

Crops and weeds from the Estany de Montcortès catchment, central Pyrenees, during the last millennium: a comparison of palynological and historical records

Valentí Rull^{1,3} · Teresa Vegas-Vilarrúbia²

Received: 22 September 2014 / Accepted: 11 March 2015 / Published online: 19 March 2015
© Springer-Verlag Berlin Heidelberg 2015

Abstract We use palynological and historical records to reconstruct the evolution of agricultural practices and their consequences on landscape development in a mid-elevation Pyrenean small lake catchment during the last millennium. A total of ten cultivated plants and eight weed taxa were recognised and their changes in time recorded in detail. Two main phases of agricultural development were identified, A1 (9th–14th centuries AD) and A2 (16th–19th centuries AD). A1 coincided with the medieval climate anomaly and began after a widespread loss of woodland by fire, as manifested in a decline of arboreal pollen from ~60 to ~30 %, which affected mainly the pine woods (~40 to ~10 %). This phase was characterised by cultivation of the cereals *Secale* and *Triticum/Avena*, with *Plantago* as the main weed, alternating with pastures dominated by *Artemisia*, in a ca. 60 year land-use rotation scheme. A1 also coincided with a feudal socio-economic system that replaced the shifting cultivation practices of the earlier inhabitants with intensive agriculture. This type of

land use was interrupted by the onset of the Little Ice Age, coinciding with a great social crisis with wars and plagues, leading to the depopulation of the zone and the recovery of woodlands. The onset of A2 coincided with the Spanish monarchy of the modern age and was characterised by *Cannabis* cultivation, which attained a maximum in the post-modern age, at the transition between feudalism and capitalism. Hemp was mainly used to supply fibre to the Spanish navy and the cultivation of this plant was mandatory until the disestablishment of this navy in AD 1834. After this date, a second socio-economic crisis took place as a consequence of massive emigration to large cities, promoted by the growing industrialisation. The combination of fossil and historical evidence significantly improves palaeoecological reconstructions in areas under heavy human impact, which is useful to enhance historical soundness, to understand how modern landscapes have been shaped and also to disentangle natural causes of ecological change from human ones.

Communicated by J.-L. de Beaulieu.

Electronic supplementary material The online version of this article (doi:10.1007/s00334-015-0525-z) contains supplementary material, which is available to authorized users.

✉ Valentí Rull
vrull@ibb.csic.es

¹ Palynology and Paleoecology Laboratory, Botanic Institute of Barcelona (IBB-CSIC-ICUB), Pg. del Migdia s/n, 08038 Barcelona, Spain

² Department of Ecology, University of Barcelona, Av. Diagonal 643, 08028 Barcelona, Spain

³ Present Address: Institute of Earth Sciences Jaume Almera (ICTJA-CSIC), Lluís Solé Sabaris s/n, 08028 Barcelona, Spain

Keywords Palynology · Historical documents · Agriculture · Landscape shaping · Pyrenees · Last millennium

Introduction

Pollen analysis of lake sediments and peat bogs has been widely used to discover the beginning and further developments of past agricultural practices and the influence of human activities in the shaping of present-day landscapes (Birks and Birks 1980; Fægri and Iversen 1989; Moore et al. 1991). In prehistoric times, palynological evidence has been essential to trace human influence on natural ecosystems, due to a lack of written documents. Recently,

the availability of both pollen and historical records has enabled the achievement of more robust and precise evidence on landscape evolution and its potential drivers, either climatic, human, or both (Ntinou et al. 2013). This is the case of the Estany de Montcortès catchment, which is situated on the southern slopes of the central Pyrenees, where detailed historical and palaeoecological records exist for the last millennium. These different types of evidence have been treated separately and combined to some extent in several studies (Corella et al. 2011, 2012, 2014; Rull et al. 2011; Scussolini et al. 2011), but their potential to show the recent trends of climatic and human influence, as well as their synergies in the shaping of modern landscapes, has not been fully exploited.

The small lake of Montcortès is especially well suited for high-resolution palaeoecological reconstruction due to its annually laminated sediments which extend back to at least 7,000 cal years BP (Corella et al. 2011). To date, the sediments of this lake have been studied on a centennial to millennial scale resolution to reconstruct the ecological dynamics of the lake communities and the surrounding vegetation in relation to climate changes and human activities (Rull et al. 2011; Scussolini et al. 2011). Earlier pollen analyses have shown that during the last millennium, landscape changes have been influenced by both human activities and climate changes (Rull et al. 2011). The full pollen diagram is provided in ESM. In this paper, we focus on the palynological proxies of agricultural practices to study in detail their evolution during the last millennium and to compare these results with historical documents about the region. We identify the pollen from cultivated plants, which have been subdivided into herbaceous crops and tree crops, and from weeds, to follow their quantitative trends in time as a record of the development of cultivation practices during the last millennium, and the potential effects of climatic changes on human practices. Then we quantitatively relate the pollen from cultivated plants and weeds to identify potential associations between these plants. Finally, we compare the results of the pollen analyses with the historical documents that are available for the Pallars region, where the lake is located, to obtain a more complete picture of the human influence on landscape development in the area of Estany de Montcortès. Similar studies in other lakes may lead to a more regional perspective of the connection between environmental and human drivers in the shaping of modern Pyrenean landscapes.

Study site

Estany de Montcortès is in Catalonia on the southern flank of the central Pyrenees in the Pallars Sobirà region at 42°19' N, 0°59' E and 1027 m a.s.l (Fig. 1). The small lake

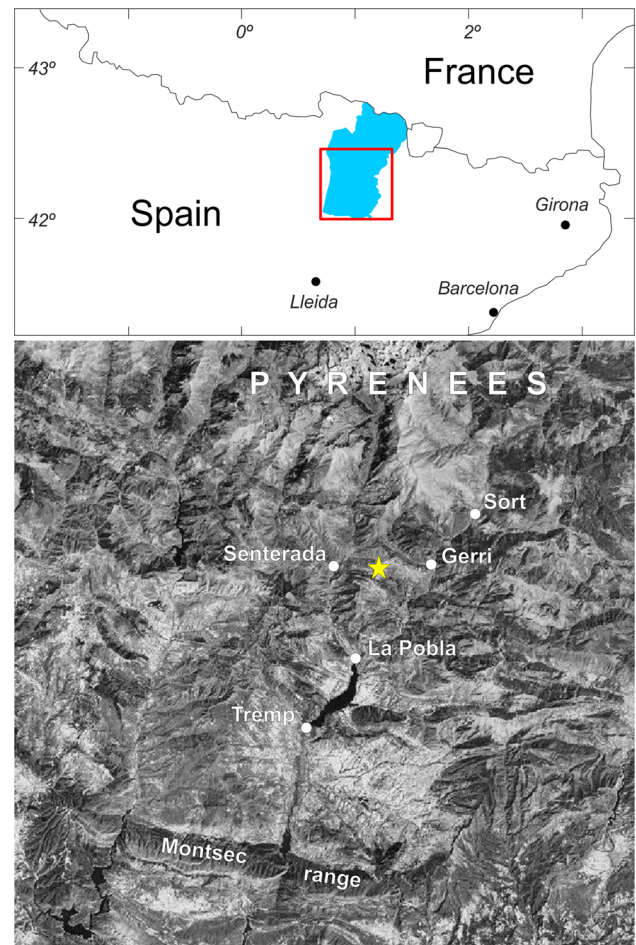
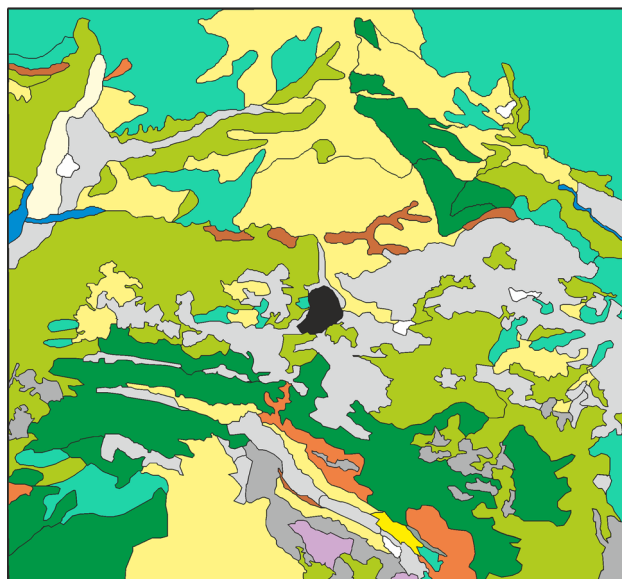


