Universitat Autònoma de Barcelona

Mid-Holocene vegetation history, climate change and Neolithic landscape transformation. Archaeopalynology in La Draga and Lake Banyoles (NE Iberian Peninsula)

Jordi Revelles López

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PhD Thesis

Mid-Holocene vegetation history, climate change and Neolithic landscape transformation. Archaeopalynology in La Draga and Lake Banyoles (NE Iberian Peninsula)

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ABSTRACT/ RESUM/ RESUMEN

Abstract

Landscape evolution was mostly controlled by climate change until the Neolithisation (after *ca*. 7.4-7.0 cal ka BP in the Iberian Peninsula) when human impact started to interfere in the natural development of vegetation. Thus, the Neolithisation process involved significant socioeconomic and ecological transformations. Changes in food production, in natural resource management and in settlement patterns originated a new way in which humans and the environment interacted.

In that context, archaeoecological evidence obtained by the analyses developed in the framework of this thesis provided relevant data about three main objectives: 1) Vegetation history, climate change and human impact during the Middle Holocene in the Lake Banyoles area; 2) Socio-ecological consequences of Neolithisation in the NE Iberian Peninsula and 3) Potential and contributions of archaeopalynology in lakeside settlement research.

This thesis is presented as a compilation of published scientific papers, all based on the application of multi-proxy analysis of both intra-site and off-site deposits in order to reconstruct environmental evolution and Neolithic landscape transformation. The methods applied have been pollen and non-pollen palynomorph (NPP) analysis, macrofossils, sedimentology and sedimentary charcoal analysis, as well as the integration of data from other archaeological and bioarchaeological studies.

Broadleaf deciduous forests around Lake Banyoles reached their maximum expansion in the phase 9.0-7.5 cal ka BP, a decline in 7.5-6.5/5.5 cal ka BP, but a recovery afterwards, showing the persistence of oak forests as the dominant vegetation until the Late Holocene. The regression of deciduous forests occurred in the context of the arrival of the first farming societies in the area in 7.27 cal ka BP but also in the context of a cooling phase evidencing the important role of climate change in amplifying the footprint of Neolithic human impact, as well as in settlement dynamics in the Lake Banyoles shore.

The practice of intensive farming models during the Early Neolithic, implying small-scale and labour-intensive cultivation, left little evidence of the impact of agriculture in off-site pollen records. While a sustainable small-scale and intensive farming system would have left scarce evidence of the impact of agriculture during the Early Neolithic, the intensive and reiterative exploitation of natural resources associated with permanent settlements led to significant landscape transformation.

The archaeopalynological study developed at La Draga was able to obtain relevant data for comprehending site formation processes, the reconstruction of palaeo-environmental evolution and human impact at a local scale and provided new data about socioeconomic practices during the Early Neolithic as well as about the use of space within a pile-dwelling site. This work evidenced the need to carry out spatial analysis in palynological studies at archaeological sites, owing to the spatial heterogeneity of results caused by human impact in terms of soil erosion, arrangement of structures and in the input of plants to the settlement (gathering, cultivation, storage, foddering).

Resum

Abans del Neolític, l'evolució del paisatge estava principalment controlada pel canvi climàtic, però, en canvi, a partir del *ca.* 7.4-7.0 cal ka AP, l'impacte humà va començar a interferir en el desenvolupament natural de la vegetació a la Península Ibèrica. Així, el procés de Neolitització va suposar una profunda transformació socioeconòmica i ecològica. Els canvis en la producció d'aliments, en la gestió dels recursos naturals i en els patrons d'assentament van originar una nova forma d'interacció entre societat i medi.

En aquest context, les evidències arqueoecològiques obtingudes amb les anàlisis desenvolupades en el marc d'aquesta tesis han aportat dades importants respecte tres objectius principals: 1) Història de la vegetació, canvi climàtic i impacte humà durant l'Holocè Mig en el Pla de l'Estany; 2) Conseqüències socio-ecològiques de la Neolitització al NE de la Península Ibèrica i 3) Potencial i contribució de l'arqueopalinologia a la recerca en assentaments lacustres.

Aquesta tesi es presenta com un compendi d'articles científics publicats, tots ells basats en l'aplicació d'anàlisis multi-proxy en dipòsits arqueològics i naturals per tal de reconstruir l'evolució ambiental i la transformació del paisatge durant el Neolític. Els mètodes aplicats han estat l'anàlisi de pol·len i palinomorfs no pol·línics (NPP), macrofòssils, sedimentologia i carbons sedimentaris, així com de la integració de dades procedents d'altres estudis arqueològics i bioarqueològics.

Els boscos caducifolis van tenir la seva màxima expansió a l'Estany de Banyoles durant la fase 9.0-7.5 cal ka AP, una davallada en 7.5-6.5/5.55 cal ka AP, i una recuperació posterior, mostrant la persistència de les rouredes com vegetació dominant fins ben entrat l'Holocè recent. La regressió dels boscos de caducifolis va ocórrer en el context de l'arribada de les primeres comunitats pageses a l'àrea en 7.27 cal ka AP, però també en el context d'una fase de refredament, mostrant així l'important paper que va jugar el canvi climàtic per amplificar l'empremta de l'impacte humà durant el Neolític, així com també en les dinàmiques d'assentament en la vora de l'Estany de Banyoles.

La pràctica d'un model agrícola-ramader intensiu, implicant un cultiu a petita escala i amb una alta inversió de treball, va deixar una lleu evidència de l'impacte de l'agricultura en registres pol·línics naturals. Mentre un model agrícola-ramader intensiu i sostenible hauria comportat un impacte limitat sobre la vegetació durant el Neolític Antic, l'explotació intensiva i reiterada de les rouredes associada amb un poblament permanent va provocar una transformació significativa del paisatge.

L'estudi arqueopalinològic desenvolupat a La Draga ha permès obtenir dades significatives per comprendre els processos de formació del jaciment, així com també la reconstrucció de l'evolució paleoambiental a escala local i obtenir noves dades sobre les pràctiques socioeconòmiques i l'ús de l'espai a l'interior de l'assentament. Aquest treball ha demostrat la importància de portar a terme anàlisis espacials en els estudis palinològics en jaciments arqueològics, degut a l'heterogeneïtat espacial causada per l'impacte humà en termes d'erosió de sòls, arranjament d'estructures i la introducció de plantes a l'assentament (recol·lecció, cultiu, emmagatzematge, farratge).

Resumen

Antes del Neolítico, la evolución del paisaje estaba principalmente controlada por el cambio climático, pero, en cambio, a partir del *ca.* 7.4-7.0 cal ka AP, el impacto humano comenzó a interferir en el desarrollo natural de la vegetación en la Península Ibérica. Así, el proceso de Neolitización supuso una profunda transformación socioeconómica y ecológica. Los cambios en la producción de alimentos, en la gestión de los recursos naturales y en los patrones de asentamiento originaron una nueva forma de interacción entre sociedad y medio.

En este contexto, las evidencias arqueoecológicas obtenidas mediante los análisis desarrollados en el marco de esta tesis han aportado datos importantes respecto a tres objetivos principales: 1) Historia de la vegetación, cambio climático e impacto humano durante el Holoceno Medio en el Pla de l'Estany; 2) Consecuencias socioecológicas de la Neolitización en el NE de la Península Ibérica i 3) Potencial y contribución de la arqueopalinología en la investigación en asentamientos lacustres.

Esta tesis se presenta como un compendio de artículos científicos publicados, todos ellos basados en la aplicación de análisis multi-proxy en depósitos arqueológicos y naturales por tal de reconstruir la evolución ambiental y la transformación del paisaje durante el Neolítico. Los métodos aplicados han sido el análisis de polen y palinomorfos no polínicos (NPP), macrofósiles, sedimentología y carbones sedimentarios, así como la integración de datos procedentes de otros estudios arqueológicos y bioarqueológicos.

Los bosques caducifolios tuvieron su máxima expansión en el Estany de Banyoles durante la fase 9.0-7.5 cal ka AP, un retroceso en 7.5-6.5/5.55 cal ka AP, y una recuperación posterior, mostrando la persistencia de los robledales como vegetación dominante hasta bien entrado el Holoceno reciente. La regresión de los bosques caducifolios se produjo en el contexto de la llegada de las primeras comunidades campesinas al área en 7.27 cal ka AP, pero también en el contexto de una fase de enfriamiento, mostrando así el importante papel que jugó el clima en la amplificación de la huella del impacto humano durante el Neolítico, así como también en las dinámicas de asentamiento en la orilla del Estany de Banyoles.

La práctica de un modelo agrícola-ganadero intensivo, implicando un cultivo a pequeña escala y con una alta inversión de trabajo, dejo una evidencia leve del impacto de la agricultura en los registros polínicos naturales. Mientas un modelo agrícola-ganadero intensivo i sostenible habría comportado un impacto limitado sobre la vegetación durante el Neolítico Antiguo, la explotación intensiva y reiterada de los robledales

asociada con un poblamiento permanente provocó una transformación significativa del paisaje.

El estudio arqueopalinológico desarrollado en La Draga ha permitido obtener datos significativos para comprender los procesos de formación del yacimiento, así como también la reconstrucción de la evolución paleoambiental a escala local y obtener nuevos datos sobre las prácticas socioeconómicas y el uso del espacio en el interior del asentamiento. Este trabajo ha demostrado la importancia de llevar a cabo análisis espaciales en los estudios palinológicos en yacimientos arqueológicos, debido a la heterogeneidad espacial causada por el impacto humano en términos de erosión de suelos, disposición de estructuras y a la introducción de plantas al asentamiento (recolección, cultivo, almacenaje, forraje).

1. INTRODUCTION

1. Introduction

1.1. Archaeoecology: an interdisciplinary approach for assessing human-environment interaction

Archaeoecology: the integration of archaeology and palaeoecology

The study of past societies only makes sense if it considers the physical support in which social reality takes place. The geosystem, a concept defined by Beroutchachvili and Bertrand (1978), consists of the natural system where societies produce and are reproduced, and is defined as a given amount of matter and energy. The geosystem not only consists of a biological component (plants and animals), but is also formed by abiotic elements (lithosphere, hydrosphere and aerosphere). The existence of an anthropic component within the biotic elements is assumed, although that does not mean that socioeconomic systems are subordinated to natural processes.

Humans, as social subjects, interact with the material world through labour[1] (Marx, 1984). Social labour, aimed at the satisfaction of human existence conditions and social needs, and phenomenologically expressed by social practices (Argelès et al., 1995; Castro et al., 1996, 1998), produces material changes in the geosystem. Therefore, society, when acting on nature through labour, alters the rhythm of natural processes and modifies the elements constituting the geosystem according to their necessities: biotic communities (plants and animals), water bodies (hydric resources) and geologic substrate (geomorphology). These elements form the environmental conditions and the landscape in a specific space and time and always consist of a historical product, the result of the dialectical relationship between natural processes and social practices.

Based on these premises, interdisciplinary approaches integrating archaeological and palaeoecological data are essential in order to determine how changes in the geosystem occurred in the past, to distinguish if they were caused by natural or social agents, or on the contrary, these changes should be understood as the product of interaction between social and natural factors. Thus, while social practices cannot be understood without considering the physical support in which they take place, the role of humans in landscape evolution and configuration cannot be omitted.

In the 1960's, the emergence of the so-called *New Archaeology* represented the onset of the integration of archaeological and palaeoecological data, and an increase in attention to environmental elements within the analysis of the archaeological record of early farmers (Sahlins, 1964; Wright, 1971). By adopting explicative premises from cultural ecology (Steward, 1955), human societies were considered extrasomatic systems of adaptation to the environment (Binford, 1972), assuming a systematic relationship

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[1] Labour is the aggregate of those mental and physical capabilities existing in a human being enabling the capacity of intentionally transform matter (Marx, 1984) or to produce and maintain social objects and subjects. Labour should be considered not as an object, but as an activity; not as value, but as a source of value (Marx, 1984 [1858]: 236). Thus, a resource value does not reside only in the use value, but also in the production value.

between the human organism and its environment in which culture is the intervening variable (Binford, 1962, 218). Nevertheless, based on a homeostatic relationship between society and environment, equilibrium was considered the determining element of the adaptation, situating causalities of changes in external factors (i.e. demography or climate change), and thus omitting conflict within societies to comprehend social change.

Based on social concepts, the environment should not be understood as a pre-existent element determining human actions, and it is essential to consider modes of production and the productive systems depending on it, in order to comprehend the social needs that determine the human management of natural resources. Thus, the geosystem is not used, felt or perceived, but exists in a relationship with productive forces and social categories (Beroutchachvili and Bertrand, 1978). In that sense, in the origins of Humanity, the physical space was a purely natural system, but, through history, physical space became progressively constructed by anthropogenic work, and the Neolithic represents a transcendental period since when anthropisation has grown exponentially. Thus, the landscape emerges as a historical product rejecting the original nature, becoming increasingly humanised (Bertrand and Bertrand, 2000, 54).

The search for a methodology integrating archaeological and palaeoenvironmental data based on a non-unidirectional and deterministic human-environment relationship is the origin of the concept of archaeoecology. Archaeoecology is defined as the study of reality through the dialectical relationship between humans and geosystem, in order to assess the environmental conditions in which societies developed and to evaluate the effects of political and economic practices on the landscape. In that context, social organization must be understood as the product of the relationship between the environment and social recognition of needs, and not a passive adaptation to a given framework.

An archaeoecological study is only viable through the integration of palaeoecological disciplines together with archaeological methods and techniques, and the integration of the archaeological record and palaeoecological records in the surroundings of the settlement under study. Thus, the reconstruction of past social activities and the impact on the environment requires an interdisciplinary approach in which several fields of research must be combined, such as archaeology, sedimentology and palaeoecology. The main goal of such an analysis should be to reveal the development of the relationship between changing environmental conditions and the factors that control climatic fluctuations, as well as the influence of all this on socioeconomic strategies.

Archaeopalynology: an active human role in landscape evolution

Palaeopalynology is defined as the study of fossil pollen and spores in sediments in order to reconstruct successive responses of vegetation to environmental and anthropic factors (D’Antoni, 2008), assuming a relationship between the number of pollen grains of taxa deposited in sediments and the number of individuals existing in the surrounding vegetation (Davis, 1963; Mosimann and Greenstreet, 1971; Green, 1983; López-Sáez et al., 2003). Several taphonomic factors influence the composition of the palynological record. Production, transport, sedimentation and post-depositional alteration of pollen grains are taphonomic processes specific to each pollen taxon (Coles et al., 1989; Campbell, 1999), and it is assumed that these processes can result in significant distortion of the fossil pollen spectra with respect to the original pollen rain (Lebreton et al., 2010). Lakes and bogs are the most appropriate deposits to approach the original pollen rain, where taphonomic processes are less frequent (Faegri and Iversen, 1989). In the last decades, the focus of palynology has been broadening, integrating non-pollen palynomorph analysis (NPP) (Van Geel et al., 1989, 1996, 2003, 2006, 2013; López-Sáez et al., 1998, 2006a; Carrión and Van Geel, 1999; Gauthier et al., 2010; Cugny, 2011; Gelorini et al., 2011) and the study of sedimentary charcoal (Rius et al., 2009, 2011; Bal et al., 2011; Pèlachs et al., 2011; Vannière et al., 2011; Pérez-Obiol et al., 2012; Finsinger et al., 2016).

