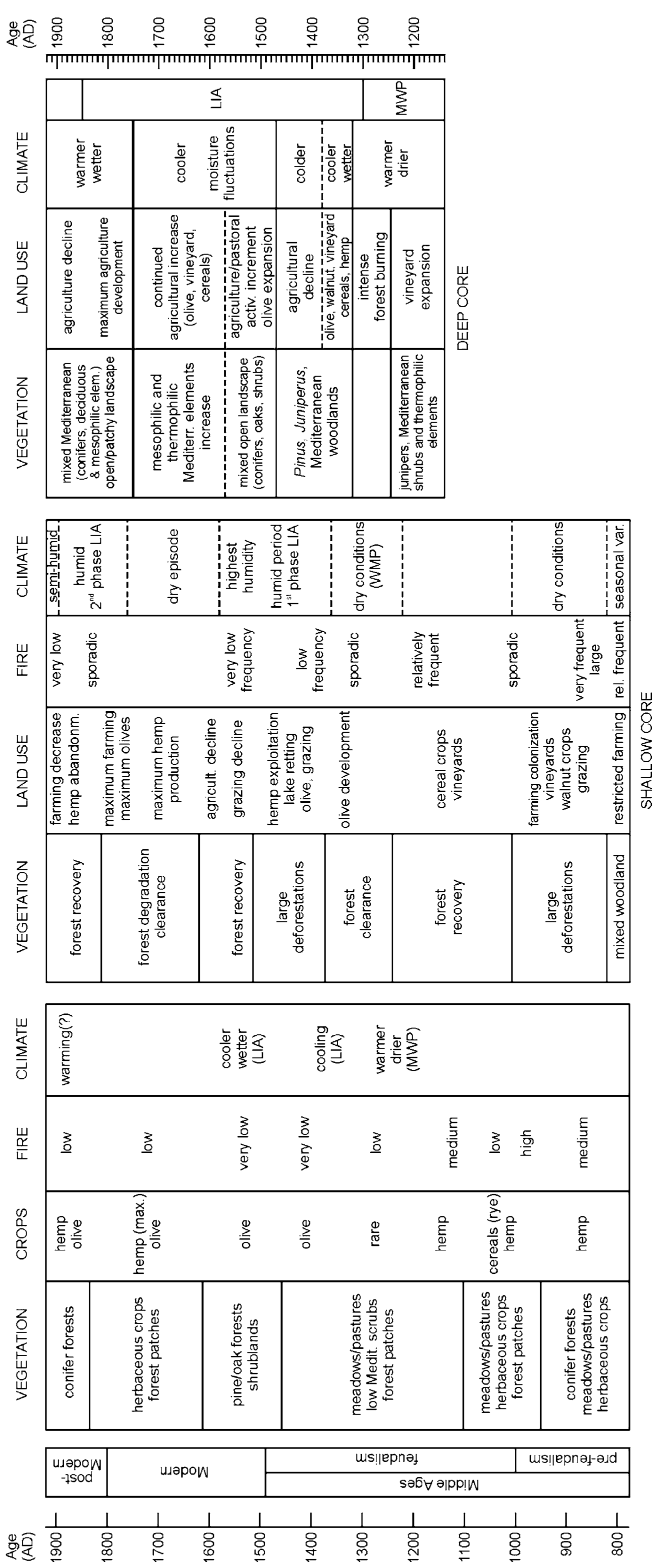

Fig. 7 Interpretation of Montcortès pollen diagram and correlations with the existing Estanya records. LIA, Little Ice Age; MWP, Medieval Warm Period

forests were dominated by *Pinus*, while in Estanya, *Quercus* (both deciduous and evergreen) were more abundant, likely because of its lower altitude. Subsequent deforestation took place in both localities, as recorded by sudden tree-pollen declines and major charcoal peaks, but it occurred first at Lake Estanya, around AD 900 (Riera et al. 2004) and then at Montcortès, where it was not completed until the end of the pre-feudal period, slightly before AD 1000. Although dating errors can not be disregarded, this northward trend would be consistent with historical records that report a conspicuous migratory trend towards the mountains caused by the northward Muslim expansion (Marugan and Oliver 2005). In this context, it is worth noting that Muslims occupied the region near Lake Estanya between around AD 720 and AD 1030, but they did not reach the Montcortès area (Riera et al. 2004; Esteban 2003). Major deforestation also coincides with the end of shifting cultivation and the beginning of a more or less permanent and extensive land exploitation, which marks the beginning of the feudal epoch. This is manifested in the development of cereal and hemp cultivation in both localities. As stated before, occasional *Olea* and *Vitis* crops are mentioned in written documents, thus the scarcity of the former and the absence of the latter in the Montcortès diagram is interpreted in terms of the required altitude for their cultivation. In the Estanya record, *Olea* pollen is also very scarce at that time, suggesting wind transport from lower altitudes, but *Vitis* is already present, though in low quantities (Riera et al. 2004).

The warming recorded at Montcortès between AD 1100 and 1350, correlated with the MWP, is paralleled at Estanya by equally warmer and drier climate, manifested by the increase of thermophilic elements in the pollen diagrams (Riera et al. 2004; Morellón et al. 2009a). During this warm and dry episode, fire events reappear at both Montcortès, around AD 1100, and Estanya, between about AD 1250 and 1300 (Morellón et al. 2009a). The first was of medium intensity and is not linked to extensive deforestation, and perhaps related to pastoralism. The second fire event was inferred from a barren, charcoal-rich layer in the deeper Estanya core (Morellón et al. 2009a), which is absent in the shallow-water core (Riera et al. 2004), and coincides with a conspicuous forest clearance event. A possible explanation for this discrepancy is that water levels were probably lower during that time, consistent with warmer and drier climate, and the shallow-water coring site was exposed, so charcoal was not deposited in the littoral zone or was removed by erosion. During this phase, agricultural activities did not experience significant changes in the lake catchments, but vineyard expansion around Estanya is worth mentioning (Morellón et al. 2009a).