Fig. 1 Map showing the Pallars region (blue area) and the study area (red box). The location of Estany de Montcortès is shown by a yellow star

is roughly kidney-shaped with a diameter between 400 and 500 m and with a maximum water depth of 30 m near the centre (Camps et al. 1976; Modamio et al. 1988). The catchment is small, and the lake is fed mainly by groundwater, with intermittent small creeks and scattered springs. The lake lies in a karst landscape that is characterised mainly by Triassic limestones, marls and evaporites and Oligocene calcareous conglomerates. Triassic ophytes outcrop mainly to the south and Quaternary lake sediments surround the present-day water body (Corella et al. 2011). The annual average air temperature of the area is 10.6 °C, ranging from 1.9 °C in January to 20.3 °C in July. The total annual precipitation is 860 mm, with March being the driest month (46.6 mm) and May being the wettest month (99.2 mm) (Corella et al. 2012). The lake lies near the altitudinal boundary corresponding to the Sub-Montane belt, which in the Pyrenees is situated at approximately 800–1,000 m a.s.l., depending on the local conditions (Vigo and Ninot 1987).

Three major woodland formations occur at the lake catchment (Fig. 2). (1) Mediterranean sclerophyllous woods represented by *Quercus rotundifolia* Lam. woods; (2) Sub-montane deciduous oak woods, which require higher precipitation and are dominated by *Q. pubescens* Willd and *Q. subpyrenaica* Villar; and (3) conifer woods of *Pinus nigra* J. F. Arnold ssp. *salzmannii* (Dunal) Franco. The herbaceous vegetation types are represented by pastures, meadows and crops. The minor vegetation types are scrub, abandoned cultivated land and badlands (Fig. 2). The local flora and vegetation around the lake have been recently described and mapped in detail by Mercadé et al. (2013), who identified 534 species corresponding to 291 genera and 76 families that were organised into 52 vegetation units (biotopes) of the CORINE system (CEC 1991), adapted to Catalonia (Vigo et al. 2005–2008). These



- Conifer woods (*Pinus nigra* ssp. *salzmannii* or *P. sylvestris*)
- Evergreen oak woods (*Quercus rotundifolia* and *Q. subpyrenaica*)
- Deciduous oak woods (*Quercus pubescens*)
- Woodless river margins
- Montane dry thickets (*Amelanchier*, *Buxus*)
- Montane mats of *Arctostaphylos uva-ursi*
- Mesophile or xerophile pastures
- Mowing meadows
- Herbaceous crops (cereals)
- Abandoned crops
- Badlands
- Urban areas (ruderal and cultivated plants)

Fig. 2 Vegetation map of the Montcortès area, according to the CORINE system (CEC 1991). Estany de Montcortès is represented by a black spot at the centre of the map

units include woods, scrub, meadows, pastures, herbaceous vegetation on temporarily or permanently flooded soils, totally or partially submerged aquatic vegetation and habitats created by humans. For a more detailed description, see Mercadé et al. (2013).

The more characteristic habitats created by human activities are former pastures or abandoned fields that are now submitted to intense overgrazing, dry extensive crop fields, deciduous tree clumps and ruderal communities. The main crops include *Hordeum distichum* L. (barley) and *Medicago sativa* L. (alfalfa). The planted trees include *Malus sylvestris* Mill. (apple), *Pyrus communis* L. (pear), several *Prunus* species, *Populus nigra* L. (black poplar) and *Salix alba* L. (white willow). The ruderal communities include nitrophilous grasslands with *Artemisia vulgaris* L. (common wormwood), *Galium aparine* L. (cleavers) and *Urtica dioica* L. (common nettle) and ruderal edges with several *Melilotus* (melilot) species and *Torilis japonica* L. (Japanese hedge parsley) (Mercadé et al. 2013).

Methods

We used the same core (MON04-1A-1K) (Fig. 1) and samples that were previously analysed by Rull et al. (2011), which were processed with standard palynological methods, including NaOH, HCl and HF treatments and density gradient centrifugation without acetolysis (Bennett and Willis 2001). Two *Lycopodium* tablets were added to each sample before chemical processing. The residues were suspended in glycerine, and the slides were mounted with glycerine jelly. Methodological details on pollen analysis and interpretation are provided by Rull et al. (2011) but a reference to the use of the term “fire incidence” seems appropriate in the context of this paper. We use “fire incidence” as a general term as we cannot differentiate between frequency and intensity. Variations in fire incidence thus means changes in either frequency or intensity of these parameters, or both. In this paper, we have introduced some significant improvements in the chronological and taxonomic resolution. A recent study of the Montcortès sediments has provided an upgraded chronology based on a new high resolution age-depth model combining radiocarbon dating with varve counting (Corella et al. 2012). In addition to a more suitable and precise chronology, this new age-depth model provides better estimations of sedimentation rates, thus improving the estimations of influx (units $\text{cm}^{-2} \text{year}^{-1}$). Furthermore, a recently published detailed botanical and phytogeographical study (Mercadé et al. 2013), together with a re-analysis of selected pollen types from the sedimentary record, have significantly enhanced the taxonomic resolution of the identification of pollen from cultivated plants and weeds.

Concerning historical records, the Pallars region has abundant and detailed documentation, some of which has already been published (Esteban 2003; Marugan and Rapolino 2005), while the rest is available in the local archives of the *Arxiu Comarcal del Pallars Sobirà* (regional archive). In this study, we have used both published and unpublished information from these sources, including documents and accounts of land use and distribution, demography, trading, diplomatic affairs and ecclesiastical issues, among others. Palaeoclimatic trends were taken from previous papers using independent physico-chemical proxies, notably sedimentological, lithological and geochemical parameters (Corella et al. 2011, 2012, 2014).