Pollen analysis enables the reconstruction of the response of vegetation against climate change, human impact and such natural processes as colonisation or migration of species. On the other hand, NPP analysis provides information about specific ecological conditions (i.e. humidity/dryness), allows the reconstruction of certain geomorphologic processes such as soil erosion events (Anderson et al., 1984; van Geel et al., 1989; López Sáez et al., 2000), verifies local occurrence of host plants that can be invisible in pollen and macrofossil analyses (van Geel et al., 2006) and enables an assessment of human impact in terms of grazing pressure (Ralska-Jasiewiczowa and van Geel, 1992; López-Merino et al., 2009; Cugny et al., 2010; Gauthier et al., 2010), fire episodes (van Geel, 1978; Simmons and Innes, 1996; Innes and Blackford, 2003; Blackford et al., 2006) or the eutrophication of water (van Geel et al., 1994, 1996; Hillbrand et al., 2014). Finally, the study of sedimentary charcoal deposited in natural deposits enables a reconstruction of fire episode history (Whitlock and Millspaugh, 1996; Higuera et al., 2007). Fire is considered an inherent element in the Mediterranean environment (Vannière et al., 2008), where both the climate and the pattern of human occupation create a unique fire-prone environment. Fire is intimately connected to fuel availability, moisture patterns and therefore to climate changes, but it is also directly linked to human activities.

According to the archaeoecological conceptualisation of the human-environment relationship, archaeopalynology is an essential tool to address archaeological issues from a different perspective. Although pollen analysis of archaeological deposits and surrounding natural deposits provides information about landscape evolution in specific historic periods, the most essential data provided by archaeopalynology concern in local or extra-local questions and the intensity of human impact (Behre, 1988). Pollen analysis at archaeological sites provides essential data to approach archaeological issues (Diot, 1984-1985; López-Sáez et al., 2003) due to the fact that human activities cause changes in the configuration of the pollen record. In that sense, an overrepresentation of herbaceous taxa and higher richness is commonly documented in archaeological deposits due to anthropic inputs (Richard and Gery, 1993; Gauthier and Richard, 2009; Jeraj et al., 2009), either intentional or unintentional.

Archaeopalynology enables not only the study of vegetation history but, also the causes of landscape configuration through integration with archaeological sites, where social practices in different historical periods are evidenced. Processes such as deforestation, soil enrichment or eutrophication, grazing pressure, exotic species introduction, establishment of cultivars (mainly cereals and legumes) or soil erosion can be assessed by archaeopalynology (Burjachs et al., 2003). Additional information can be obtained through NPP analysis, applied less frequently in archaeological contexts, such as evidence of livestock within settlements or in the surroundings (van Geel et al., 1983, 2003); and determining the season of certain archaeological structures (Kvavadze and Kakhiani, 2010).

The study of pollen and NPP in archaeological sediments provides relevant data about human impact at a local scale (Guathier and Richard, 2009; Jeraj et al., 2009; Gassiot et al., 2012), as well as essential information to comprehend site formation processes. Several taphonomic processes occur in aerial/subaerial mineral deposits such as archaeological sites where they can deform the original deposition of pollen and NPP. The integration of archaeopalynological and spatial analyses may be able to reconstruct the dynamics of formation of the archaeological record and obtain crucial information to assess the use of space within the settlement. In that context, the identification of differential depositional environments may evidence anthropic events or activity areas within a settlement.

The main aim of this PhD thesis is the study of vegetation history and human-environment interactions. Given the potential described above, an archaeopalynological approach will be carried out to develop this research. First of all, in a more regional and longer chronological focus, vegetation history and landscape transformation during the Mid-Holocene will be addressed in the Lake Banyoles area. Afterwards, the consequences of Neolithisation on the human-environment relationship will be assessed through the combination of palaeobotanical records from La Draga and natural deposits in its surroundings. Finally, at a more local scale, the application of archaeopalynology in a specific archaeological site (La Draga) will provide the opportunity to evidence the usefulness of this kind of approach to assess local human impact, site formation processes and use of space within a Neolithic pile-dwelling.

1.2. Middle Holocene: vegetation history, climate change and human impact

The onset of the Holocene led to the expansion of forests at the expense of Late Glacial steppes due to the establishment of a warmer and more humid climate, reaching a maximum expansion of broadleaf deciduous forests after 9.5-9.0 cal ka BP in the Iberian Peninsula (Carrión et al., 2010; Pérez-Obiol et al., 2011; González-Sampériz et al., 2017). The Early Holocene was characterised by a warm humid climate and as a period of nature-dominated environmental processes in the western Mediterranean. The 8.2 cal ka BP event has been considered the boundary between the Early and the Middle

Holocene, according to the geochronological classification by Walker et al. (2012), a global cooling episode detected in ice cores (Hammer et al., 1986; Alley et al., 1997; Bond et al., 1997; 2001; Alley and Ágústsdóttir, 2005), in high-resolution cave speleothems (Neff et al., 2001; Boch et al., 2009) and attested in marine regional records in the Mediterranean (Cacho et al., 2001; Frigola et al., 2007) and pollen records in Iberia (Riera, 1993; Davis and Stevenson, 2007; Carrión and van Geel, 1999; Carrión, 2002; Carrión et al., 2001a, 2001b; Pantaleón et al., 1996, 2003; López-Sáez et al., 2007; González-Sampériz et al., 2008; Pérez-Sanz et al., 2013) and in the Central Mediterranean (Sadori and Narcisi, 2001; Magri and Parra, 2002; Peyron et al., 2011). Furthermore, this cooling episode has been proposed as a motor of social change, as the cause of crisis, migrations or abandonment of past hunter-gatherer societies (Fernández-López de Pablo and Gómez-Puche, 2009; González-Sampériz et al., 2009; Mercuri and Sadori, 2011), it is an argument repeatedly used to explain the Neolithisation process in the Mediterranean area (Weninger et al., 2006, 2009; Berger and Guilaine, 2009).

Some authors place the boundary between the Middle and the Late Holocene in the transition from the Subboreal to the Subatlantic climatic period (2.5 cal ka BP) (Roberts et al., 2011). However, it is becoming increasingly accepted to place the boundary in the global aridification episode dated to 4.2 cal ka BP (Mayewski et al., 2004, Staubwasser and Weiss, 2006, Wanner et al., 2011; Renssen et al., 2012; Walker et al., 2012; Innes et al., 2014), when Bond event 3 occurred (Bond et al., 2001). This event is reflected in increasing aridity in proxy records from the Mediterranean (Bar-Matthews et al., 1997; Cullen et al., 2000; Narcisi, 2000; Frumkin et al., 2001; Magri and Parra, 2002; Arz et al., 2006; Drysdale et al., 2006; Parker et al., 2007; Di Rita and Magri, 2009; Roberts et al., 2011). The 4.2 cal ka BP has also been proposed as the cause of crisis or collapse of past societies, like the Akkadian empire in Mesopotamia (Weiss et al., 1993; De Menocal, 2001), the Egypt Old Kingdom, (Stanley et al., 2003), the Harappan civilization in the Indus valley (Staubwasser et al., 2003) and a contributing factor to migration processes and cultural change in the transition from the Chalcolithic to Early Bronze Age in the Iberian Peninsula (Lillios et al., 2016).

In fact, despite being a relatively stable climatic period, the Holocene has been punctuated by cooling and drying oscillations (Fig.1), and the Mid-Holocene was no exception. Apart from the aforementioned boundaries in 8.2 and 4.2 cal ka BP, two main cooling phases should be noted in the Mid-Holocene. First of all, cooling and dry episodes have been documented during the 2nd half of the 8th millennium cal BP: the cooling phase documented in Greenland ice core records in 7.4 cal ka BP (Bond et al., 1997, 2001), in Minorca Sea records (7.4-6.9 cal ka BP, with the central age in 7.2 cal ka BP, Frigola et al., 2007), arid phases recorded in Iberian lacustrine records (7.5-7.0 cal ka BP in Vegas et al., 2009; 7.5 cal ka BP in Pérez-Sanz et al., 2013) and episodes of reduced rainfall in *ca.*7.4 cal ka BP in Hoti Cave (Oman) (Neff et al., 2001), Soreq Cave (Israel) (Bar-Matthews et al., 1999) and Antro del Corchia (Italy) (Zanchetta et al., 2007).

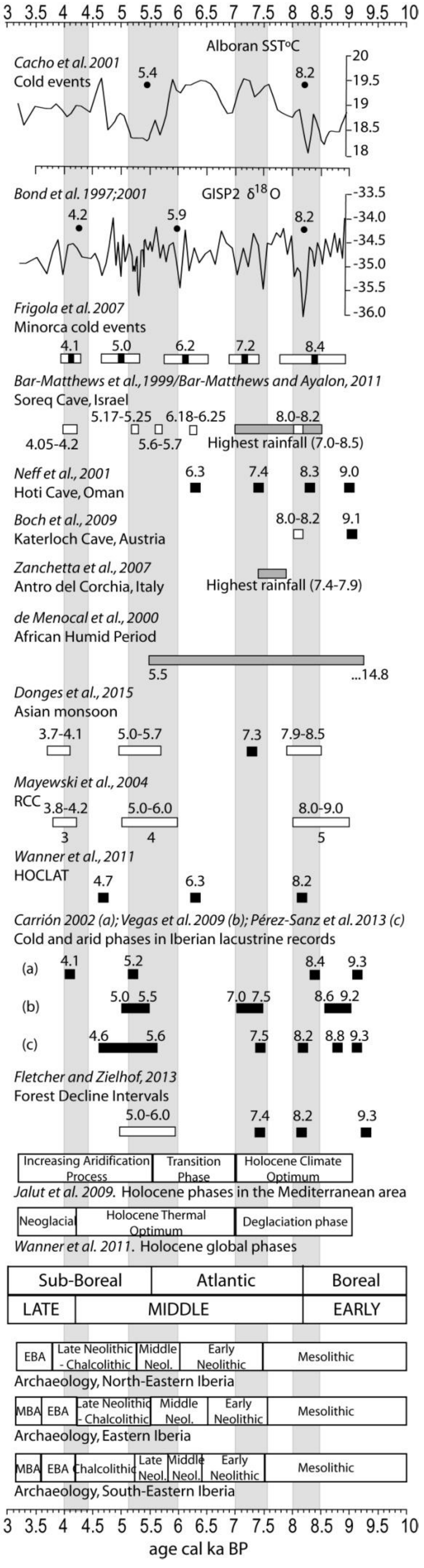

Figure 1.

Mid-Holocene cooling and dry episodes.

Secondly, during the 6th millennium cal BP crucial oscillations shaped the contemporary climate. The weakening of the West African monsoon system associated with the end of the African Humid period in *ca*. 6 cal ka BP (De Menocal et al., 2000; Renssen et al., 2003) and Bond event 4 in 5.9 cal ka BP (Bond et al., 1997, 2001) originated cooling episodes causing environmental changes. Afterwards, progressive globally cooler conditions are attested from *ca*. 5.5 cal ka BP onwards, leading to the onset of an increasing aridification process in the Western Mediterranean (Jalut et al., 2009). In that context, many palaeoclimatic records show changes in precipitation seasonality starting from *ca*. 5.5 cal ka BP, with the establishment of drier conditions in Mediterranean areas (particularly in summer), associated with a decrease in insolation maxima and general reorganization of atmospheric circulation (Jalut et al., 2009; Magny et al., 2012). In the NE Iberian Peninsula this hydrological change is well represented in Lake Estanya (Morellón et al., 2009), but also in marine sediments in the Balearic Sea (Frigola et al., 2007), as well as in Western Mediterranean pollen diagrams (Jalut et al., 2000; Pérez-Obiol et al., 2011; Aranbarri et al., 2014).

Undoubtedly, the Mid-Holocene is a topic of debate when referring to the causes of environmental change, differing between supporters of climatic causation or anthropogenic explanations. In that context, the Mid-Holocene has been defined as a ‘mélange’ between nature-dominated environmental change during the Early Holocene and the human-dominated Late Holocene (Roberts et al., 2011). Thus, the Mid-Holocene is an interesting period to study human-environment interactions and to assess the causation of ecological changes.

The various climatic fluctuations occurring during the Holocene affected the development of vegetation. The establishment of a warmer humid climate in the Early Holocene allowed the expansion of forests, leading to the establishment of dense deciduous broadleaf forests, with the characteristic dominance of deciduous *Quercus* and *Corylus* in pollen records (Jalut et al., 2009; Carrión et al., 2010; Pérez-Obiol, 2011). The phase of maximum expansion of mesophilous forests and the transition from wetter to drier conditions during the Mid-Holocene (the so-called Holocene Climate Optimum), is observed in the Mediterranean area in the transition to the Late Holocene (5.0-4.0 cal ka BP) it affected vegetation with the expansion of the sclerophyllous Mediterranean forests (Jalut et al., 2000; Sadori and Narcisi, 2001; Carrión et al., 2010; Pérez-Obiol et al., 2011; Roberts et al., 2011). Nevertheless, this process of replacement of broadleaf deciduous by sclerophyllous forests was not always homogeneous, as some sub-Mediterranean climate areas, such as the northern shores of the central Mediterranean, show the resilience of broadleaf deciduous woodland until the Late Holocene (Sadori et al., 2011).

Human activities should also be considered in order to comprehend environmental changes since the Middle Holocene. In fact, some authors regard the adoption of farming activities as the onset of the Anthropocene (Ruddiman, 2003; Ruddiman et al., 2015). The adoption of farming practices involved the transformation of landscapes by deforestation processes, as shown in some pollen records in the Mediterranean area

(Riera and Esteban-Amat, 1994; Sadori and Narcisi, 2001; Yll et al., 2003; Drescher-Schneider et al., 2007; Colombaroli et al., 2008; Vannière et al., 2008; Kouli and Dermitzakis, 2008; Vescovi et al., 2010; Marinova et al., 2012). Other environmental consequences of increasing human impact were the proliferation of fire episodes (Vannière et al., 2008; Carcaillet et al., 2009; Tinner et al. 2009), acceleration in soil erosion processes (Dearing, 1994; Dotterweich, 2008; Dusar et al., 2011; Simonneau et al., 2013; Notebaert and Berger, 2014) and the eutrophication of water (Hillbrand et al., 2014). In historical terms, the Mid-Holocene (8.2-4.2 cal ka BP) consists of the geochronological period contemporary with Late Prehistory in the western Mediterranean, from late hunter-gatherer societies (Late Mesolithic) to the development of Bronze Age societies, and represents the climatic and environmental framework of the Neolithisation process, a relevant historical period that will be widely addressed in section 1.3.

Attempts to explain Mid-Holocene landscape changes in terms of purely natural or purely anthropogenic causes alone would be misplaced. The issue is not whether people altered Mediterranean ecosystems during the Mid-Holocene, but rather at what point this impact became detectable, and what form it took (Roberts et al., 2011: 5). In that context, the different studies developed in the framework of this PhD thesis will assess human-environment interactions during the Mid-Holocene, in order to comprehend the influence of both climate change and human management of natural resources in the evolution of environmental conditions.