The LIA cooling initiated around AD 1350 in Montcortès was also identified in Estanya, where several moisture fluctuations occurred until the nineteenth century. Morellón et al. (2009a) suggested several humidity oscillations, while Riera et al. (2004) proposed the occurrence of a dry episode between about AD 1600 and AD 1750, and two humid phases before and after, respectively (Fig. 7). The LIA onset was characterized, in both lake records, by a decline of cultivated plants, suggesting agriculture depression. This coincides with the so-called “low medieval crisis,” characterized by intense depopulation and land abandonment. It is estimated that about one-third of the population emigrated and concentrated in larger towns in the southern lowlands (Marugan and Oliver 2005). The move is attributed to the combined effect of climate deterioration, a “black death” epidemic that occurred in AD 1348, local wars, and the probable collapse of the feudal system (Fig. 3) (Esteban 2003; Marugan and Rapalino 2005). Despite this agricultural crisis, both the Montcortès and Estanya records document a progressive increase of *Olea* pollen, culminating around AD 1500, which is interpreted as an expansion of olive crops in the region (Riera et al. 2004; Morellón et al. 2009a). According to written documents, an expansion of olive and vineyard crops occurred during this time in the southern lowlands, so it is probable that most of the recorded *Olea* pollen was transported upslope to the lake catchments by wind (Cañellas-Boltà et al. 2009).

The end of feudalism and the beginning of the Modern epoch (AD 1500) is characterized in Montcortès by forest recovery, also documented in Estanya, where a cooler, but wetter climate has been suggested (Riera et al. 2004). During the sixteenth century, pollen records show some spatial heterogeneity with respect to land use (Fig. 7). This is probably due to the contrasting histories of lowlands used mainly for agriculture, and highlands used mostly for pasture and cattle raising since the beginning of the Modern epoch, a consequence of land privatization (Bringué 2005). In the seventeenth century, a dramatic increase in hemp pollen was recorded in Montcortès and in the Estanya shallow core, coinciding with a dry episode and another forest clearance event (Riera et al. 2004). As noted, the lack of written documentation about hemp cultivation around Montcortès makes it difficult to know if the *Cannabis* pollen peak was due to cultivation, retting, or both. High amounts of hemp pollen (10–80%), together with the presence of a suitable environment, are indicative of retting (Mercuri et al. 2002). At Montcortès, a suitable environment is provided by the lake and hemp pollen represents about 40–60% at that time, which strongly suggests retting. Anyway, it seems that the hemp industry was a predominant activity in the region at that time. In the British Isles, similar *Cannabis* pollen peaks, indicating increased hemp cultivation and retting, have been associated with phases of expansion of the naval industry, to satisfy the growing demand for hemp fiber used to make ropes and sails (Godwin 1967a, b; Schofield and Waller 2005). In Montcortès, the maximum of hemp pollen is recorded at 35 cm (AD 1757), which falls within a period of maximum development of ship building (AD 1750–1775) in Barcelona (Fig. 1) and other nearby Catalan shipyards, linked to a phase of general economic prosperity and intensification of transcontinental commerce with America (Andreu 1981; Delgado 1994). A similar hemp pollen maximum was recorded in the Estanya shallow-water core at about the same time (AD 1760), and was interpreted in similar terms, thus suggesting a regional event linked to maximum agrarian expansion in Spain that occurred during the seventeenth and eighteenth centuries (Riera et al. 2006). By contrast, no peak in hemp pollen was recorded in the Estanya deep-water core, where this pollen type is comparatively less abundant and does not display significant changes through time (Morellón et al. 2009a). Sedimentologic and taphonomic factors cannot be ignored, and more records are still needed to provide a satisfactory explanation.

Conclusions

A detailed comparison of the Montcortès and Estanya records for the last millennium makes it clear that human activities have played a major role in the vegetation change history and have been crucial for shaping southern Pyrenean landscapes (Ejarque et al. 2009; Pèlachs et al. 2009a, b). Intense climatic shifts, i.e., the MWP and the LIA, are still recognizable using particular plant associations, for example the low Mediterraean scrub in Montcortès. Minor oscillations, however, are likely obscured by the consequences of human land use. This is especially true for moisture changes, as the appearance or disappearance of plant assemblages commonly used as humidity proxies, for example forests, have been determined mainly by human activities rather than by climatic conditions. Biological fossil records require independent evidence to interpret them in terms of climatic or anthropic factors, to avoid circular reasoning (Leroy 2010). Fortunately, in the case of Lakes Montcortès and Estanya, abundant independent evidence is available from both sedimentological and documentary sources, which greatly strengthens paleoecological interpretation. In this study, both independent lines of evidence were used to try to disentangle the potential forcing factors behind the vegetation changes recorded by pollen analysis. In general, vegetation patterns in time and human land-use changes show a high degree of temporal coincidence, but climate-human-landscape relationships are complex and there is still room to improve our interpretations. For example, climate has both a direct influence on natural communities, but also an indirect one, by affecting human practices and modifying the anthropic element of change. It would be interesting to further investigate this aspect. Another interesting issue, which is already being pursued, is generating a detailed paleolimnological reconstruction using aquatic proxies combined with sedimentological and physico-chemical evidence. Montcortès is especially suited for such studies because it has annually laminated sediments (Corella et al. 2010). Also, comparison of pollen and aquatic remains records would be useful to know the magnitude and time lag of the response of the organisms to environmental changes and, in this way, to evaluate their potential usefulness as paleoclimatic indicators.

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