Results and interpretation

The identified cultivated plant and weed taxa are listed in Table 1. Before analysing in detail the chronological trends of these taxa during the last millennium, we will resolve the major landscape changes that occurred in the lake catchment area with emphasis on woodland dynamics in relation to human activities, notably fire, agriculture and climate changes.

Landscape evolution

An important conclusion of the earlier palaeoecological reconstruction (Rull et al. 2011) was that, of the two main types of woodland that were present in the catchment,

conifer woods of *Pinus nigra* ssp. *salzmannii* and evergreen sclerophyllous oak woods dominated by *Quercus rotundifolia* (Mercadé et al. 2013), only the pine woods were significantly affected by human activities during the last millennium, whereas the oak woods showed a more or less constant pollen signal over time. The main trends in landscape evolution are summarised in Fig. 3 using pollen and charcoal records. During the 8th and 9th centuries, coniferous woods dominated the landscape while crops and weeds were almost absent, but an intensification of burning practices (Burning Phase I or BI) led to intensive clearance of woodland (Woodland Clearance 1 or C1) and a great increase in agriculture. As a result, the woods were significantly reduced at the beginning of the 10th century. This situation, here called Agricultural Phase 1 (A1), lasted until the 14th century, coinciding with the medieval climate anomaly (MCA) which was characterised by a warmer and drier climate. The onset of the little ice age (LIA) by the mid 14th century brought a recovery of woodland (R1) and a significant reduction in agriculture, which reached its lowest point around the mid 15th century, when crops and weeds attained a minimum that was similar to that of the 8th and 9th centuries. In this case, climate would have been a decisive factor, as the recovery of the woodland coincided with the onset of a colder climate with a higher frequency of heavy rainfall events, suggesting wetter conditions (Corella et al. 2014). Increased moisture could have favoured expansion of woodland (R1), whereas colder conditions would have caused land abandonment from the migration of human populations to lower elevations (Rull et al. 2011). A second

Table 1 Cultivated plants and weeds identified in Lake Montcortès sediments using pollen and botanical data

| Type | Genera/species | Common names |
|-------------------------|-------------------------------|---|
| Cultivated trees | <i>Castanea sativa</i> Mill. | Castanyer, castaño, sweet chestnut |
| | <i>Cupressus</i> -t | (Xiprer, ciprés, cypress) |
| | <i>Juglans regia</i> L. | Noguera, nogal, walnut |
| | <i>Olea europaea</i> L. | Olivera, olivo, olive tree |
| | <i>Prunus avium</i> -t | (Cirerer, cerezo, cherry) |
| Cultivated herbs | <i>Cannabis sativa</i> L. | Cànem, càñamo, hemp |
| | <i>Hedysarum</i> L. | Pipirigall, zulla, sweetvetch |
| | <i>Linum</i> L. | Lli, lino, flax |
| | <i>Secale cereale</i> L. | Sègol, centeno, rye |
| Weeds | <i>Triticum/Avena</i> | Blat/civada, trigo/avena, wheat/oat |
| | <i>Artemisia</i> L. | Artemísies, ajenjos, wormwoods |
| | <i>Centaurea</i> L. | Centàuries, centaureas, knapweeds |
| | <i>Chenopodium</i> L. | Blets, cañizos, goosefoots |
| | <i>Convolvulus</i> L. | Corretjoles, correhuelas, bindweeds |
| | <i>Echium vulgare</i> L. | Llengua de bou, vivorera, viper's bugloss |
| | <i>Plantago lanceolata</i> L. | Plantatge, llantén, plantain |
| | <i>Polygonum aviculare</i> L. | Passacamins, centinodia, knotgrass |
| <i>Rumex acetosa</i> L. | Agrella, acedera, red sorrel | |

Common names are in Catalan, Spanish and English, respectively

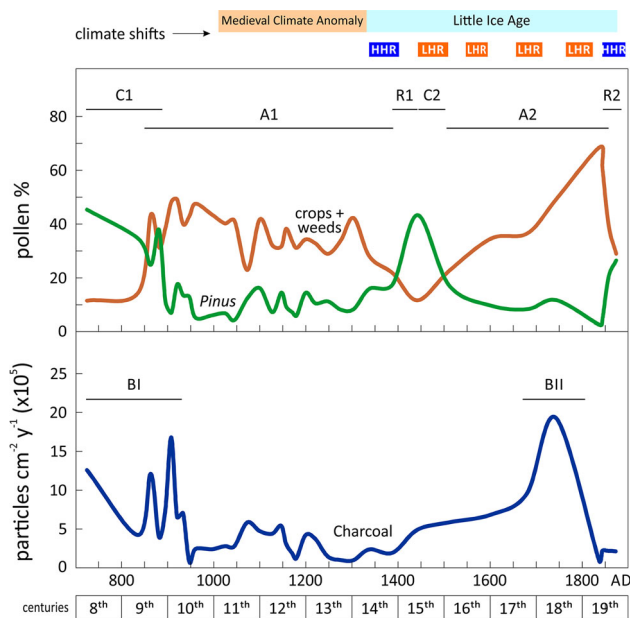


Fig. 3 Pollen percentages of *Pinus*, as a representative of coniferous woods, and agricultural indicators (crop + weed taxa) compared with charcoal influx, as a proxy for fire incidence. The main climatic events are indicated above, according to Corella et al. (2012, 2014). HHR high frequency of heavy rainfall episodes, LHR low frequency of heavy rainfall episodes

phase of woodland clearing (C2) began at the end of the 15th century, but this time the burning was not especially intense, although it showed a subtle intensification between the 14th and 15th centuries. Again, the climate seems to have been more influential, as the reduction in woodland and increase in crops coincided with a phase of reduced frequency of heavy rainfall, suggesting a drier climate. This situation of woodland decline with crop and weed increases persisted until the beginning of the 19th century and is here called Agricultural Phase II (A2). During this phase, crops and weeds experienced a continuous increase. Burning practices were moderate until the end of the 17th century, when a second burning intensification (Burning Phase II or BII) peaked in the mid 18th century, leading to a significant decline in arboreal pollen from ~ 70 to ~ 20 % (Rull et al. 2011). Crops and weeds peaked in the middle of the 19th century and then decreased abruptly at its end, coinciding with a similarly rapid recovery of woodland (R2). This recovery coincided with a second event of increased heavy rainfall frequency, and thus a wetter climate, combined with the absence of burning practices, probably due to a generalised abandonment of land by the population, who migrated to the cities during the industrial revolution (Rull et al. 2011).