1.3. Neolithic: the adoption of the farming mode of production

Neolithisation

Neolithisation led to profound socioeconomic changes, involving innovation in food production, management of resources, social organization and settlement patterns. Besides, the adoption of the farming mode of production inplied a new way in which society and environment interacted and the onset of an increasing process of anthropisation and landscape transformation. The changes involved in the adoption of this new mode of production have suggested different causal explanations, in terms of climate change (Berger and Guilaine, 2009; Childe, 1952; Gronenborn, 2009; Richerson et al., 2001; Weninger et al., 2006), disequilibrium between population and resources or productive capacity (Binford, 1968; Renfrew, 1973), demography (Bocquet-Appel, 2002; Cohen, 1981), transformation of mechanisms of social reproduction (Testart, 1982; Vicent, 1990), the appearance of a new ideology (Cauvin, 1994, 2000; Thomas, 1988) or a new system of values involving the social dominance of nature (Hodder, 1990). In any case, the transformation of subsistence strategies from hunting and gathering to farming involved significant changes in the economy, ideology and social organization, as well as in the relationship between humans and the environment. In that sense, the study of the various environmental changes occurring during the Early and Mid-Holocene becomes especially important in order to characterise the environmental framework and possible constraints across Europe during the Neolithisation process.

The Neolithic consists of the appearance of organizational strategies based on the inclusion of the appropriation of reproductive cycles of some plants and animals within mechanisms of social production and reproduction. Therefore, the shift from hunting and gathering to farming is viewed as a *change in the way in which culture and environment interacted* (Wright, 1971, 457). Domestication allowed human management of resource reproduction, making their availability artificial. Nevertheless, Neolithic research should not be focused only on domestication processes, but also on relationships established in labour organization and in the distribution, use and consumption of the goods produced. Moreover, these new productive processes are involved in the global productive process, where other tasks are included, such as subject production and the maintenance of both objects and subjects (Castro et al., 2005). Therefore, when referring to transformations from the hunter-gatherer to the farming mode of production, attention must be paid not only to changes in production, but also to the social relationships that determined them (Vicent, 1990).

Apart from this debate on its causes and mechanisms, the Neolithic led to the economic and social foundations on which present-day societies are based, such as diversified food production and storage techniques, surpluses, sedentism, labour specialization, social complexity, and ultimately state institutions (Banks et al., 2013). These changes in food production, in natural resource management and in settlement patterns originated the onset of progressive human impact on the landscape that, together with climatic oscillations during the Holocene, caused considerable changes in the original geosystem. These changes place the Neolithisation process in the centre of the discussion on the origins of the Anthropocene, in terms of the human alteration of ecosystems (Ruddiman, 2003; Ruddiman, 2013; Ruddiman et al., 2015) and of human niche-constructing behaviour, modifying ecosystems through the domestication of plants and animals (Smith and Zeder, 2014).

The expansion of the first farming societies and the practice of intensive agriculture implied a limited impact on the landscape (Bogaard, 2004b). This limited impact should be understood in terms of small-scale forest modifications that can be traced across Europe following the chronological gradient associated with the Neolithisation process, starting in south-eastern Europe in the 9th millennium cal. BP (Kouli and Dermitzakis, 2008; Marinova et al., 2012) and reaching the opposite extreme of the continent at the beginning of the 6th millennium cal. BP (O'Connell and Molloy, 2001; Woodbridge et al., 2012).

The arrival of the first Neolithic groups in the Iberian Peninsula is dated to 7650–7600 cal. BP, so this was the last region to adopt farming in the Mediterranean area. Their territorial expansion was discontinuous but rapid, extending over coastal regions and some inland areas following the course of the rivers in less than two centuries (Bernabeu et al., 2009, 2014). Settlement patterns of the first farming communities in Iberia were characterised by the documentation of the first permanent open-air settlements, such as La Draga (Bosch et al., 2000, 2011), Mas d'Is (Bernabeu et al., 2003), Los Castillejos (Afonso et al., 1996), Los Cascajos (García Gazólaz and Sesma, 2001) or La Revilla del Campo and La Lámpara (Rojo et al., 2008).

The first evidence of Neolithic occupation in NE Iberia is dated in the second half of the 8th millennium cal. BP. The gap in human presence in the region during the first half of the 8th millennium cal. BP indicates that the Neolithisation of the NE Iberian Peninsula was the result of migration of farming populations to uninhabited territories (Zilhao, 2000, 2011). In contrast, on the eastern coast of the Iberian Peninsula, interaction between indigenous Mesolithic communities and the arriving farming communities has documented (Bernabeu, 1997, 2002; Bernabeu et al., 2009). Although the main innovation in this period is the appearance of open-air permanent settlements: Font del Ros (Berga, Barcelona) (7390–7260 cal. BP, Bordas et al., 1995), Sant Pau del Camp (Barcelona) (7265–7075 cal. BP, Molist et al., 2008) and La Draga (Banyoles, Girona) (7270–6750 cal. BP, Bosch et al., 2012), the earliest dates of Neolithic occupations in NE Iberia correspond to caves and rock-shelters: Balma Margineda (Sant Julià de Lòria, Andorra) (7860–7390 cal. BP, Guilaine, 1995), Bauma del Serrat del Pont (Tortellà, Girona) (7480–7280 cal. BP, Alcalde and Saña, 2008) and Cova de Can Sadurní (Begues, Barcelona) (7430–7240 cal. BP, Edo et al., 2011).

Economy and landscape transformation during the Neolithic

The transformation of social organization, economic practices and settlement patterns in the Neolithic resulted in intensification in the exploitation of natural resources and an increase in disturbance signals in palaeoecological records. The character of early farming in Europe has been widely discussed. Evolutionist proposals used to consider the first farming practices as extensive and characterised by a low investment in labour, only becoming intensive after technological and demographic changes (Boserup, 1965). Another farming model proposed was shifting slash-and-burn cultivation as an adaptation by early farmers to the densely wooded landscape of central Europe (Clark, 1952). Nevertheless, bioarchaeological research carried out in recent decades has shown that intensive mixed farming (small-scale, labour-intensive cultivation integrated with small-scale herding) is probably the most plausible model across Central and South-east Europe (Bogaard, 2004a; Marinova, 2007), in North-west Europe (Bogaard and Jones, 2007) and in some areas of the Western Mediterranean (Antolín, 2013; Antolín et al., 2014, 2015; Pérez-Jordà and Peña-Chocarro, 2013). The large variety of crops, documented in the Early Neolithic in the Iberian Peninsula, with different requirements, processing and uses, implies that the first farmers quickly imported or acquired a wide range of agrarian knowledge. According to Halstead (1990, 1996), farmers can protect themselves against failure and climate instability by growing a diversity of crops with different growth requirements and tolerances. In that sense, the cultivation of small plots with a wide range of different crops may have been the result of a conscious strategy designed to minimize risk (Zapata et al., 2004). However, a transition towards an extensive form of agriculture based on the cultivation of a reduced number of cereal species is documented for the Middle-Late Neolithic period (Antolín, 2013; Antolín et al., 2015; Pérez-Jordà and Peña-Chocarro, 2013).

Archaeozoological research has also identified small-scale intensive herding (Halstead, 1989). In fact, an intensive farming model would imply close integration of agriculture and husbandry, with livestock kept within the settlements, the use of crops as fodder and the introduction of manuring (Bogaard et al., 2013). Thus, the adoption of farming practices also involved husbandry and grazing pressure is reflected in the progressive occurrence of dung indicators in microfossil records in periods of deforestation and expansion of grasslands and ruderal taxa. This is extensively documented in Iberia during the Middle and Late Holocene, especially in high mountain areas (Carrión, 2002; Riera et al., 2006; Miras et al., 2007; Ejarque et al., 2010; López-Merino et al., 2010a; Miras et al., 2010; Orengo et al., 2014).

As mentioned above, new economic activities were involved in a global productive process in which other tasks would have also influenced landscape transformation. Although social exploitation of woodland resources has been crucial since the origins of Humanity, (as a source of food by means of hunting-gathering strategies, firewood to obtain luminescent and calorific energy, raw materials to make tools and constructions), the first farmers had to deal with new forest management strategies adapted to new necessities. The sedentary settlement patterns, the more intensive productive activities (agriculture and husbandry) increasingly reiterated in the territory, the growing population and the new productive processes (i.e. ceramic technology) implied more resources and greater diversification.

In this respect, anthropogenic impact on the landscape during the early Neolithic, involving deforestation, expansion of secondary woodland formations or pyrophilous and ruderal taxa has been documented in the Pyrenees (i.e. Gassiot et al., 2012; Miras et al., 2007; Orengo et al., 2014), and the central Catalan coast (Antolín et al., 2011; Riera and Esteban-Amat, 1994; Riera et al., 2007). The impact of the first farmers has also been documented in the rest of the Iberian Peninsula in different intervals between the second half of the 8th millennium cal. BP and the 7th millennium cal. BP: in north-western Iberia (Ramil-Rego and Aira, 1996; Ramil-Rego et al., 1994), in the north (Iriarte, 2009; López-Sáez and López-Merino, 2007; López-Merino, 2009; López-Merino et al., 2010; Peñalba, 1994), in central Iberia (Aranbarri et al., 2015; López-Sáez, 2002; López-Sáez et al., 2005); the Ebro valley (González-Sampériz, 2004; López-Sáez et al., 2006b), eastern Iberia (Carrión and van Geel, 1999; Dupré et al., 1996; Yll et al., 2003); south-western Iberia (López-Sáez et al., 2007a, 2007b/2008; van der Knaap and van Leeuwen, 1995) and in southern Iberia (Carrión et al., 2001, 2007; Cortés et al., 2008; Fernández et al., 2007). Although several causes are proposed by different authors, all of them agree that these changes were the result of human intervention, in which the woodland was opened up for several purposes. In some cases, evidence of fire has been found (Kaal et al., 2008; Martínez Cortizas et al., 2009; Riera et al., 2004) although this was not a general trend.

Despite this evidence of landscape transformation during the early stages of Neolithisation in Iberia often being associated with farming activities, the low values or absence of Cerealia-type pollen and weeds in some sequences is noticeable (Carrión et al., 2007; Iriarte et al., 2007/2008; López-Merino, 2009; López-Merino et al., 2010; López-Sáez et al., 2007a, 2007b/2008; Peñalba, 1994; Pérez-Díaz et al., 2015; Ramil-Rego and Aira, 1996). On the other hand, concentrations of Cerealia-type pollen have been documented at many archaeological sites (Burjachs, 2000; Fernández-Eraso, 2007/2008; Iriarte, 2001; Iriarte et al., 2005; López-Sáez et al., 2006b, 2007a, 2007b/2008; Pérez-Obiol, 1994), probably as the result of crop processing within the settlement, the practice of storage or the location of crop fields in the surroundings. This situation might be linked with the low impact of intensive farming in small plots on a regional scale.

In conclusion, the intensive and continued exploitation of forests for various activities would have become an important mechanism of landscape transformation since the Neolithic. In that context, one of the main objectives of this PhD thesis will be evaluate the social and ecological consequences of Neolithisation in the Lake Banyoles area.

1.4. Wetlands and lakeside settlements.

Despite sporadic evidence of settlement in wetland environments during the Mesolithic (Coles, 2004; Schlichtherle, 2004, Menotti et al., 2005), the generalization of settling in wetland environments occurred from the Neolithic onwards (Menotti, 2004). This kind of settlement is obviously more common and abundant in Central Europe, where large lacustrine and wetland areas are part of the landscape. However, despite the lack of large lacustrine and wetlands areas, there is some evidence of lakeside settlements in the Mediterranean region: Dispilio in Greece (Hourmouziades, 1996) and La Marmotta, Isolino-Virginia and Villaggio delle Maccine in Italy (Fugazzola Delpino et al., 1993; Baioni et al., 2005; Angle et al., 2014). La Draga (Girona, Spain) represents an exceptional find in the Iberian Peninsula and the oldest lakeside settlement (7.27-6.75 cal ka BP), only exceeded by La Marmotta (7.6-7.2 cal ka BP), in the European context.

One of the main features of this particular environment is the richness of archaeological records due to the good preservation of organic remains in anoxic conditions and the possibility of integrating palaeo-environmental data from the surroundings of the settlements. For that reason, these contexts become a scenario of collaboration between the different disciplines of bioarchaeology and geoarchaeology that enable reconstructions of palaeo-environmental and socioeconomic aspects of past societies. Specifically, archaeoecological research focused on wetland areas can obtain significant information about landscape evolution based on available palaeo-environmental data; the reconstruction of vegetation history and assessment of human impact. Moreover, these contexts allow a detailed characterization of economic strategies through archaeobotanical and archaeozoological analyses due to the exceptional bioarchaeological records. Finally, the well-preserved wooden architectural remains allow a better comprehension of the use of space within the settlement by the application of spatial analysis/geostatistics, and, therefore, are able to obtain detailed knowledge about social practices and human-environment interaction during a specific historical period.

A wetland is defined as an ecosystem saturated in water, shallow water or just saturated soil, either permanently or seasonally, where organic plant material is decomposed (Mitsch and Gosselink, 2007). The main feature of wetlands is the biological productivity and diversity and the characteristic vegetation growing in wet conditions (hydrophytes) or permanently flooded conditions (aquatic). Hydrology is the main factor determining the configuration of wetland vegetation (amount of water, nutrients, pH) and different kinds of wetland environments exist depending on the hydrology, formation process and vegetation factors: marsh, swamp, bog, fen and carr. While a marsh is dominated by herbaceous hydrophytes on the banks of lakes and streams, a carr environment is characterised as a waterlogged woodland, and a reed swamp represents the ecosystem between them. Bog and fen are types of mires or peatlands, bogs characterised by the accumulation of mosses (mostly *Sphagnum*) and fens by their mineral-rich and alkaline water.

The characteristic swampy environment in lakeside settlements required a specific kind of construction adapted to wet environments. Thus, lake or pile dwellings would have been built on stilts and platforms above the water, but coexistence with land constructions is possible, as attested in some European regions (Leuzinger, 2000; Menotti, 2001). In fact, settlement in wetlands could affect the preservation of agricultural products and could give rise to diseases, as well as the obvious vulnerability to lake-level fluctuation (Ebersbach, 2012).

The exceptional archaeological record in lakeside settlements enables the reconstruction of economic practices, providing detailed information about gathering, hunting, agriculture, husbandry and forest resource management, as well as about productive and consumption activities within the settlement. Besides, while anthropogenic sediments from lakeside settlements cannot be regarded as an ideal archive for palaeo-environmental reconstruction given the overrepresentation of taxa introduced by humans, they represent an essential document to focus on socio-historical research questions (Doppler et al., 2010). Another important contribution of lakeside settlements is the possibility of precise chronological control through the application of dendrochronological studies due to the good conservation of wood used for construction (Fletcher, 1978; Billamboz, 2005, 2013). It is not always easy to obtain a clear picture of settlement structuring, shape and distribution of huts, especially in cases of lack of dendrochronological studies and in settlements that have been only partially excavated (Schlichtherle, 2004; Ebersbach, 2012; Menotti, 2012). In this case, integration of multidisciplinary analyses and the spatial analysis of archaeological remains by geostatistics becomes indispensable.

The last contribution of the good preservation of wooden remains in lakeside settlements is the possibility to identify the taxa that were used for construction, and therefore felled, and assess the impact on the landscape of this activity. In fact, a strong reduction in forest cover was observed in coincidence with the establishment of pile-dwellings in Italy during the Late Neolithic (Palù di Livenza, Pini, 2004) and Bronze Age (Tabina di Magreta, Bertolani Marchetti et al., 1988; Montale, Mercuri et al., 2006;

Poviglio Santa Rosa; Cremaschi et al., 2006; Lucone, Tinner et al., 2006; Valsecchi et al., 2006; Ledro, Magny et al., 2009; Lavagnone, De Marinis et al., 2005; San Savino, Angelini et al., 2014; Mezzano, Sadori et al., 2004). This process was also attested during the Bronze Age in the Swiss Circum-Alpine region (ZH-Mozartstrasse, Menotti 2001; Bodman-Schachen 1, Rösch 1996; Zurich-Alpenquai, Jacomet and Brombacher, 2009).