In summary, two main phases of agricultural expansion were recorded in the Estany de Montcortès catchment in the last millennium: A1, between the 10th and 14th centuries, and A2 between the 16th and 19th centuries. The

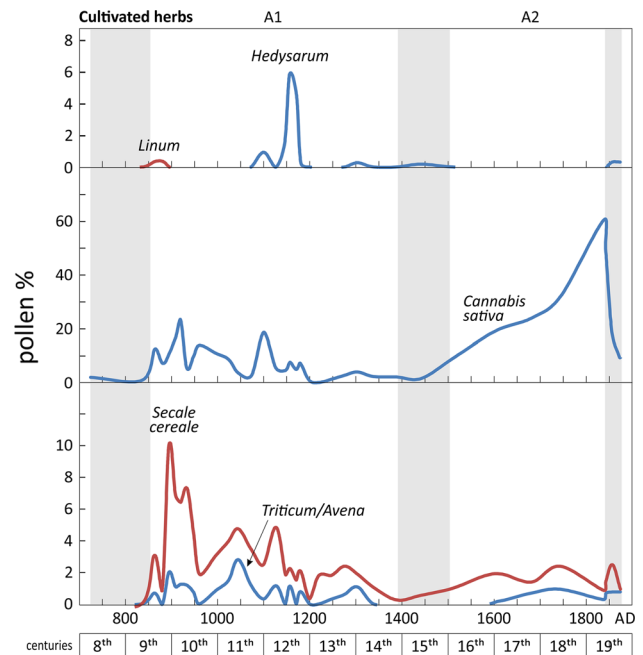


Fig. 4 Pollen percentages of cultivated herbs

first phase began after intensive woodland clearance by fire and coincided with the MCA, whereas the second one began after woodland clearance linked to aridification and burning and coincided with the LIA. In the following section, Agricultural phases A1 and A2 are analysed in detail based on the identified crop and weed taxa (Table 1).

Agricultural development

The crop and weed taxa are subdivided for clarity into cultivated herbs, cultivated trees and weeds. Cultivated herbs show clear differences between A1 and A2 (Fig. 4). All of the herbs were present in A1 with *Cannabis sativa* (hemp) and *Secale cereale* and *Triticum/Avena* (cereals) being dominant. *Secale cereale* (rye) peaked at the beginning of the 10th century and significantly decreased afterwards. In general, the abundance of cultivated herbs decreased between the 13th and 14th centuries. *Linum* spp. (flax) appeared only in the 9th century, while *Hedysarum* spp. (sweetvetch) abundance was significant only during the 12th century. During A2, all of the cultivated herbs remained at low values except for hemp, which maintained an increase, peaking to ~ 60 % in the middle of the 19th century and abruptly decreasing afterwards (Fig. 4).

The records of cultivated trees are also clearly distinct between A1 and A2 (Fig. 5). In A1, *Castanea sativa* (sweet chestnut) was dominant, although it decreased between the 10th and 12th centuries when *Cupressus*-type slightly increased. The difficulty of differentiating *Cupressus* and *Juniperus* pollen, however, prevents us from being certain

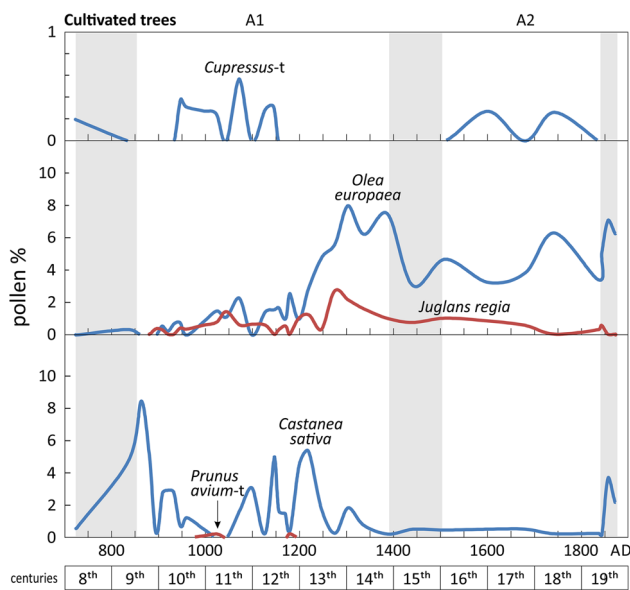


Fig. 5 Pollen percentages of cultivated trees

that this pollen type corresponds to cypress. *Olea europaea* (olive) and *Juglans regia* (walnut) abundances were low during most of this phase (A1) but significantly increased at the end, in the 13th and 14th centuries, coinciding with the general decrease of cultivated herbs (Fig. 3). *Prunus avium*-type appeared sporadically during the 11th and 12th centuries. Cherry may occur naturally in the Montortès area, hence its presence is not necessarily an indication of its cultivation. During the second phase (A2), only *Olea* showed significant values, although olive was not as abundant as it was at the end of A1, due to a decrease coinciding with the previously mentioned woodland recovery of the 15th century (Fig. 3).

Weeds were mostly concentrated during phase A1, in which *Plantago lanceolata* (plantain) and *Artemisia* spp. (wormwoods) were clearly dominant (Fig. 6). The remaining weed taxa were around or below 1 %, except for *Chenopodium* spp. (goosefoots), which were slightly more abundant. In general, weeds were present throughout phase A1 except for *Centaurea* spp. (knapweeds) and *Echium vulgare* (viper's bugloss), which showed local and low abundance in isolated peaks. Remarkably, *Plantago* and *Artemisia* exhibited opposite trends in the alternation of their respective maxima and minima during A1 (Fig. 6). During Phase A2, only *Plantago*, *Artemisia* and *Chenopodium* were present continuously but always with significantly lower values (<5 %) compared to A1. It is worth mentioning that goosefoots were the only weeds with similar values in A1 and A2.

In summary, Phase A1 (9th–14th centuries) was characterised by *Cannabis*, cereals and *Castanea* cultivation together with the maximum abundance and diversity of weeds, since all of the recorded weed taxa were present during this phase. At the end of this phase in the 13th and

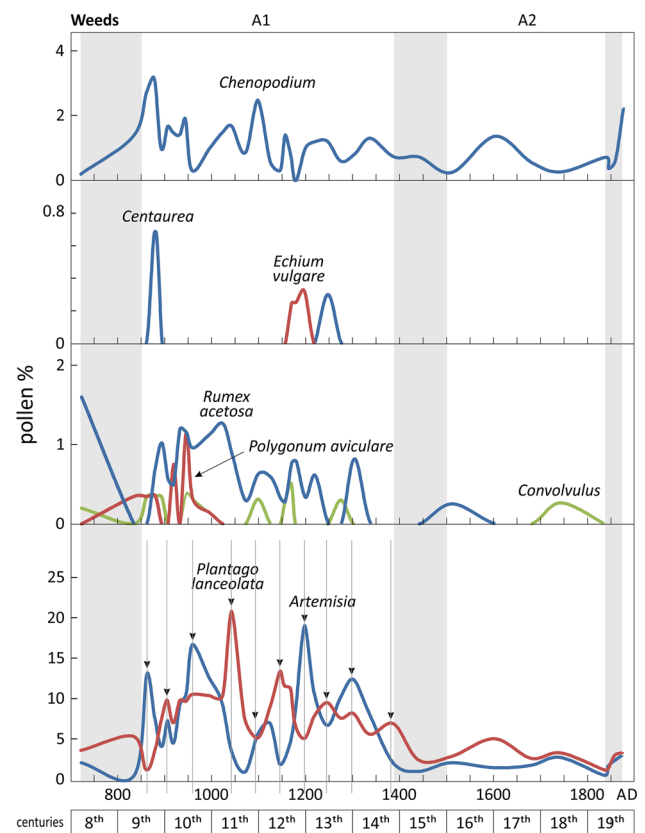


Fig. 6 Pollen percentages of weeds. Arrows indicate events of opposite trends between *Plantago lanceolata* (plantain) and *Artemisia* spp. (wormwoods)

14th centuries, herb crops decreased, and the tree crops *Olea* and *Juglans* dominated the scene without significant changes in weeds. All the crop and weed taxa significantly decreased during the ensuing woodland recovery associated with a wetter climate and human emigration to the lowlands in the 15th century. During Phase A2 in the 16th–mid 19th centuries, herbaceous crops were dominated by *Cannabis*, and tree crops consisted mainly of *Olea* groves; weeds underwent a drastic reduction in both abundance and diversity. The maximum *Cannabis* abundance was recorded in the mid 19th century and then abruptly decreased. Previous studies suggest the possibility of *Cannabis* retting in the waters of Estany de Montcortès as the main source for pollen in its sediments during this phase, rather than cultivation (Rull and Vegas-Vilarrúbia 2014).