The study area will be described in the next section, that is, the lacustrine environment of Lake Banyoles and the lakeside settlement of La Draga. The case study of La Draga and Lake Banyoles represents an exceptional opportunity to carry out an interdisciplinary approach to the objectives described in this introduction. The application of combined bioarchaeological and geoarchaeological research will provide an exceptional record to characterise palaeo-environmental evolution and human management of the landscape during the Neolithic at local and extra-local scales. In this way, records from the Lake Banyoles area will contribute new data to the discussion about the social and ecological impact of Neolithisation in the Iberian Peninsula.

1.5. Objectives

The goal of the thesis is the study of vegetation history and human-environment interaction during the Middle Holocene in the NE Iberian Peninsula. Specific, objectives have been mentioned in the course of the different sections of this introduction and they can be summarized around three main questions that will be used to articulate the later Scientific Papers and Discussions sections:

- *Vegetation history, climate change and human impact during the Middle Holocene in the Lake Banyoles area.*

This objective refers to the broadest scope of this PhD thesis, both in spatial and chronological terms. Causation of changes in vegetation will be addressed, trying to assess climate oscillations and human activity impact during the Middle Holocene (8.2-4.2 cal ka BP). The focus of this research is the Lake Banyoles area, but the data will be put in the context of the NE Iberian Peninsula.

- *Socio-ecological consequences of Neolithisation in the NE Iberian Peninsula.*

One of the main objectives of this research is evaluating the consequences of the adoption of the farming mode of production in social and ecological terms and, therefore, in the interaction between humans and environment. This objective will be addressed on an extra-local scale, assessing human impact in the Lake Banyoles surroundings during the early Neolithic, especially during the occupation of La Draga (7.27-6.75 cal ka BP).

- *Potential and contributions of archaeopalynology in lakeside settlement research.*

The last objective is focused on a local scale, with the aim of assessing the possibilities that the integration of palynological analysis offers to archaeological research. Firstly, site formation processes in pile-dwelling sites and human impact in the immediate surroundings of the settlement of La Draga are evaluated. Finally, the integration of archaeopalynology and geostatistics try to demonstrate the utility of pollen and NPP analysis to identify different environments or activity areas within a lakeside settlement.

2. STUDY AREA

2. Study area

2.1. Geography

Lake Banyoles is located within the municipalities of Banyoles and Porqueres, in the north-eastern Iberian Peninsula (Catalonia), in the region of Pla de l’Estany, one of the regions in the province of Girona (Fig. 2). For a better comprehension for international readers not familiar with Catalan geography, Pla de l’Estany region has been called the “Lake Banyoles area” in the published papers.

Pla de l’Estany consists of a plain around Lake Banyoles (173 m asl.), 35 km from the Mediterranean Sea and 50 km south of the Pyrenees, surrounded by medium-height mountains (600-985 m asl.). It is bounded by La Garrotxa (a pre-Pyrenean mountainous region with a topography marked by deep valleys −250-300 m asl.− and steep mountainous areas −highest peaks at 1558 m asl.−) to the north-west, L’Empordà basin connecting with the Mediterranean coast (few m asl.) to the north-east, and the region of Gironès to the south (Fig. 2).

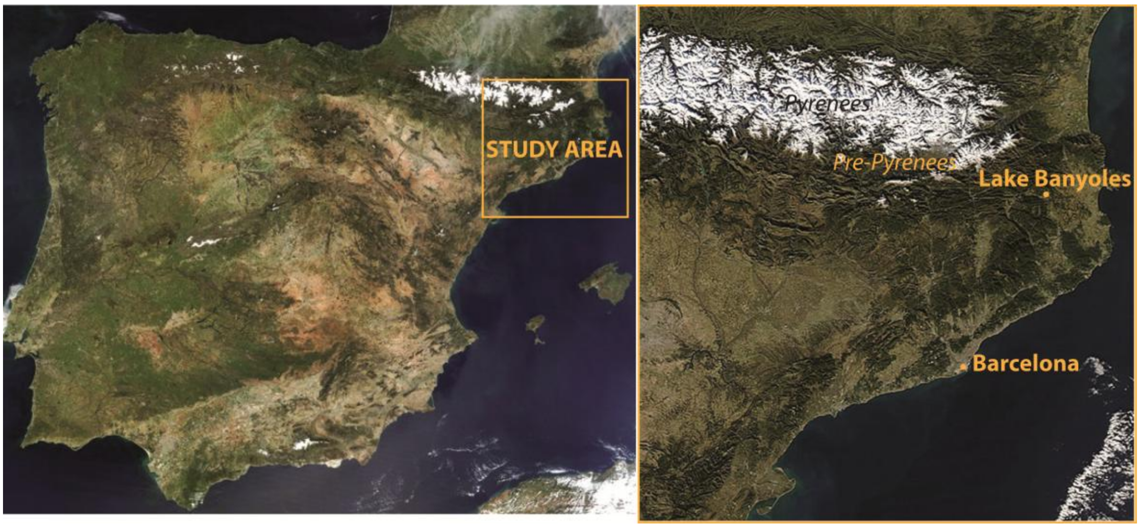

Figure 2. Location of the study area in the context of Iberia (left) and location of Lake Banyoles in the context of NE Iberia (right).

2.2. Climate

The climate in the NE Iberian Peninsula is defined as Mediterranean but with variations depending on the altitude and distance from the sea. The relief has a powerful influence on the climate in this region. The Mediterranean coast has low and irregular precipitation and the highest mean annual temperature (with a limited extent due to the presence of mountain ranges near and parallel to the coast). The humid Mediterranean or sub-Mediterranean located in inland regions is characterized by higher precipitation and cooler temperatures (see Fig. 3). Finally, the continental Mediterranean has low precipitation and contrasting temperatures, very warm in summer and cold in winter.

The climate in the Lake Banyoles area is defined as humid Mediterranean or sub-Mediterranean, with an annual precipitation of 750 mm and a mean annual temperature of 15°C. The average maximum temperature during July and August is 23°C, and the average minimum is 7°C in winter. The minimum monthly precipitation (10 mm) occurs during summer and in December. The climate in Banyoles follows the dynamics of the pre-Pyrenean area, with higher annual precipitation and lower mean annual temperature when compared with coastal areas and with southern inland regions (Fig. 3).

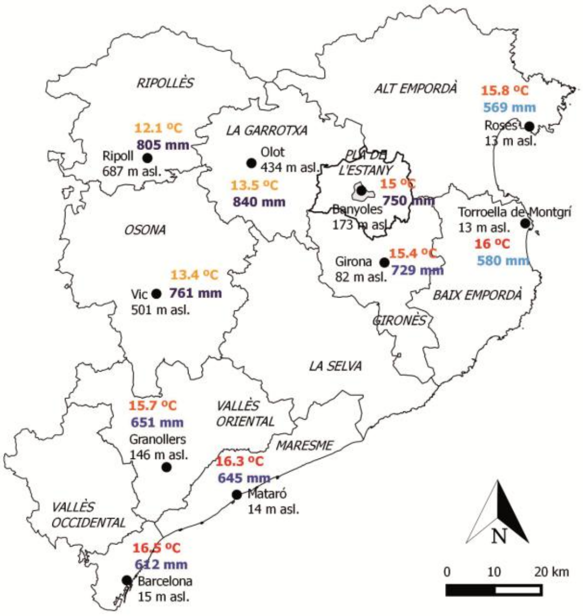

Figure 3. Climatic data from regions in NE Catalonia. Precipitations are represented in blue (higher values in dark blue, lower in slight blue) and temperatures in orange (higher values in dark orange, lower in slight orange).

2.3. Vegetation

The landscape in the NE Iberian Peninsula is extremely diverse due to the heterogeneous orography and climate in the territory. The vegetation is characterised by the presence of Meso/Thermo-Mediterranean vegetation on the Mediterranean coast and in the continental interior, with the dominance of evergreen sclerophyllous forests (*Quercus ilex*, *Quercus coccifera*, *Pinus halepensis*, *Pinus sylvestris*) and shrublands (maquia and garrigue). In the sub-Mediterranean area, located in inland regions close to the pre-Pyrenean slopes (500/1000-1600/1800 m asl.), humid Mediterranean forests (mixture of pines and deciduous *Quercus*, *Corylus avellana* and *Fagus sylvatica*) dominate in the landscape. Finally, boreal conifer forests (*Pinus uncinata* and *Abies alba*) are present in the subalpine zone (1600-2300 m asl) in the Pyrenees (Fig. 4).

Pla de l'Estany consists of a transition area between humid forests in the nearby mountainous area of La Garrotxa and the dominance of sclerophyllous trees on the coast. Dense vegetation formations in the mountains surrounding Lake Banyoles are dominated by a mixed forest of evergreen oak (*Quercus ilex*, *Quercus coccifera*, *Rhamnus alaternus*, *Phillyrea media*, *Ph. angustifolia*), deciduous oak (*Quercus humilis*, *Buxus sempervirens*, *Ilex aquifolium*) and pine forest (*Pinus halepensis*). In this context, shrublands (*Erica arborea*, *Rosmarinus officinalis*) are well represented. Along the lakeshore, there are helophytic communities represented by *Phragmites australis*, *Typha angustifolia*, *Lythrum salicaria* and several cyperaceous species (Gracia et al., 2001) and a riparian forest with *Fraxinus angustifolia*, *Alnus glutinosa* and *Salix atrocinerea*.

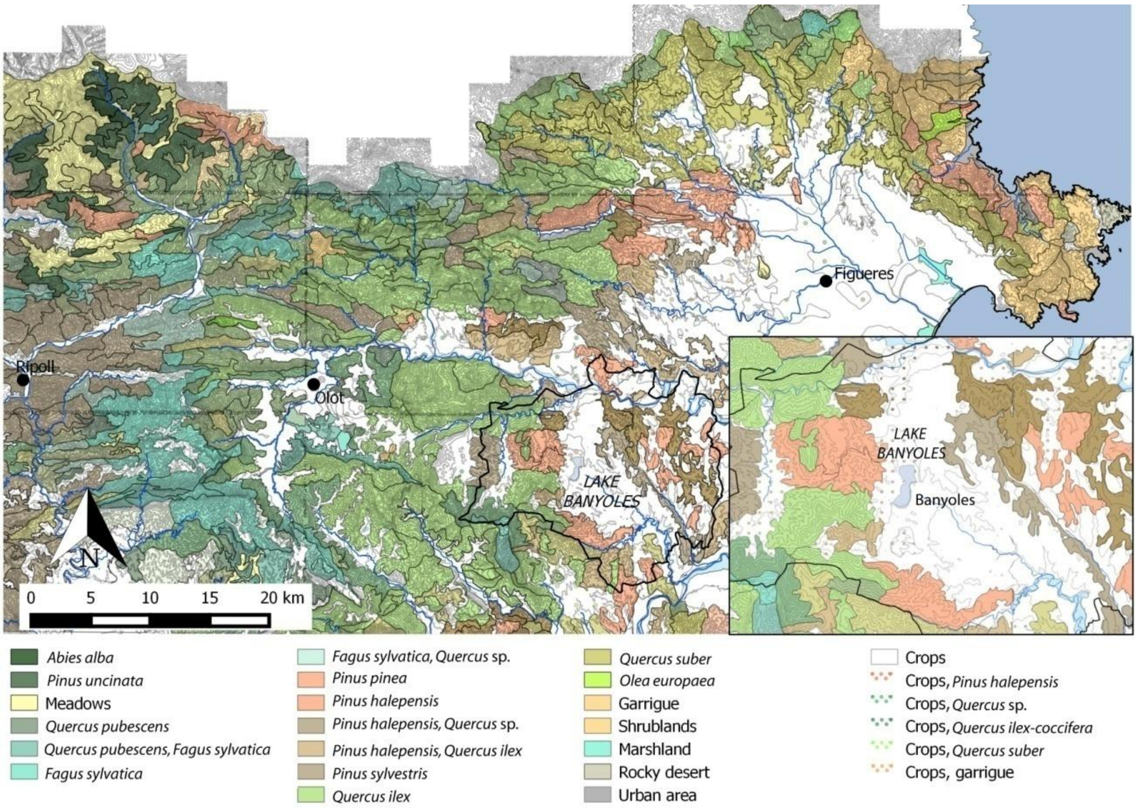

Figure 4. Map of vegetation in NE Catalonia. Source for vegetation map: Mapa Forestal de España (Zona 10)

2.4. Lake Banyoles

The lacustrine area of Lake Banyoles represents an outstanding Quaternary geological record. The formation of the lake is attributed to intense karstification, which is favoured by both the geological setting and the tectonic situation (Höbig et al., 2012). The pre-lacustrine substrate is composed by a sequence of Eocene formations: Perafita Formation (dolomites of the Late Ypresian), Beuda Formation (gypsum of the Early Lutetian) and Banyoles Formation (marls of the Late Lutetian). The dissolution of the Beuda Formation caused several dolines to form the multi-basin Lake Banyoles. This substrate is covered by Quaternary terrigenous deposits (Bischoff et al., 1994; Martínez et al., 1997; Höbig et al., 2012). The Pleistocene stratigraphy derived from the cores is characterised by carbonate-rich littoral calcarenites and muds covered by a Holocene peat layer (Pérez-Obiol and Julià, 1994; Valero-Garcés et al., 1998; Höbig et al., 2012). Systematic core exploration along the lakeshore during the 2008 and 2009 fieldwork (Bosch et al., 2010) enabled the identification of Holocene peat and organic clay deposits (Fig. 5) and the recovery of Holocene sedimentary sequences to apply detailed environmental analyses. Clayish and silty sediments would have been transported to the lake from streams while peat deposits would have formed by the deposition of decomposing organic matter from the lakeshore vegetation.

Lake Banyoles is a karst lake associated with a large karst aquifer system located in a tectonic depression, fed by underground water coming from the region of Alta Garrotxa (20 km away to the north-west). The lake is approximately 2100 m long and 750 m wide with an average depth of 15 m that in several locations can reach up to 46 m (Casamitjana et al., 2006; Höbig et al., 2012). The lake water is supersaturated in calcite, causing precipitation, and thus constituting the main component of the lake sediments (Bischoff et al., 1994). Lake Banyoles is defined as oligo-mesotrophic, and water temperatures range between 8–25 °C on the surface and 8–17 °C in deep water (Serra et al., 2002). Discharge is mainly carried out by five artificial outlets on the SE edge of Lake Banyoles (Serra et al., 2005) built by Benedictine monks since the 9th century.