Crop-weed associations

In this section, we attempt to establish quantitative relationships among the recorded taxa that could be indicative of coincidence in time, thus suggesting potential associations between crops and weeds. Statistical correlations for the more abundant taxa are shown in Table 2. Among

Table 2 Pearson product-moment correlation coefficients among the recorded crop and weed species using untransformed percentages

| | <i>Cannabis</i> | <i>Secale</i> | <i>Triticum/Avena</i> | <i>Olea</i> | <i>Juglans</i> | <i>Castanea</i> |
|--------------------|-----------------|---------------|-----------------------|-------------|----------------|-----------------|
| <i>Artemisia</i> | −0.296 | 0.115 | 0.004 | −0.226 | 0.261 | 0.278 |
| <i>Plantago</i> | −0.430* | 0.400 | 0.524** | −0.299 | 0.191 | −0.140 |
| <i>Chenopodium</i> | −0.116 | 0.192 | 0.149 | −0.342* | −0.135 | 0.511** |
| <i>Rumex</i> | −0.268 | 0.418* | 0.345* | −0.564** | −0.095 | −0.140 |

Taxa with sporadic appearances (i.e. high frequency of null values) are not considered

Significance level * 0.05; ** 0.01

herbaceous crops, the more significant correlations ($\alpha < 0.01$) are between *Triticum/Avena* and *Plantago lanceolata*. In addition, significant ($\alpha < 0.05$) correlations were found between *Secale cereale* and *Triticum/Avena* with *Rumex acetosa* (sorrel). *Cannabis sativa* did not show significant correlations with any of the weeds that were recorded in the pollen analysis. Among the tree crops, the greatest significant correlation ($\alpha < 0.01$) occurred between *Castanea sativa* and *Chenopodium* spp. No weed was correlated with *Juglans regia*, and two weeds were negatively correlated with *Olea europaea*, namely *R. acetosa* ($\alpha < 0.01$) and *Chenopodium* ($\alpha < 0.05$). It is noteworthy that *Cannabis* was not associated with any weed, and *Artemisia* was not correlated with any crop.

This correlation analysis suggests that *P. lanceolata* and *R. acetosa* were the main weeds that were associated with cereal crops and that *Chenopodium* spp. were related in some way to *Castanea* cultivation. No particular weed seemed to be associated with *Cannabis*, *Olea* or *Juglans* cultivation. *Artemisia* seems not to have been a weed in the types of crops that were recorded in the Estany de Montcortès catchment during the last millennium.

Comparison with historical records

Historical records were subdivided into three main periods, namely the Middle Ages, modern age and post-modern period. In this section, we summarise the main historical events with emphasis on land use, and we attempt to correlate these trends with our palynological record (Fig. 7). Historical trends are based on Madoz (1845–1850); Andreu (1981); Delgado (1994); Sanz (1995); Esteban (2003); Marugan and Oliver (2005); Bringué (2005); Farràs (2005); Balasch et al. (2008); Rull et al. (2011); Rull and Vegas-Vilarrúbia (2014) and our own investigations of the local archives of the *Arxiu Comarcal del Pallars Sobirà*.

Middle Ages

Based on both historical and pollen records, the part of the middle ages that was studied here has been subdivided into three phases:

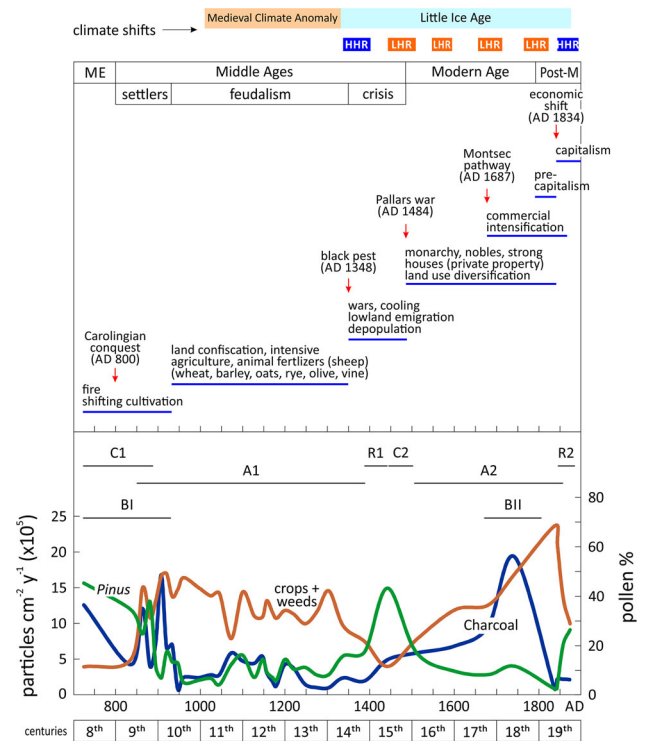


Fig. 7 Comparison between historical and pollen records

Phase I (settlers, BI-C1)

Our record begins in the 8th century, when the Montcortès area was close to the border between the Muslim empire which was expanding from the south and the Carolingian empire to the north. By AD 800, this region was conquered by the Carolingians and was overpopulated by a mixture of Carolingians, indigenous Iberian people and remnants of the Roman and Muslim cultures, as well as people coming from the south to escape from the Muslim northward expansion. The land was subdivided into small autonomous properties that were ruled by communities of freemen (settlers), which were grouped in small villages. The property documents were issued by the church, mainly the monastery of Gerri, or the nobles, the Counts of Pallars, who received a production-dependent variable income from the settlers. Burning was commonly done to prepare

the land for shifting cultivation, the dominant agricultural practice at the time, but woodlands were not entirely removed and were intensively used to obtain wood, litter, fruits and other products. The stock-raising, mainly of sheep, seems to have been less developed than was the growing of crops, and vertical transhumance between the lowlands in winter and highlands in summer within the same valley was a common practice.

In the Montcortès area, as shown by pollen records, this transitional phase comprising the 8th and 9th centuries corresponded to Burning Phase I (BI), characterised by a peak in fire incidence, a dramatic reduction in woodland and the start of pollen records from cultivated plants, notably *Secale cereale*, *Cannabis sativa* and *Linum*. A peak of *Artemisia*, commonly associated with ruderal vegetation communities and grazed lands (Behre 1981), may reflect the beginning of livestock farming.