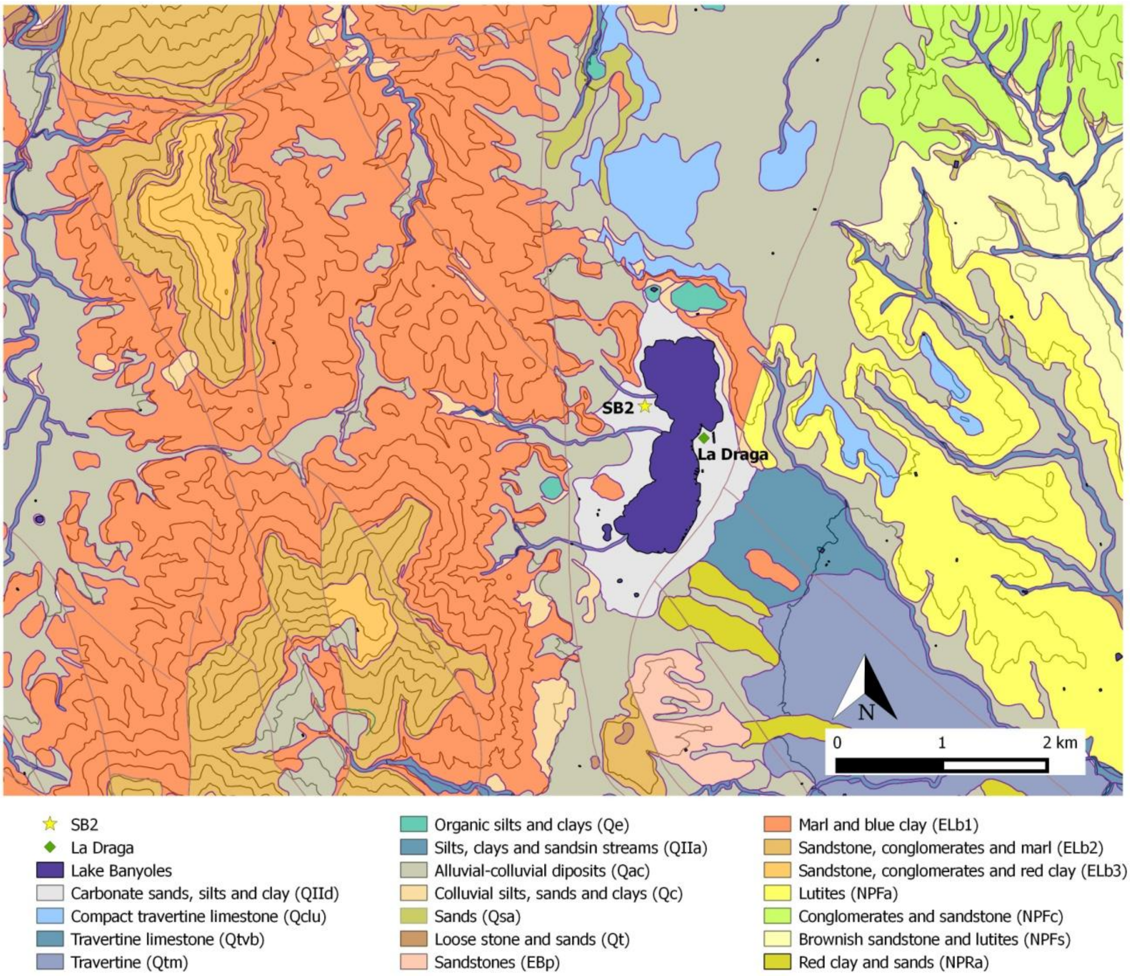

Figure 5. Geological context in the Lake Banyoles area. Source: Institut Cartogràfic de Catalunya ICC).

2.5. La Draga

La Draga is located on the eastern shore of Lake Banyoles (173 m asl) (Girona, Spain) (Fig. 1). The site provides evidence of one of the earliest farming societies in open-air settlements in NE Iberia, dated to 7.27-6.75 cal ka BP (Bosch et al., 2012; Palomo et al., 2014). Despite the site occupying an area of over 8000 m^2 (Bosch et al., 2000), archaeological investigations to date (Bosch et al., 2000, 2006, 2011; Palomo et al., 2014, 2016) have concentrated on an area of *ca*. 3000 m^2 (of which 945 m^2 have been excavated, in the northern part of the settlement, where the site is best preserved) (Fig. 6). Fieldwork was undertaken in multiple seasons from 1991 to 2016. From 1991 to 1995 and 2013 to 2016, the excavations concentrated on Sector A, where the archaeological level is above the water table and hence waterlogged conditions have not continued until the present. The archaeological level is in the phreatic layer in Sector B (excavated from 1997 to 2005) and Sector C is totally under water (excavated between 1994 and 2005). New excavations in 2010-2013 focused on an area of 58 m^2 called Sector D (Fig. 7), which is located to the south of Sector B and displays similar preservation conditions.

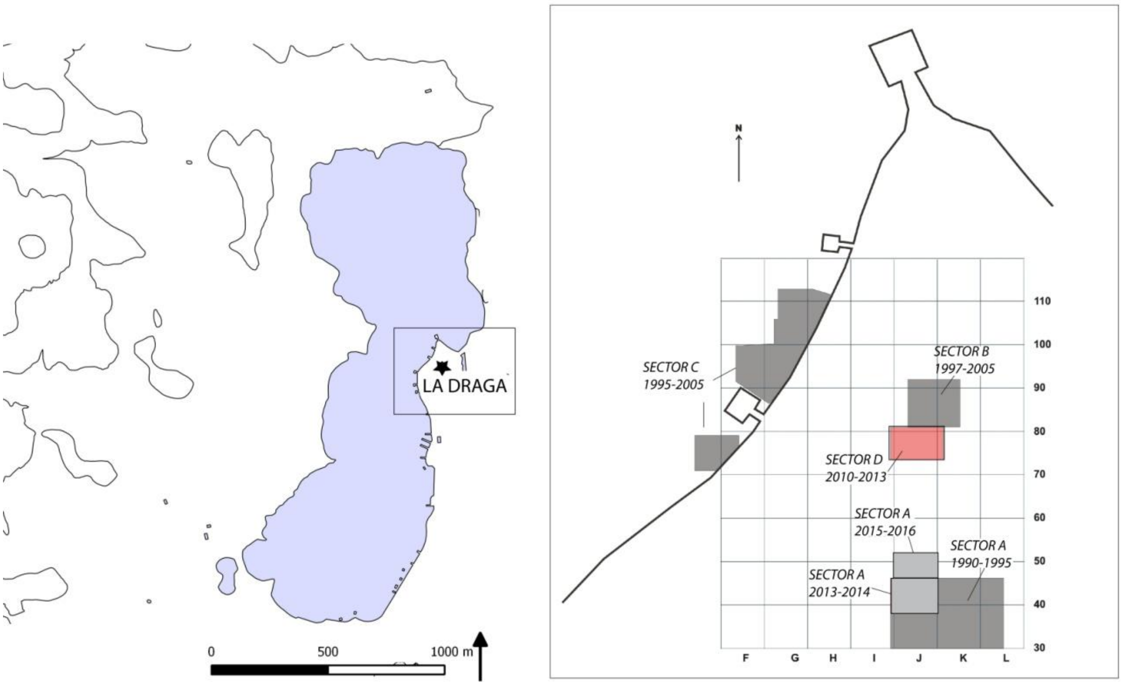

Figure 6. Location of La Draga on the eastern shore of Lake Banyoles (left) and location of excavated sectors (right). In red, the sector studied in this thesis (Sector D).

Two different construction phases during the early Neolithic occupation (both dated within the late Cardial Neolithic according to pottery styles) have been documented in Sector D: Phase I (7.27–6.93 cal ka BP) is characterized by the collapse of wooden structures, which have been preserved in an anoxic environment; Phase II (7.16–6.75 cal ka BP) presents several pavements of travertine stone. The levels in Phase II enjoyed less optimal conditions of preservation and the organic material is mainly found in a charred state, although some hard-coated uncharred material is found occasionally (Bosch et al., 2000, 2011; Antolín, 2013; Palomo et al., 2014).

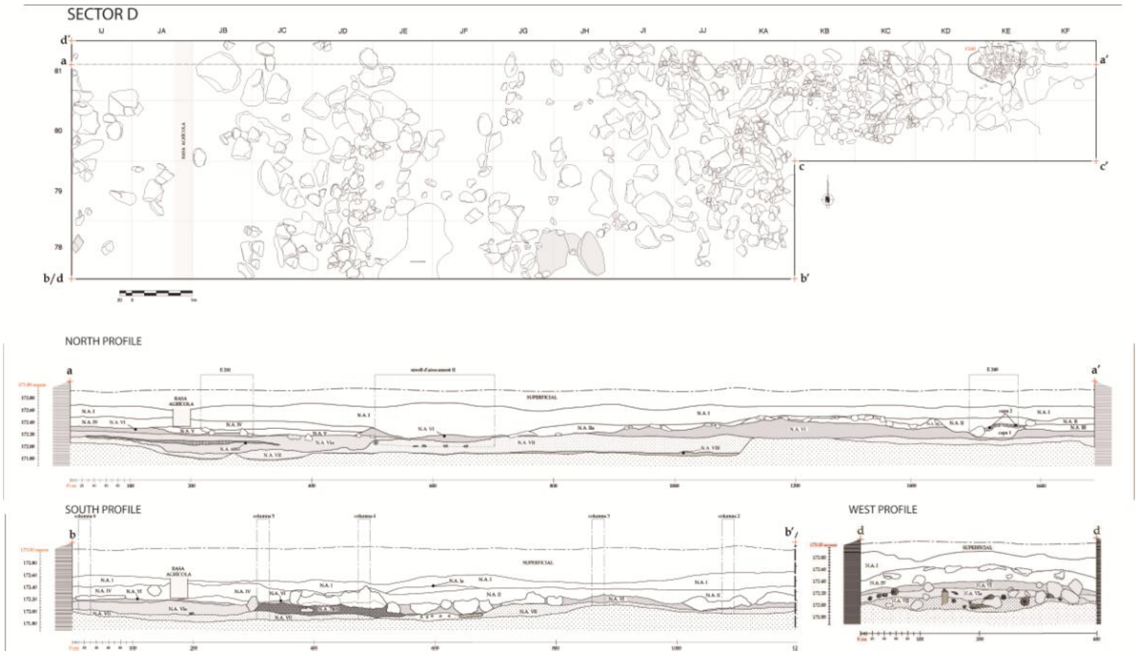

Figure 7. Plan view and cross sections of SectorD.

Phase I at La Draga is characterised by a palimpsest of wooden remains, and it is difficult to define the shape and location of huts and structures. The huts would have been built on stilts and platforms above the water, but the coexistence of land constructions is possible, as attested in other European regions (Leuzinger, 2000; Menotti, 2001). In that context, the 1st Phase sediments (Level VII) would have been formed in exterior areas, between constructions and beneath the huts, in a wetland environment at least seasonally puddled.

The waterlogged context of Phase I provided excellent preservation of the bioarchaeological record (Fig. 8), constituting by far the richest assemblage from the early Neolithic period in the Iberian Peninsula. The available zooarchaeological (Saña, 2011; Navarrete and Saña, 2013) and archaeobotanical (Antolín, 2013) data recovered at La Draga are indicative of small-scale, labour-intensive cultivation and small-scale herding in an intensive mixed farming strategy (Antolín et al., 2014).

According to the species identified in the charcoal analysis, firewood was gathered in oak forests and the riparian vegetation surrounding the site. Oak was the most frequently gathered species and was used as fuel and timber. River bank vegetation was also frequently exploited and, in this case, both arboreal taxa and the shrub and lianoid layer were used (Piqué, 2000; Caruso-Fermé and Piqué, 2014). The impact of Neolithic communities in the surroundings of the settlement also seems to be confirmed by the increased presence in shrub taxa in the charcoal assemblage during the latter occupation phase at La Draga (Caruso-Fermé and Piqué, 2014).

Figure 8. Exceptional bioarchaeological remains recovered in the site of La Draga. a) Ornaments in a *Prunus avium* pit and bone, b) charred cereal grains, c) basketry, d) cattle skull, e) wooden tools, f) oak posts

Previous pollen analyses undertaken in Lake Banyoles (Pérez-Obiol and Julià, 1994) showed a fall in oak values around 7.0 cal ka BP, thus coinciding with the Neolithic settlement. Nevertheless, this previous work was hindered by low chronological resolution in the Early/Mid-Holocene part of the sequence and therefore a new sequence was necessary in order to understand vegetation changes that occurred during this period. The regression of deciduous *Quercus* has also been attested in previous analyses at La Draga (Pérez-Obiol, 1994; Burjachs, 2000), which show high oak values in pre-occupation layers and a major decline in this taxon in the 1st phase layers.

3. MATERIAL AND METHODS

3. Material and methods

Diverse material and methods have been employed to carry out this PhD thesis, most of them developed by the PhD candidate, while others consist of contributions from co-authors. In this section, the materials studied in the frame of this thesis will be described, as well as the methods applied by the candidate. Finally, a description of the contribution of co-authors is detailed in the last sub-section.

3.1. Sampling

Different sampling strategies were developed for achieving the goals stated in the introduction. First of all, a core (SB2) was extracted in the Lake Banyoles shore to carry out the study of a sedimentary sequence from a natural deposit. Then, the sampling at the archaeological site of La Draga (Sector D) followed two different strategies: vertical sampling to obtain a diachronic record of the various layers and phases; and horizontal sampling of the 1st phase (Level VII) in order to carry out spatial analysis of pollen and non-pollen palynomorphs (NPP).

3.1.1. The SB2 core

A 370 cm long core (SB2 core) was obtained from the western shore of Lake Banyoles (42°07′44.70″N 2°45′06.64″E, Alt. 174 m asl) (Fig. 5). The choice of the coring location was based on systematic core exploration along the lakeshore during the 2008 and 2009 fieldwork seasons (Bosch et al., 2010). The results of that exploration enabled the identification of peat and organic clay deposits, allowing the recovery of a complete sequence of Holocene sediments for detailed environmental analyses. The SB2 core was drilled beside the place where the S96 core was extracted in 2009, near the Riera del Castellar river, the main watercourse draining to the lake. The location near the river allows the detection of changes in its terrigenous input to the lake. For this purpose, a Van Walt/Eijkelkamp mechanical drilling machine was used. SB2 core was located 160 m away from the present lakeshore. Four stratigraphical units were distinguished (Fig. 9), based on sedimentary facies: yellowish-brown silt (0–159 cm), greyish silty clay (159–174 cm), dark silty clay (174–281 cm) and carbonate sands (281–370 cm).

The intermediate organic dark silty clay unit exhibited outstanding pollen preservation and high resolution sampling (contiguous 1cm thick samples between 179 and 281 cm) was carried out. The age-depth model was built using the smooth spline interpolation method based on 6 AMS dates (Table 1), located at 173, 201, 215, 237, 257 and 276 cm depth (Fig. 9), but pollen and sedimentary charcoal were analysed up to 281 cm depth. Therefore, the age-depth curve (Fig. 10) (Fig. 2) was extended over the undated 5 cm, as it was within the same sedimentary facies. The studied organic unit ranges between 8.9 cal ka BP and 3.35 cal ka BP, and thus allows the reconstruction of the vegetation history from the late Early Holocene to the Late Holocene, covering Late Prehistory from the Mesolithic to the Bronze Age.

Figure 9. Sedimentary sequence of SB2 core. Dates BP are indicated and high-resolution analysis (every 1 cm) was applied in the green section.

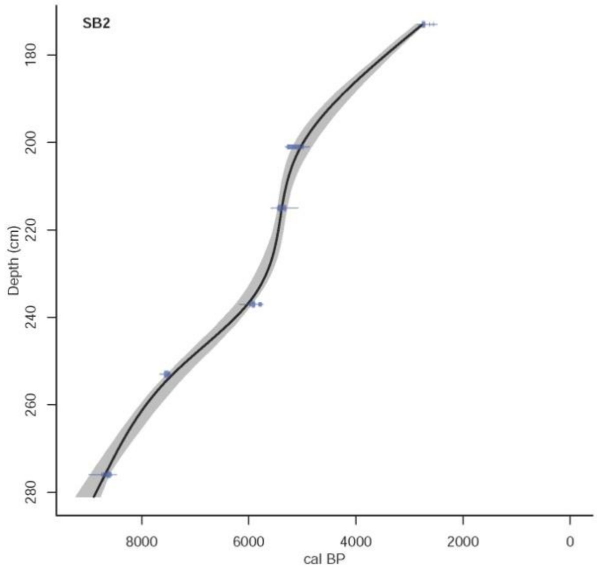

Figure 10. Age-depth model based on six AMS radiocarbon dates. Estimation of age along the entire profile by a smooth spline technique using Clam 2.2 (Blaauw, 2010).

3.1.2. La Draga: archaeological profiles in Sector D

In order to obtain information on the palaeo-environment of the Early Neolithic communities that occupied La Draga, two sequences (South and West) were collected from the profiles of the site (Fig. 11) for pollen, NPP and macrofossil analyses during an archaeological excavation in 2012. Subsampling consisted of retrieving about 2 or 3 1cm-thick samples per layer (see Table 1 and Fig. 11) for LOI (loss on ignition) and pollen and NPP analyses, and one 25 cm^3 sample per layer for macrofossil analysis. During an excavation in 2014, one new sequence (West II) was subsampled in the field, retrieving samples every 5 cm for LOI, pollen and NPP analyses.

Table 1. Sedimentological description of archaeological layers at the site of La Draga.

Phase	Layer	Description
Post-Neolithic	I	Peat, affected by modern agricultural works in some points of the site (i.e. south profile).
	II	Base of the peat layer, covering archaeological layers.
La Draga	III	Clay with abundant travertine inclusions, above travertine pavement.
2nd phase	IV	Greyish terrigenous clay among travertine stone structure.
	VI	Greyish terrigenous clay below travertine stone pavement.
	7001	Charred storage structure.
La Draga	VIa	Dark grey clay, with abundant charred particles, filling up the collapse of wooden structures.
1st phase	VII	Dark organic clay below collapse of wooden structures.
Pre-Neolithic	IX	Lake marl, natural sediments before Neolithic settlement.

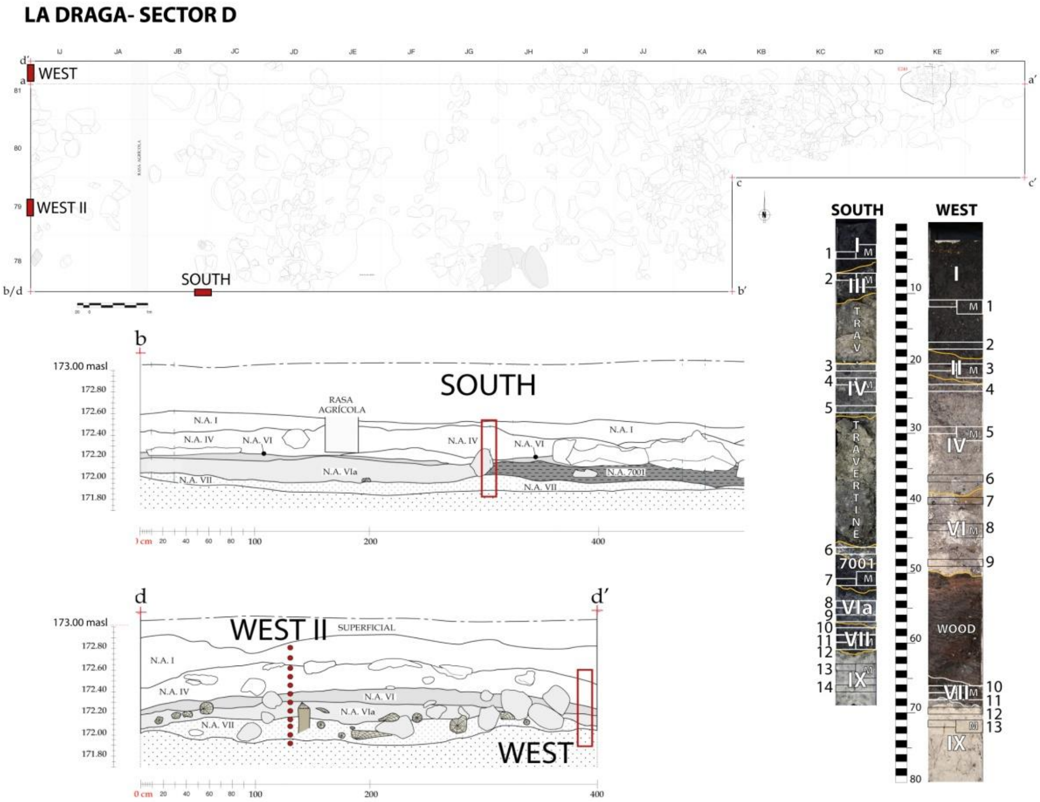

Figure 11. Plan view and cross section of Sector D at La Draga. Red rectangles in the plan view mark the spatial distribution of the three sequences analysed. In the cross section, red rectangles show columns in the West and South profiles; red dots, subsamples retrieved in the field from West II profile.

3.1.3. La Draga: horizontal sampling in Sector D

The sampling strategy consisted of retrieving sediment samples from Level VII in Sector D (Fig. 12), 1 cm^3 for Loss on Ignition (LOI), 3 cm^3 for pollen and NPP and 5 cm^3 for macrofossil identification. For paleoparasitological analysis, samples of 10 to 50 g of sediment were collected and sent to the Chrono-environment laboratory (Besançon, France). Sector D, consisting of a surface area of 58 m^2, 20 m from the lake shore, was excavated from 2010 until 2013, although samples for pollen and NPP analyses were collected in the 2012 and 2013 fieldwork seasons. For that reason, only the western part of Sector D (32 m^2) has been analysed. Level VII consist of dark organic clay preserved in anoxic conditions and formed during the 1st phase of occupation at La Draga (7270–6930 cal BP). Coordinates were attributed to each sample considering the centroid in a one square-metre grid.

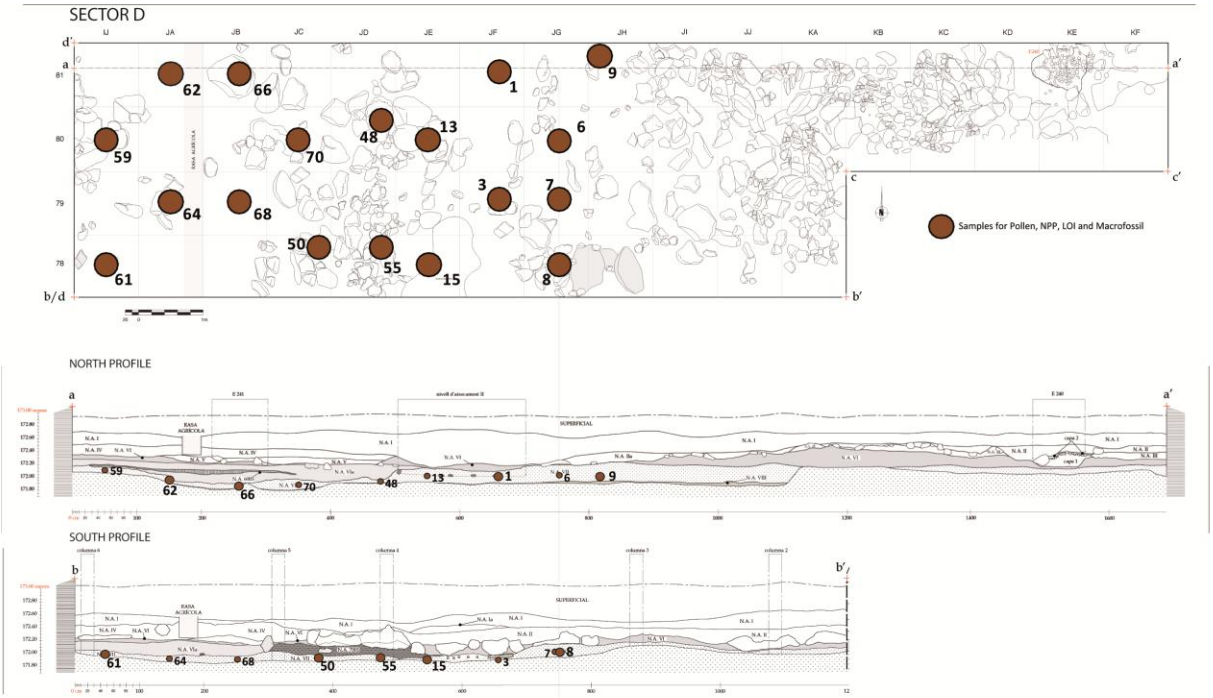

Figure 12. Plan view, cross-section and location of Level VII samples (brown dots).

3.2. Pollen and NPP analysis

The preparation of the samples followed standard methods (Burjachs et al., 2003) using treatment with HCL, NaOH, flotation in heavy liquid, HF and final mounting in glycerine. Samples from the core SB2 were processed in the Laboratori d'Arqueobotànica in IPHES (Tarragona, Spain), while samples from La Draga were prepared in the Laboratori de Botànica in Universitat Autònoma de Barcelona (Bellaterra, Barcelona, Spain).

300–350 terrestrial pollen grains were counted in the core SB2 using a Nikon Eclipse 50i microscope (GEODE Laboratoire, Université Toulouse Jean Jaurès- CNRS), fitted with ×10 oculars and a ×50 objective. In the case of La Draga samples, the minimum pollen sum was chosen according to an experimental study (see Annex 1). In that context, 300-500 pollen grains were counted using an Olympus Bx43 microscope (Laboratori d'Arqueobotànica, Universitat Autònoma de Barcelona) fitted with ×10 oculars and ×40/60 objectives: 300-350 in inorganic sediments and in non-anthropic sediments, and 400-500 in organic sediments affected by human impact, where anthropogenic taxa are overrepresented. Cyperaceae, *Typha latifolia*, *Typha/ Sparganium* (and *Alnus* in SB2) were excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Reille (1992) and Cerealia-type was defined according to the morphometric criteria of Faegri and Iversen (1989). Pollen concentration is expressed in pollen grains/gram of sediment (pollen grains/cm^3 of sediment in Revelles et al., submitted) following the volumetric method (Loublier, 1978).

Non-pollen palynomorph (NPP) percentages correspond to NPP/pollen sum of terrestrial taxa. NPP identification followed van Geel (1978, 2001), van Geel et al. (2003), Gelorini et al. (2011) and Cugny (2011). Given the scarcity of palaeorecords providing descriptions and illustrations of non-pollen palynomorphs in the Iberian Peninsula, further accentuated in NE Iberia, some NPP were described for the first time and named using a code with the prefix UAB (Universitat Autònoma de Barcelona) and a sequential number. The pollen analysis was carried out under the supervision of Dr. F. Burjachs (ICREA-IPHES-URV) and the NPP analysis was carried out in the IBED (University of Amsterdam) under the supervision of Dr. B. van Geel.

3.3. Sedimentary charcoal analysis

Contiguous samples of 1 cm^3 were retrieved from the core, soaked in 10%NaOH solution for 24 h for peat digestion, then in 30% H_2O_2 solution for 24 h to bleach non-charcoal organic material (Rhodes, 1998). Quantification of charred particles was performed with the sieving method (Carcaillet et al., 2001) with a 150 μm mesh size (Clark, 1988; Ohlson and Tryterud, 2000) in order to reconstruct local fire history. Charcoal concentration (charcoal particles/cm^3) was expressed as charcoal accumulation rate (charcoal particles/cm^2 years^{-1}) based on the sedimentation rate estimated by the age-depth model. This analysis was carried out in GEODE Laboratoire (Université Toulouse Jean Jaurès- CNRS), under the supervision of Dr. D. Galop and Dr. W. Finsinger.

3.4. Macrofossil analysis

Samples of 25 cm3 (5 × 2.5 × 2 cm) were retrieved at 10 cm intervals from different pollen zones and sedimentological units in the core SB2 and from every layer in South and West archaeological profiles at La Draga. The samples were boiled in 5% KOH solution for peat digestion and sieved with a 150 μm mesh size. Then, macrofossils were transferred to a Petri dish and scanned using a stereoscopic microscope (10–50×).

Moss leaves, cyperaceous epidermal tissues, and small seeds (*Juncus* sp.) had to be mounted onto temporary slides and examined at high magnifications (100–400×). Identifications were made with literature and reference collections of seeds and vegetative plant remains (Cappers et al., 2006; Mauquoy and van Geel, 2007). In the case of La Draga, only vegetal tissues, fungal macro-remains, bryozoans and insects have been identified, given that seeds and fruits, charcoal and wooden remains from La Draga have already been widely analysed and published (Piqué, 2000; Bosch et al., 2006; Antolín, 2013; Caruso-Fermé and Piqué, 2014; Antolín and Jacomet, 2015; López, 2015). This analysis was carried out in IBED (University of Amsterdam) under the supervision of Dr. B. van Geel, with the assistance of Dr. O. Brinkkemper (Cultural Heritage Agency of the Netherlands, Amersfoort) for the identification of seeds from the SB2 core.

In the case of the horizontal sampling at La Draga, 5 cm^3 samples were boiled in 5% KOH solution for peat digestion and sieved with a 150 µm mesh size. Then, macrofossils were transferred to a Petri dish and scanned using a stereoscopic microscope (10–50×) in the Laboratori d'Arqueobotànica (Universitat Autònoma de Barcelona). Seeds and fruits, vegetal tissues, fungal macro-remains, bryozoans and insects have been identified, according to literature and reference collections (Cappers et al., 2006; Mauquoy and van Geel, 2007). The identification of seeds and fruits was carried out by A. Berrocal under the supervision of Dr. F. Antolín (IPAS, University of Basel, Switzerland).

3.5. Loss on Ignition (LOI)

Samples of 3 g were retrieved from the archaeological profiles and samples of $1cm^3$ from Level VII for the application of the loss on ignition (LOI) method (Heiri et al., 2001). Firstly, samples are dried for 48 h at 60 °C. Afterwards, organic matter is oxidized for 4 h at 550 °C to carbon dioxide and ash. In a second reaction, carbon dioxide is evolved from carbonate for 4 h at 950 °C, leaving oxide. The weight loss during the reactions is measured by weighing the samples before and after heating and this weight loss is closely linked to the organic matter and carbonate content of the sediment (Bengtsson and Enell, 1986). A molecular conversion factor (weight loss at 950 °C × 2.27) was used to assess the proportion of carbonates ($CaCO^3$) in the sediment (Dean, 1974), where 2.27 is the result of molecular weight of $CaCO^3$ (100.088 g/mol)/molecular weight of CO^3 (44.009 g/mol). This analysis was carried out in the Laboratori del Grup de Recerca en Àrees de Muntanya i Paisatge (Universitat Autònoma de Barcelona).

3.6. Numerical analysis

Several statistical methods have been applied in the studies compiled in this PhD thesis, from the age-depth model and CharAnalysis in the SB2 core to the Multivariate analysis and application of geostatistics to the record from La Draga.

The numerical analyses involved in the SB2 core were the age-depth modelling by Clam 2.2. (Blaauw, 2010) and the statistical analysis of sedimentary charcoal by CharAnalysis (Higuera et al., 2009). Training in both methods was carried out under the supervision of Dr. W. Finsinger, firstly in GEODE Laboratoire (Université Toulouse Jean Jaurès-CNRS), then in CBAE (Université Montpellier II- CNRS).