Phase II (feudalism, A1)

In the 10th century, the feudal system was consolidated, and the settlers' properties were confiscated by the nobility and the church, who demanded tax payments and the delivery of surplus production, in order for the people to continue to live in and use the confiscated lands. In the Pallars region, however, feudalisation was not complete, and a number of settler communities remained. Shifting cultivation and fire were replaced by a more controlled and permanent land exploitation involving the use of animal fertilisers. Due to the lack of efficient transport, it was common to combine crops and pastures in the same area to assure a permanent fertiliser supply. This type of land use underwent a remarkable expansion during the 10th and 11th centuries, especially on wet areas, such as river margins, lake shores and wetlands, and lasted until the 13th century. The more frequent crops were cereals (*Triticum*, *Hordeum*, *Avena* and *Secale*), *Olea* and *Vitis* (grape), depending on the particular characteristics of each site. A crop rotation alternating grains and legumes was usual to prevent soil impoverishment. *Olea* was not documented in the Pallars region until the 11th century, and olive cultivation was not promoted until a century later. Olive does not tolerate low temperatures and it was cultivated mostly in the southern lowlands; the area around Estany de Montcortès was near the northern boundary of olive cultivation during the 11th and 12th centuries. Another important cultivated tree during that time in the Pallars region, mainly on riverbanks, was *Juglans regia*, which gave its name *noguera* to the more important rivers of the zone. During the middle ages, *Vitis* cultivation was usual in Pyrenean localities that were above 1,000 m elevation. The existence of vineyards has been documented in the Pallars region since the 9th century, and they seem to have been

important in several places around Montcortès during the 11th century at Gerri de la Sal and the 14th century at Sort. Estany de Montcortès was also used for fishing between the 11th and 13th centuries. The coexistence of larger territories under the control of the church and the counts with smaller areas that were ruled by autonomous settlers led to a mixed intensive and extensive cattle farming with both vertical and horizontal transhumance and frequent disputes over land ownership and boundaries.

The pollen record that was studied here roughly agrees with these historical observations and adds additional insights. Indeed, fire incidence is notably reduced compared to the former phase, and crops and weeds show a consistent and maintained expansion of farming, especially of cereals and *Cannabis*, between the 10th and 13th centuries. Interestingly, *Cannabis* is not mentioned in the historical records, but its relevance in pollen records is clear in terms of both continuity and percentage (10–20 %). There is evidence of widespread *Cannabis* cultivation in other pre-Pyrenean areas (Riera et al. 2004, 2006). This agricultural expansion occurred during the MCA when the climate was warmer and drier than that of today. Slightly higher temperatures would have favoured cultivation, and drier climates would have been compensated by the availability of a permanent water source; the lake did not dry out, as shown by paleolimnological evidence (Scussolini et al. 2011). Another discrepancy between the historical and pollen records is the occurrence of legume cultivation. In our pollen records, the pollen of legumes (*Hedysarum*) has been recorded only during a short interval in the 12th century, coinciding with a minimum of cereal pollen, which would be consistent with crop rotation only in this particular time interval. However, another type of rotation seems evident in the pollen record, as suggested by the alternation of *Plantago* and *Artemisia* during this phase. As has been previously shown, *Plantago* was the main weed that was associated with cereal cultivation, whereas *Artemisia* did not show any significant correlation with any of the cultivated plants. The well-known nitrophilous character of *Artemisia* and its usual association with ruderal communities and grazed sites (Behre 1981) suggest rotation between cereal cultivation and pastures as another strategy of soil fertilisation. A closer examination reveals that this alternation occurred every ~40 to ~70 years, with an average of ~60 years. The occurrence of a continuous background signal from both *Plantago* and *Artemisia*, note that their pollen never disappears, suggests that crop growing and cattle raising were performed at the same time in the catchment, possibly in a mosaic pattern. In this case, the peaks of either *Plantago* or *Artemisia* could be indicative of the human activity near the lake, and the background signal might represent more distant places. Indeed, modern pollen sedimentation studies have shown

that the pollen of both *Plantago* and *Artemisia* may be well dispersed, giving a low to moderate regional signal (Court-Picon et al. 2006).

The remarkable increase in *Olea europaea* pollen that was recorded in the 13th century contrasts with the historical information, according to which olives were cultivated only in the southern lowlands, below Estany de Montcortès. However, recent studies on modern pollen sedimentation along elevational gradients in the Pyrenees have shown that olive pollen can be found in significant amounts at high altitudes up to at least 2,600 m elevation (Cañellas-Boltà et al. 2009). Therefore, the *Olea* curve could be used as a regional signal of the expansion of *Olea* cultivation early in the 13th century. That of *Juglans regia* would be similar. *Vitis vinifera* exhibits opposite trends to *Olea*, as historical documents report its usual cultivation in the Pyrenees above 1,000 m since the 9th century, but vine pollen is absent from the entire Montcortès record, which is probably due to the absence of vineyards around the lake, as well as the low dispersion ability of *Vitis* pollen from lowland localities, where grapevine cultivation is well documented as at Gerri and Sort.

Phase III (medieval crisis, R1-C2)

A significant crisis occurred during the 14th and 15th centuries, between AD 1350 and 1487, coinciding with wars, a devastating “black death” plague epidemic in 1348, and the LIA cooling. In the Pallars region, the higher and poorer parts of the valleys were abandoned and experienced a significant depopulation, which led to the disappearance of many villages and the concentration of the population in larger, lowland towns. It has been estimated that one third of the population nuclei disappeared, with the consequent abandonment of their respective lands, crops, pastures, woods and natural resources. Some historians interpret such a crisis not only in terms of external constraints, such as climate deterioration or societal calamities, but also as the natural consequence of the development of the feudal system, which ended in a socio-economical and ecological collapse.

The palynological footprint of this crisis is a decrease of all of the cultivated plants and weeds and a relatively rapid recovery of coniferous woods, likely due to decreasing human pressure. Cereal cultivation and livestock raising probably disappeared from the lake catchment as suggested by zero or near-zero values for *Secale* and *Triticum/Avena*, as well as the weeds *Plantago* and *Artemisia*. *Olea* also decreased but remained in moderate percentages (4–6 %), probably as a consequence of pollen dispersal from lowlands. As previously suggested, cooler and wetter climatic conditions that are linked to the onset of the LIA could have been involved.

Modern Age (A2-BII)

With the medieval crisis, feudalism ended as a political system and was replaced by a monarchy. The county of Pallars was conquered by the army of the King of Aragon in the Pallars war (1484–1487) and transformed into a marquisate. From this point, a trend towards the privatisation of natural resources began. This process was led by the so-called “strong houses”, which originated in the freemen communities that persisted during the time of feudalism, which were owned by families that were progressively enriched by absorbing the properties of others (“poor houses”) who were unable to pay the constantly increasing taxes. As a result, the feudal system, based on the communal (although not equalising) property concept, was progressively replaced by an agrarian individualism leading to an oligarchic society. The recovery from the medieval crisis was relatively rapid, and by the 16th century the number of houses in the marquisate had multiplied by 2.5; however, the high population levels of the 11th to 13th centuries were never attained again. A significant immigration proceeded from Gascony (now France) to the north. This period is characterised by the constant conflicts between the “strong” families, defenders of private property, and the nobility, dukes and marquises linked to the Crown, as the heirs of the former communal society.