The application of multivariate analysis (PCA, DCA, correlation analysis –Past v.3.12.) and geostatistics (testing adjustment of models of distribution –Systat v.13–, spatial autocorrelation by Moran's i –SpaceStat 4–, interpolation by algorithms of Kriging –Rockworks 17– and Inverse Distance Weighting –Past v.3.12.–) was carried out under the supervision of Dr. J.A. Barceló in Laboratori d'Arqueologia Quantitativa (LAQU) at Universitat Autònoma de Barcelona.

3.7. Other methods and techniques

The sedimentological study of the SB2 core performed by S. Cho, under the supervision of Dr. E. Iriarte in the Laboratorio de Evolución Humana (Universidad de Burgos), and consisted of the stratigraphical characterization, sedimentary facies description, mineralogical analysis by X-ray diffraction (XRD) and a high-resolution geochemical analysis (XRF core scanner).

In the macrofossil samples from the SB2 core where charcoal macro-remains were recovered, the identification was carried out by Dr. R. Piqué with an Olympus BX51 optical microscope in the Laboratori d'Arqueobotànica (Universitat Autònoma de Barcelona).

Although they did not directly analyse the materials involved in this PhD thesis, other co-authors contributed data from their studies at La Draga that substantially improved the quality of papers, enabling the integration of diverse (bio)archaeological data essential for the kind of interdisciplinary research that was one of the purposes of this PhD thesis. Dr. F. Antolín and Dr. R. Buxó provided carpological data in Revelles et al. (2014); Dr. M. Berihuete, plant tissues data in Revelles et al. (2014); Dr. R. Piqué and Dr. L. Caruso, anthracological data in Revelles et al. (2014); Dr. López-Bultó, dendrological and wooden architecture data in Revelles et al. (2014) and Revelles et al. (submitted); N. Morera, spatial analysis data in Revelles et al. (submitted); A. Berrocal, carpological data in Revelles et al. (submitted); C. Maicher and Dr. M. Le Bailly, parasitological data in Revelles et al. (submitted) and archaeological data from La Draga by Dr. A. Palomo, Dr. R. Piqué and Dr. X. Terradas in Revelles et al. (2014, 2015, submitted).

4. SCIENTIFIC PAPERS

The scientific papers have been divided in base of the three main objectives stated in the introduction. This PhD thesis is composed by a total of 6 publications, 2 papers for each objective. Despite some papers provide data and answer to more than one of the objectives, they are mainly focused on one of them. Thus, the papers Revelles et al. (2015; in Palaeogeography, Palaeoclimatology, Palaeoecology) and Revelles and van Geel (2016; in Review of Palaeobotany and Palynology) are linked to the objective *Vegetation history, climate change and human impact during Middle Holocene in in the Lake Banyoles area.* The papers Revelles et al. (2014; in Environmental Archaeology) and Revelles (2016; in Journal of Archaeological Science: Reports) belong to the objective *Socio-ecological consequences of Neolithisation in the Lake Banyoles area* and Revelles et al. (2016; in Review of Palaeobotany and Palynology) and Revelles et al. (submitted to Journal of Archaeological Science) to the objective *Potential and contributions of archaeopalynology in lakeside settlements research.*

4. 1. VEGETATION HISTORY, CLIMATE CHANGE AND HUMAN IMPACT DURING MIDDLE HOLOCENE IN THE NE IBERIAN PENINSULA.

- Mid-Holocene vegetation history and Neolithic land-use in the Lake Banyoles area (Girona, Spain).
- Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia).

4.1.1. Mid-Holocene vegetation history and Neolithic land-use in the Lake Banyoles area (Girona, Spain).

Palaeogeography, Palaeoclimatology, Palaeoecology, 2015, 435: 70-85.

Mid-Holocene vegetation history and Neolithic land-use in the Lake Banyoles area (Girona, Spain).

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Abstract

This paper focuses on high-resolution analysis of pollen and sedimentology and botanical macro-remains analysis in a core from Lake Banyoles (Girona, Spain). The core sequence comprises a high resolution mid-Holocene (*ca*. 8.9‑3.35 cal ka BP) vegetation succession, and sedimentological, geochemical and geomorphological proxies are related to both climatic and anthropogenic causes. Deforestation processes affected natural vegetation development in the Early Neolithic (7.25‑5.55 cal ka BP) and Late Neolithic (5.17‑3.71 cal ka BP), in the context of broadleaf deciduous forest resilience against cooling and drying oscillations. Changes in sedimentation dynamics and in lake water level caused the emergence of dry land on the lake margin where riparian forest was established from 5.55 cal ka BP onwards. The data show that in the context of an increasing aridification process, Neolithic land-use played an important role in vegetation history and environmental evolution.

Keywords: Neolithic land-use, Pollen, Macrofossils, Geochemical analysis, Lake Banyoles, Iberian Peninsula

1. Introduction

The Holocene, despite being a relatively stable climatic period compared to the previous glacial period, has been punctuated by cooling and drying oscillations recorded in oxygen isotope data of ice cores (Grootes et al., 1993; O'Brien et al., 1995; Grootes and Stuiver, 1997), coral records (Beck et al., 1997), stalagmites (Bar-Matthews et al., 1999; Zanchetta et al., 2007; Boch et al., 2009; Moreno et al., 2010;), marine archives (Sirocko et al., 1993; Bond et al., 1997; Cacho et al., 2001, 2006; Fletcher et al., 2010, 2013), and lacustrine records (Harrison and Digerfeldt, 1993; Magny, 1998; Magny et al., 2003, 2013; Giraudi et al., 2011).

These climatic fluctuations lead to environmental variability. The temperate and humid climate in Early Holocene favoured the development of deciduous broadleaf forests in southwest Europe (Jalut et al., 2009), vegetation that was frequently dominant in the Mediterranean region of the Iberian Peninsula (Burjachs et al., 1997; Carrion et al., 2010; Pérez-Obiol, 2007; Pérez-Obiol et al., 2011). Afterwards, an increasing aridification process correlated with decreasing insolation and summer temperatures in theNorthern Hemisphere (Porter and Denton, 1967; Denton and Karlén, 1973), caused the development of sclerophyllous and evergreen forests following a south‑north gradient in different areas of the Mediterranean region (Carrion et al., 2010; Denèfle et al., 2000; Jalut et al., 2000, 2009; Roberts et al., 2001; Sadori and Narcisi, 2001; Sadori, 2013).

Nevertheless, human activities should be considered in order to comprehend environmental changes occurred since Middle Holocene onwards. In fact, some authors place the adoption of farming activities in the onset of the Anthropocene (Ruddiman, 2003; Ruddiman et al., 2015). Thus, the anthropogenic factor should be kept in mind as a relevant element in vegetation evolution from the start of the Neolithic onwards, as shown by several studies in the Mediterranean area (Riera and Esteban-Amat, 1994; Dupré et al., 1996; Carrión and van Geel, 1999; Sadori and Narcisi, 2001; Yll et al., 2003; Carrión et al., 2009). In this paper we focus on a mid-Holocene pollen record from Lake Banyoles, when the establishment of the first farming societies changed the relationship between humans and environment, resulting in the onset of an increasing process of landscape disturbance.

The Lake Banyoles area is remarkable for its evidence of early farming communities in the Iberian Peninsula, such as those attested at La Draga archaeological site, and also for the possibility it provides of relating the archaeological sites with palaeoecological records obtained from lacustrine and peat deposits in the lake surroundings. Previous palaeoecological analyses have been carried out in the study area (Pérez-Obiol and Julià, 1994; Höbig et al., 2012). Pérez-Obiol and Julià (1994) mainly focused on the Pleistocene records, but they also presented data about the vegetation cover at the onset of the Holocene in Banyoles, showing the dominance of broadleaf deciduous tree forests, especially deciduous *Quercus* and *Corylus*.

La Draga is a waterlogged Neolithic site on the eastern shore of Lake Banyoles. The archaeological research carried out at the site revealed evidence for intensive farming activity during the late 8th and early 7th millennium cal BP (Tarrús, 2008; Palomo et al., 2014). After eighteen years of excavations at the site, a new research project was started in 2008, including a survey of the lake shores (both on land and under water), aiming to locate new evidence of settlement sites and human activity of prehistoric societies (Bosch et al., 2010; Terradas et al., 2013). Holocene sediments were cored at locations placed at regular distances along the lakeshore during the 2008 and 2009 fieldwork seasons.

The reconstruction of past social activities and the impact on the environment requires an interdisciplinary approach in which several fields of research must be combined, such as archaeology, sedimentology and palaeoecology. The main goal of such an analysis should be to reveal the development of the relationship between changing environmental conditions and the factors that control climatic fluctuations, as well as the influence of all this on socioeconomic strategies.

Therefore, the main goals of this study are: i) to comprehend vegetation change patterns and their causes. ii) To evaluate the relationship between vegetation patterns and sedimentation dynamics and their possible link with environmental changes. iii) To assess the impact on the landscape of the first farming societies.

2. Study area

2.1. Environmental and geographical settings

The study site is located in the northeastern Iberian Peninsula, 35 km from the Mediterranean Sea and 50 km south of the Pyrenees (Fig. 1). Lake Banyoles is a karst lake associated with a large karst aquifer system located in a tectonic depression, fed by underground water. The lake is approximately 2100 m long and 750 m wide with an average depth of 15 m that in several locations can reach up to 46 m (Casamitjana et al., 2006; Höbig et al., 2012).

The climate in the Banyoles region is defined as humid Mediterranean, with an annual precipitation of 750 mm and a mean annual temperature of 15 °C. The average maximum temperature during July and August is 23 °C, and the minimum average is 7 °C in winter. The minimum monthly precipitation (10 mm) occurs during summer and in December.

Dense vegetation formations in the mountains surrounding Lake Banyoles, are dominated by a mixed forest of evergreen oak (*Quercus ilex*, *Quercus coccifera*, *Rhamnus alaternus*, *Phillyrea media*, *Ph. angustifolia*), deciduous oak (*Quercus humilis*, *Buxus sempervirens*, *Ilex aquifolium*) and pine forest (*Pinus halepensis*) (Fig. 1). In this context, shrublands (*Erica arborea*, *Rosmarinus officinalis*) are well represented. Along the lakeshore, there are helophytic communities represented by

Phragmites australis, *Typha angustifolia*, *Lythrum salicaria* and several cyperaceous species (Gracia et al., 2001).

2.2. Archaeological background

Located half-way along the eastern shore of Lake Banyoles, La Draga is the most important archaeological site in the region, providing a detailed bioarchaeological record that is unique for the Iberian Peninsula thanks to anoxic preservation conditions, with an Early Neolithic (Cardial Neolithic) occupation (7.27‑6.75 cal ka BP; Bosch et al., 2012; Palomo et al., 2014).

Other evidence of prehistoric settlements around the lake are scarce (Tarrús, 2000). An individual burialwas found in Fàbrica Agustí -not far from La Draga- and attributed to the Middle Neolithic (Fig. 1). On the opposite lake shore there is some evidence of the Late Neolithic-Chalcolithic and Late Bronze Age located around the church of Santa Maria de Porqueres, as well as worked wooden remains, probably a canoe, documented by underwater surveying and dated in 3.20-3.18 cal ka BP (Bosch et al., 2012).

In a more regional perspective, there is some evidence of occupation in Serinyà Caves (4‑5 km away from Lake Banyoles) and Esponellà Caves (10 km away). At those sites several archaeological remains from the early Neolithic to the Early Bronze age were found during the 20th century (Tarrús, 2000). The most outstanding are specified in Table 1 and Fig. 1. Most of the sites are small rock shelters where the finds were casual, or made in the course of old archaeological excavations. These occupations were dated indirectly, based on ceramic styles. Regional chrono-cultural periods have been established by Barceló (2008).

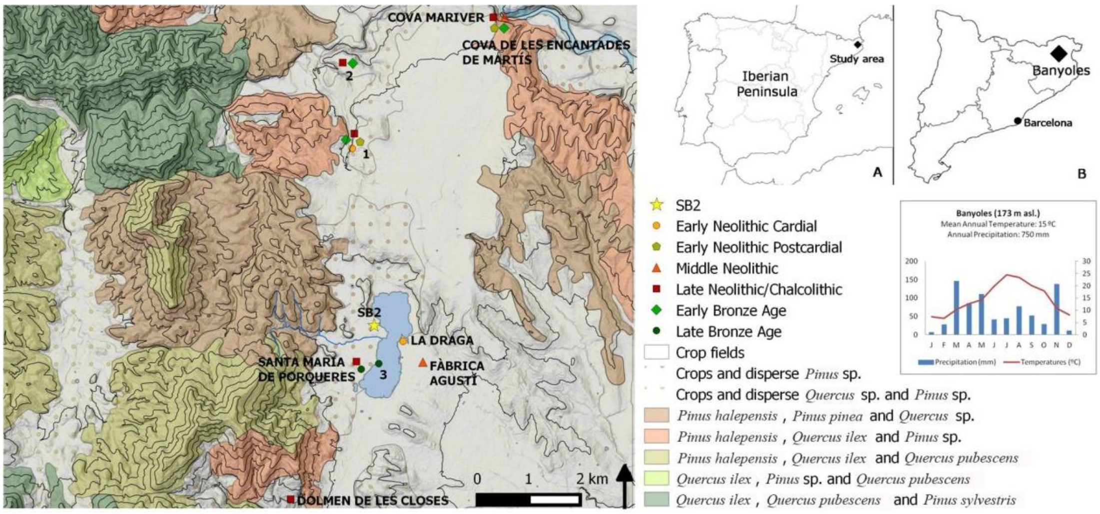

Figure 1. Location of the coring site and surrounding archaeological sites. Source for vegetation map: Mapa Forestal de España (Zona 10). Climogram: precipitation and temperatures data in 2013 recorded in the station of Banyoles.

1. Cova de Reclau Viver, Cova d'en Pau, Mollet III, Cova de l'Arbreda, Cova d'en Costa, Cau del Roure.
2. Cau d'en Salvador, Cova dels Encantats de Serinyà, Cau d'en Quintana.
3. Worked wooden remains, probably a canoe, recovered by underwater surveying.

3. Material and methods

3.1. Core sampling

A 370 cm long core (SB2 core) was obtained from the western shore of Lake Banyoles (42°07′ 44.70″ N 2°45′ 06.64″ E, Alt. 174 m a.s.l.) (Fig. 1). The choice of the coring location was based on a systematic core exploration along the lakeshore during the 2008 and 2009 fieldwork seasons (Bosch et al., 2010). The results of that exploration enabled the identification of peat and organic clay deposits, allowing the recovery of a complete sequence of Holocene sediments for more detailed environmental analyses. The SB2 core was drilled beside the place where the S96 core was extracted in 2009, near the Riera del Castellar river, the main watercourse draining to the lake. The location near the river allows the detection of changes in its terrigenous input to the lake. For this purpose, a Van Walt/Eijkelkamp mechanical drilling machine was used. SB2 core is located 160 m away from the present lakeshore. Four stratigraphical units were distinguished, based on sedimentary facies: yellowish-brown silt (0‑159 cm), greyish silty clay (159‑174 cm), dark silty clay (174‑281 cm) and carbonate sands (281‑370 cm). The intermediate organic dark silty clay unit exhibited outstanding pollen preservation, in terms of variability and pollen concentration, and it corresponds with the start and development of the prehistoric settlements along the lake margins. Palynological and sedimentary charcoal data were partially published in Revelles et al. (2014), focusing on the Neolithisation period. The present study includes the intermediate unit, covering late Early Holocene to Late Holocene.