During modern times, the main crop by far was *Triticum*, followed by *Hordeum* and *Avena*. *Triticum spelta* (spelt) and *Panicum miliaceum* (broomcorn millet) are also mentioned, but they were not significant. Concerning *Olea*, *Vitis* and pastures, there is a clear distinction between the northern and southern territories. For climatic reasons, olive groves and vineyards were located mainly in the southern lowlands, although *Vitis* reached further to the north than *Olea*. In contrast, pastures, and as a consequence, livestock were more abundant in the north. From the 15th to the 18th centuries, there was a clear trend towards agriculture and livestock diversification. Pastures, which in the past were almost restricted to riverbanks and wetlands, underwent a significant expansion that was linked to technological improvements in water transport and irrigation. Consequently, stock raising with sheep, goats, pigs and cattle also increased. Legume cropping for commercial purposes also increased and wheat was progressively replaced by rye. Vineyards almost disappeared from the northern area by the end of the 18th century. The more characteristic feature of this period was the great development of pastures and livestock raising, which had profound social and economic consequences. Smaller livestock, mainly sheep, were used for meat and wool, while cattle were dedicated mainly to cultivation and transport. Despite the existence of private property, the exploitation model of livestock was communally based,

and any activity in this sense was regulated by strict rules. Disputes about the boundaries, rights of use and rights of way of pastures were frequent between nobility and private owners and also between the owners themselves. The exploitation of woodlands, however, was carried out in a particular fashion and always for subsistence reasons. The main product was wood for building. The renting of pasture and woodland for exploitation was common practice. Other natural resources were salt, lime, iron and other minerals and the products of hunting and fishing. In other areas of the southern Pyrenees, notably on highlands, mining and related activities were an important activity during the late Holocene, which caused significant woodland modifications (Pèlachs et al. 2009). So far, we have not found evidence of similar practices in the Montcortès area, but this might be addressed in future studies. Commerce has been important since 1687, when a pathway through the Montsec mountains was opened. This related to the decline of the mountain vineyards, as wine began to be obtained from the southern lowlands.

The Montcortès pollen record does not match with the regional scenario of growing crops and raising livestock that is provided by the above historical records. Cereal cultivation and grazing practices did not recover at the lake catchment. The only cultivated plant showing a significant and lasting increase was *Cannabis*, coinciding with a maintained woodland clearing and a moderate increase in fire practices that abruptly accelerated at the end of the 17th century, culminating in a second burning peak (BII). This acceleration in fire incidence coincided with the opening of the Montsec pathway and the intensification of trade with the southern lowlands, although a clear relationship has not yet been established between these. *Cannabis* was continuously grown in large amounts, but there are no historical records of *Cannabis* cultivation in the lake catchment at that time. It has been suggested that Estany de Montcortès was an important place for hemp retting, an essential step for obtaining fibre from this plant, requiring water immersion. The maintained *Cannabis* increase coincided with the spectacular development of the Spanish royal navy and the strong bias of the country's agriculture towards *Cannabis* cultivation and retting to supply the necessary fibre for ropes and sails. Probably, the Montsec pathway may have been important for transporting hemp fibre and possibly wood from the Montcortès area to the lowland manufacturing centres.

Post-modern period

The 19th century was the transition between a feudal world and a capitalist one with the boundary at AD 1834. The period before this date is known as the pre-capitalist or pre-industrial period.

Pre-capitalism (A2)

During that time, the Pallars region was comparatively isolated due to the absence of a well-developed road system, which led to the development of a diversified subsistence economy system to increase self-sufficiency. Concerning land use, two well-differentiated areas existed: the lake basin, or the southern lowlands, and the mountains to the north. The location of Estany de Montcortès was between these areas. The basin was primarily agricultural. Olive groves and vineyards expanded at the expense of cereal crops and woods, and oil and wine surplus production was sold in the market. In contrast, cereals would often be imported from neighbouring areas. To improve cereal production, crop rotation was sometimes done by alternating wheat with legumes and hemp. In the mountains, the raising of sheep, cattle and horses and woodland exploitation were the dominant practices. The internal cattle markets were very active. Wood was sold mainly to northern French territories, using the rivers as a means of transport. Small-scale agriculture growing legumes, potatoes and forage and raising poultry and pigs was also done for subsistence. A number of pre-industrial manufacturing activities that were associated with these land use practices reinforced the self-subsistence economic character of this period. The main energy sources were rivers.

Again, our Montcortès pollen record shows a remarkable difference from the regional picture, as *Cannabis* was still increasing, and the other cultivated plants were virtually absent, except for *Olea*, which exhibited a pollen increase coinciding with the historical reports of the increased cultivation of olives in the lowlands. Once more, *Vitis* pollen is absent, probably for pollen dispersal reasons. *Cannabis* attained a maximum close to the date of the political and economic change from feudalism to capitalism (AD 1834), and coinciding with the start of the dismantling of the royal navy. Before this date, *Cannabis* cultivation was mandatory for land tenants, who were forced to sell most of the hemp harvest to the royal navy. The *Cannabis* increase also coincided with the period of maximum development of shipbuilding in Barcelona and at other nearby shipyards (AD 1750–1775), which was a phase of general economic prosperity and intensification of commerce with America. Once more, *Cannabis* cultivation at the lake catchment is not documented historically at that time, but active hemp fields existed in the surrounding lowlands as at La Pobla, Gerri de la Sal and Senterada around the peak of *Cannabis* pollen at Montcortès in the 1840s.

Capitalism (R2)

Since the establishment of the capitalist system, the subsistence economy went into crisis, and the Pallars

population diminished by one third, partly a manifestation of the general European agricultural crisis of the mid 19th century together with the consequences of some local conditions and events, including unfavourable climates and crop pests. For example, a phase of unfavourable climate has been documented during the second half of the 19th century that significantly affected crops and culminated with the floods of AD 1907. Socially, the main consequence of this crisis was the emigration of part of the Pallars population to Barcelona and the surrounding cities, attracted by the industrial activity, and abroad, notably to South America. During this period, despite the economic and demographic crisis, a modernisation process began which affected both infra-structure and society, including, for example, the remarkable improvement in communications via road and rail, as well as significant urban modernisation.

The socio-economic crisis that is documented in the historical records is paralleled by a dramatic decrease of *Cannabis* cultivation and/or retting after AD 1834, a minimum of fire incidence and the rapid recovery of conifer woods, probably because of the massive abandonment of the Pallars region. The palaeoclimatic record also shows a phase of high frequency of heavy rainfall events (HHE) at the same time as the floods that are documented in the historical records.

Final remarks

The combined use of pollen and historical records has notably improved our knowledge of the recent history of the Estany de Montcortès catchment compared to the studies that have been published so far, especially in terms of the influence of agricultural and other human practices in the shaping of modern landscapes. However, there is still much room for improvement, particularly in terms of historical and palaeoecological precision, as well as in terms of spatial scope. Further studies should focus on the possibility of enhancing the resolution of palaeoecological reconstruction using annual laminations and the development of similar comparative studies in other Pyrenean and pre-Pyrenean lakes to obtain a more regional picture of recent landscape development and of the potential drivers that are involved. Of particular interest is the high-resolution study of recent centuries to disentangle natural events such as some climatic changes from the ecological changes resulting from human activities.

Acknowledgments This work was supported by project MONTCORTES-500, which was funded by the Ministry of Economy and Competitiveness (CGL2012-33665). The authors are grateful to the *Arxiu Comarcal del Pallars Sobirà*, especially to the director, Carme Maria Marugan, for her help with historical documentation.

References

- Andreu M (1981) La financiación de la industria naval en Barcelona (1745–1760). *Pedralbes* 1:267–294
- Balash C, Becat J, Marugan C et al (2008) Les riudes del segle XX al Pallars Sobirà: 1907, 1937 i 1982. Generalitat de Catalunya, Departament de Cultura i Mitjans de Comunicació, Barcelona
- Behre K-E (1981) The interpretation of anthropogenic indicators in pollen diagrams. *Pollen Spores* 23:225–245
- Bennett KD, Willis KJ (2001) Pollen. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments: terrestrial, algal, and siliceous indicators, vol 3. Kluwer, Dordrecht, pp 5–32
- Birks HJB, Birks HH (1980) Quaternary palaeoecology. Arnold, London
- Bringué JM (2005) L'edat moderna. In: Marugan CM, Rapalino V (eds) Història del Pallars. Dels orígens als nostre dies. Pagès Editors, Lleida, pp 87–120
- Camps J, Gonzalvo I, Güell J et al (1976) El lago de Montcortès, descripción de un ciclo anual. *Oecol Aquat* 2:99–100
- Cañellas-Boltà N, Rull V, Vigo J, Mercadé A (2009) Modern pollen-vegetation relationships along an altitudinal transect in the Central Pyrenees (southwestern Europe). *Holocene* 19(1):1,185–1,200
- CEC (Commission of the European Communities) (1991) CORINE biotopes manual—habitats of the European Community. Office for Official Publications of the European Communities, Luxembourg
- Corella JP, Moreno A, Morellón M et al (2011) Climate and human impact on a meromictic lake during the last 6000 years (Montcortès Lake, Central Pyrenees, Spain). *J Paleolimnol* 46:351–367
- Corella JP, Brauer A, Mangili C et al (2012) The 1.5-ka varved record of Lake Montcortès (southern Pyrenees, NE Spain). *Quat Res* 78:323–332
- Corella JP, Benito G, Rodríguez-Lloveras X et al (2014) Annually-resolved lake record extreme hydro-meteorological event since AD 1347 in NE Iberian Peninsula. *Quat Sci Rev* 93:77–90
- Court-Picon M, Butler A, De Beaulieu JL (2006) Modern pollen/vegetation/land-use relationships in mountain environments: an example from the Champsaur valley (French Alps). *Veget Hist Archaeobot* 15:151–168
- Delgado JM (1994) La indústria de la construcció naval catalana (1750–1850). *Drassana* 2:34–39
- Esteban A (2003) La humanización de las altas cuencas de la Garona y las Nogueras (4500 aC–1955 aC). Organismo Autónomo de Parques Nacionales, Ministerio de Medio Ambiente, Madrid
- Fægri K, Iversen J (1989) Textbook of pollen analysis, 4th edn. In: Fægri K, Kaland PE, Krzywinski K (eds.) Wiley, Chichester
- Farràs F (2005) El Pallars contemporani. In: Marugan CM, Rapalino V (eds) Història del Pallars. Dels orígens als nostre dies. Pagès Editors, Lleida, pp 121–144
- Madoz P (1845–1850) Diccionario geográfico-estadístico-histórico de España y sus posesiones de ultramar. Estudio Literario-Tipográfico de P. Madoz y L. Sagasti, Madrid
- Marugan CM, Oliver J (2005) El Pallars medieval. In: Marugan CM, Rapalino V (eds) Història del Pallars. Dels orígens als nostre dies. Pagès Editors, Lleida, pp 45–86
- Marugan CM, Rapalino V (2005) Història del Pallars. Dels orígens als nostre dies. Pagès Editors, Lleida
- Mercadé A, Vigo J, Rull V et al (2013) Vegetation and landscape around Lake Montcortès (Catalan pre-Pyrenees) as a tool for palaeoecological studies of lake sediments. *Collect Bot* 32:87–101
- Modamio X, Pérez V, Samarra F (1988) Limnología del lago de Montcortès (ciclo 1978–1979). *Oecol Aquat* 9:9–17
- Moore PD, Webb JA, Collinson ME (1991) Pollen analysis. Blackwell, Oxford

- Ntinou M, Badal E, Carrión Y, Menéndez JL, Ferrer R, Pina J (2013) Wood use in a medieval village: the contribution of wood charcoal analysis to the history of land use during the 13th and 14th centuries A.D. at Pobla d'Ifach, Calp, Alicante, Spain. *Veget Hist Archaeobot* 22:115–128
- Pèlachs A, Nadal J, Soriano JM, Molina D, Cunill R (2009) Changes in Pyrenean woodlands as a result of the intensity of human exploitation: 2000 years of metallurgy in Vallferrera, northeast Iberian Peninsula. *Veget Hist Archaeobot* 18:403–416
- Riera S, Wansard G, Julià R (2004) 2000-year environmental history of a karstic lake in the Mediterranean Pre-Pyrenees: the Estanya lakes (Spain). *Catena* 55:293–324
- Riera S, López-Sáez JA, Julià R (2006) Lake responses to historical land use changes in northern Spain: the contribution of non-pollen palynomorphs in a multiproxy study. *Rev Palaeobot Palynol* 141:127–137
- Rull V, Vegas-Vilarrúbia T (2014) Preliminary report on a mid-19th century Cannabis pollen peak in NE Spain: historical context and potential chronological significance. *Holocene* 24:1,378–1,383
- Rull V, González-Sampériz P, Corella J et al (2011) Vegetation changes in the southern Pyrenean flank during the last millennium in relation to climate and human activities: the Montcortès lacustrine record. *J Paleolimnol* 46:387–404
- Sanz V (1995) *D'artesans a proletaris: La manufactura del cànem a Castelló, 1732–1843*. Diputació de Castelló, Castelló
- Scussolini P, Vegas-Vilarrúbia T, Rull V et al (2011) Middle and late Holocene climate change and human impact inferred from diatoms, algae and aquatic macrophyte pollen in sediments from Lake Montcortès (NE Iberian Peninsula). *J Paleolimnol* 46:369–385
- Vigo J, Ninot J (1987) Los Pirineos. In: Peinado M, Rivas-Martínez F (eds) *La vegetación de España*. Universidad de Alcalá de Henares, Madrid, pp 349–384
- Vigo J, Carreras J, Ferré A (2005–2008) *Manual dels hàbitats de Catalunya*, vol 1–8. Departament de Medi Ambient i Habitatge, Generalitat de Catalunya, Barcelona