3.2. Sedimentology

The sedimentological study consisted of the stratigraphical characterization, the sedimentary facies description, the mineralogical analysis by X-ray diffraction (XRD) and a high-resolution geochemical analysis (XRF core scanner). The cores were split in two halves and imaged with a high-resolution digital camera in a core-scanner. The lithofacies were defined after visual and microscopic smear slide observations (Schnurrenberger et al., 2003).

The elemental composition of sediments was obtained by using an AVAATECH XRF core scanner at a resolution of 1 cm and under two different working conditions: i) with an X-ray current of 1000 μA, at 10 s count time and 10 kV X-ray voltage for the measurement of Al, Si, P, S, Cl, Ar, K, Ca, Ti, and Rh; and ii) with an X-ray current of 2000 μA, at 25 s count time, 30 kV X-ray voltage and using a Pd filter, for the measurement of Ni, Cu, Zn, Ga, Ge, As, Br, Rb, Sr, Y, Zr, Nb and Pb. The XRF results are expressed as counts per second (cps) and only chemical elements with mean cps over 1000 were considered to be statistically significant.

Whole sediment mineralogy was characterized by X-ray diffraction with a Bruker D8 Discover Davinci and relative mineral abundance was determined using the Difract software. Results are expressed in percentages related to the total dry weight of the sample.

3.3. Radiocarbon dating and age-depth model

The age-depth model was based on six Accelerator Mass Spectrometry (AMS) radiocarbon dates on bulk sediment (peaty clay) (Revelles et al., 2014). Calibration to years cal BP was made using Clam 2.2. (Blaauw, 2010) based on the data set IntCal13.14C (Reimer et al., 2013) (Table 2).

3.4. Pollen analysis

Contiguous 1 cm thick samples were retrieved from the core. The preparation of the samples followed standard methods (Burjachs et al., 2003) using treatment with HCL, NaOH, flotation in heavy liquid, HF and final mounting in glycerine. 300 – 350 terrestrial pollen grains were counted using a Nikon Eclipse 50i microscope, fitted with ×10 oculars and a ×50 objective. Cyperaceae, *Typha latifolia*, *Typha*/ *Sparganium* and *Alnus* were excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Reille (1992) and Cerealia-type was defined according to the morphometric criteria of Faegri and Iversen (1989). Non-pollen palynomorph (NPP) identification followed van Geel (1978, 2001) and van Geel et al. (2003).

3.5. Sedimentary charcoal analysis

Contiguous samples of 1 cm^3 were retrieved from the core, soaked in 10% NaOH solution for 24 h for peat digestion, then in 30% H2O2 solution for 24 h to bleach non-charcoal organic material (Rhodes, 1998). Quantification of charred particles was performed with the sieving method (Carcaillet et al., 2001) with a 150 µm mesh size (Clark, 1988; Ohlson and Tryterud, 2000) in order to reconstruct local fire history. Charcoal concentration (charcoal particles/cm^3) was expressed as charcoal accumulation rate (charcoal particles/cm^2 $years^{-1}$) based on sedimentation rate estimated by the age-depth model.

3.6. Macro-remains analysis

Samples of 25 cm^3 (5× 2.5 × 2 cm) were retrieved at 10 cm intervals from different pollen zones and sedimentological units, boiled in 5% KOH solution for peat digestion and sieved with a 150 µm mesh size. Then, macrofossils were transferred to a Petri dish and scanned using a stereoscopic microscope (10 – 50×).Moss leaves, cyperaceous epidermal tissues, and small seeds (*Juncus* sp.) had to be mounted onto temporary slides and examined at high magnifications (100 – 400×). Identifications were made with literature and reference collections of seeds and vegetative plant remains (Cappers et al., 2006; Mauquoy and van Geel, 2007).

In the samples where charcoal macro-remains were recovered, the identification was carried out by viewing the pieces in the three anatomical planes of the wood (transversal, radial longitudinal and tangential longitudinal). The samples were observed with an Olympus BX51 optical microscope and compared with reference samples of modern wood and identification keys published in specialized literature (Schweingruber, 1990).

Table 1. Prehistoric occupations framed in chronocultural periods according to probability intervals established by means of sets of high reliability dates (Barceló, 2008).

Chronocultural period	Chronology	Site
Early Bronze Age	3.71-2.9 cal ka BP	Cova d'en Pau
Early Bronze Age	3.71-2.9 cal ka BP	Encantats de Serinyà
Early Bronze Age	3.71-2.9 cal ka BP	Cova Mariver
Early Bronze Age	3.71-2.9 cal ka BP	Cau del Roure
Early Bronze Age	3.71-2.9 cal ka BP	Cau d'en Salvador
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Mollet III
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Cova Mariver
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	L'Arbreda
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Cau d'en Quintana
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Cau del Roure
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Cova d'en Pau
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Reclau Viver
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Encantades de Martís
Late Neolithic - Chalcolithic	5.17-3.71 cal ka BP	Encantats de Serinyà
Middle Neolithic	5.95-5.25 cal ka BP	Cova del Reclau Viver
Middle Neolithic	5.95-5.25 cal ka BP	Cova Mariver
Middle Neolithic	5.95-5.25 cal ka BP	Encantades de Martís
Early Neolithic -Epicardial and Postcardial-	6.95-5.55 cal ka BP	Cova d'en Pau
Early Neolithic -Epicardial and Postcardial-	6.95-5.55 cal ka BP	Cova Mariver
Early Neolithic -Epicardial and Postcardial-	6.95-5.55 cal ka BP	Reclau Viver
Early Neolithic -Epicardial and Postcardial-	6.95-5.55 cal ka BP	Mollet III
Early Neolithic –Cardial-	7.35-6.95 cal ka BP	L'Arbreda

Table 2. Radiocarbon dates, SB2 core (Banyoles). Calibration to years cal. BP was performed with Clam 2.2 (Blaauw, 2010) based on the data set IntCal13.14C (Reimer et al., 2013).

Sample depth (cm)	Lab. code	Type	AMS radiocarbon date BP	Cal. yr BP (2σ range) 95% prob.	Cal. yr BP in diagram
173	SUERC-38761 (GU26454)	Bulk sediment	2590± 30	2732–2876	2759
201	Beta-325839	Charcoal	4480± 30	4836–5171	5030
215	SUERC-38760 (GU26453)	Bulk sediment	4650± 30	5292–5452	5383
237	SUERC-49224	Bulk	5148± 30	5948–6239	6024

	(GU31929)	sediment			
253	SUERC-49225 (GU31930)	Bulk sediment	6645± 31	7171–7518	7418
276	SUERC-38759 (GU26452)	Bulk sediment	7855± 30	8609–8947	8685

4. Results

4.1. Chronology

The 6 dates obtained are expressed as intercepts with 2σ ranges (Table 2). The age-depth model was built using the smooth spline interpolation method. The dated samples are located at 173, 201, 215, 237, 257 and 276 cm depth, but pollen and sedimentary charcoal were analyzed up to 281 cm depth. Therefore, the age-depth curve (Revelles et al., 2014) (Fig. 2) was extended over the undated 5 cm, as it was within the same sedimentary facies. The age-depth relationship was used to plot the data (Figs. 4‑7).

The studied organic unit ranges between 8.9 cal ka BP and 3.35 cal ka BP, and thus allows the reconstruction of the vegetation history from the late Early Holocene to Late Holocene, covering Late Prehistory from the Mesolithic to the Bronze Age.

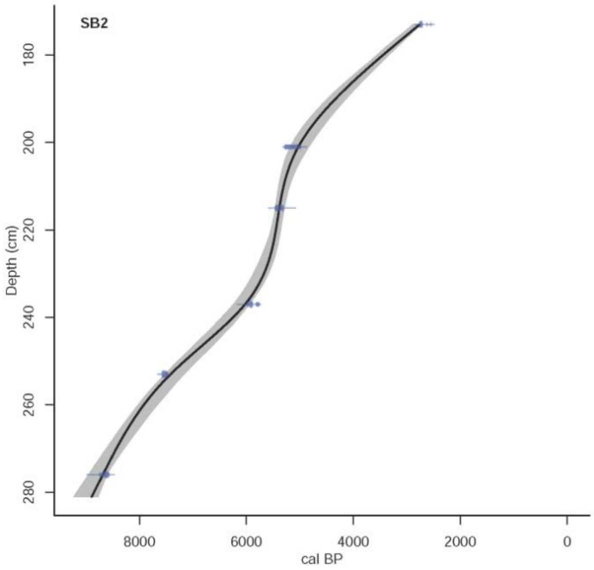

Fig. 2. Age-depth model based on six AMS radiocarbon dates. Estimation of age along the entire profile by a smooth spline technique using Clam 2.2 (Blaauw, 2010). From Revelles et al. (2014).

4.2. Sedimentology

4.2.1. Lithofacies and geochemistry

The analyzed core interval is characterized by high organic matter content, due to the lakeshore plant accumulation that formed a clay rich peaty facies. The high-resolution geochemical analysis was able to detect changes in the geochemical and mineralogical composition and the relative abundance of organic matter in the sediments and to differentiate 3 sedimentary facies (Table 3). The main changes are shown as variations in organic matter content reflected in bromine (Br), a biophile halogen that is fixed by plants, the allochthonous fluvial input of clay minerals represented by variations in titanium (Ti), a common element in clay minerals, and in the autochthonous carbonate (CaCO3) clay content, reflected in calcium (Ca) variations.

> Subunit 1: the oldest subunit extents from 8.9 cal ka BP to 7.2 cal ka BP (281 to 251 cm depth). It is characterized by the onset of peaty organic facies on top of shallow carbonate lacustrine sands. A rapid but gradual increase in Br (Fig. 3) points to the colonization of the lakeshore by vegetation, while lacustrine fine carbonate muds are being deposited (Ti/Ca curve in Fig. 3). However, the organic content (Br) starts decreasing progressively from 8.3 cal ka BP (267 cm), coinciding with the gradual increase of siliciclastic mud input (see Ti/Ca curve in Fig. 3) to the lakeshore environment.
>
> Subunit 2: extends from 7.2 cal ka BP to 4.2 cal ka BP (251 to 189 cm depth). The base coincides with the onset of the Neolithic site of La Draga. This subunit is characterized by a relatively low organic content of the peaty facies and an increasing content of siliciclastic mud. The organic content (Br) decreases until *ca*. 6.0 cal ka BP and maintains relatively constant until *ca*. 5.6 cal ka BP when it shows a tendency to increase, but it is interrupted by at least 3 strong minima at *ca*. 5.5 cal ka BP, 5.3 cal ka BP and 4.3 cal ka BP (Fig. 3). These tendencies and minimum peaks of organic matter (Br) anti-covariate with the changes observed in siliciclastic content (Ti/Ca) denoting that organic content varies depending on the quantity (sedimentation rate) of siliciclastic mud reaching the lakeshore.
>
> Subunit 3: extends from 4.2 cal ka BP to 2.7 cal ka BP (189 to 159 cm depth). This subunit is characterized by the strong decrease of allochthonous siliciclastic input to minimum background values (see Ti/Ca curve in Fig. 3) and the instauration of carbonate fine sedimentation. The organic content shows a vegetal matter-rich peaty layer at the bottom from 4.2 to ca. 3.6 cal ka BP and a less organic, but still rich, interval from 3.6 until *ca*. 3.0 cal ka BP. The organic content varies due to a higher carbonate sand presence in the upper half of this subunit.

4.3. Pollen analysis

The pollen analysis shows a mid-Holocene vegetation succession, reacting to both climatic and anthropogenic causes. Percentage pollen curves are presented in Fig. 4A and B (selected pollen taxa and sedimentary charcoal values) and in Fig. 6 (pollen categories, sedimentary charcoal values and NPP taxa and categories) using Tilia software (Grimm, 1991‑2011). Two main pollen zones and seven pollen subzones were defined using a stratigraphically constrained cluster analysis (CONISS) (Grimm, 1987):

Table 3. Lithofacies defined for the SB2 core Unit 2 sequence, including sedimentary facies and main compositional parameters (mineralogical content (%) and geochemical content of selected elements (cps)) and depositional environments and/or process interpreted for each subunit.

Subunit	**Sedimentary facies**	**Composition parameters**	**Depositional environment/processes**
1	281-251 cm. Dark-grey to black, massive, organic matter carbonate-rich peaty silts with vegetal remains. Less organic towards the top. Fine grained mud composed of millimetre to centimetre-size plant remains, dark amorphous organic matter, gypsum crystals and carbonate grains of reworked littoral bioclasts (ostracods and charophytes).	Mineralogy: Calcite = 3-15%, Gypsum = 13-66%, Clay minerals= 17-54%, Quartz = 5-18% Geochemistry: Si: 14677-2785 Ti: 4524-947 Br: 1905-677 Ca: 476042-5054	Vegetated lakeshore with increasing allochtonous terrigenous silt sedimentation and minor authigenous carbonate sedimentation. Frequent subaereal exposure intervals due to small water level variations.
2	251-189 cm. Olive grey to black, laminated organic matter carbonate-rich silts. Lamination is due to variable content of organic matter. More organic, peaty, towards the top. Fine grained laminated carbonate-rich mud. Contains abundant organic components as root and coarse plant remains, amorphous organic matter, gypsum crystals and bioclasts (ostracods, charophytes and shell fragments).	Mineralogy: Calcite = 10-46%, Gypsum = 13-32%, Clay minerals= 30-43%, Quartz =11-34% Geochemistry: Si: 60854-4463 Ti: 17506-1911 Br: 1260-290 Ca: 333623-33926	Vegetated lakeshore. Maximum input events of allochthonous terrigenous mud and relative decrease of organic matter. Subaereal exposure intervals due to small water level variations.
3	189-174 cm. Greyish black to black, organic matter rich silts with a carbonate sand interval (174-181 cm). Greyish black carbonate-rich mud composed of plant remains (millimetre to centimetre-size), amorphous organic matter, translucent filaments, gypsum crystals and shell fragments. Greyish black to black yellowish brown carbonate sand in fine-grained organic-rich carbonated matrix with shell fragments and ostracods.	Mineralogy: Calcite = 7-42%, Gypsum =2-37%, Clay minerals= 39-52%, Quartz = 3-35% Geochemistry: Si:14677-2785 Ti: 4524-947 Br: 1905-677 Ca: 476042-5054	Vegetated lakeshore with decreasing allochtonous terrigenous input and occasional carbonate sand transport towards the lake margin. Subaereal exposure intervals due to small water level variations.

- Sub-zone A1a (8.9-7.6 cal ka BP): high values of arboreal pollen (>85%) and vegetation cover dominated by deciduous *Quercus*, *Corylus* and *Pinus*.

- Sub-zone A1b (7.6-7.25 cal ka BP): starts with the beginning of the continuous *Abies* curve. It corresponds with a deciduous *Quercus* and *Pinus* decrease and with the last *Corylus* maximum. In this phase a non-arboreal pollen expansion (15-20%) occurs, with an increase in Poaceae and Cyperaceae values.

- Sub-zone B1a (7.25‑6.05 cal ka BP): is characterized by the significant fall in deciduous *Quercus* values, the start of a decreasing trend of *Corylus*, the increase in *Pinus* and *Abies*, the appearance of a continuous *Tilia* curve, and the expansion of non-arboreal pollen, mainly Poaceae, but also of other herbs like Asteraceae, *Artemisia*, Apiaceae, Chenopodiaceae and *Plantago*, and shrubs, specially *Erica*. This zone displays the highest values of Cyperaceae, the start of continuous curves of monolete spores, *Glomus*, and the rise in algae values.

- Sub-zone B1b (6.05‑5.55 cal ka BP): is marked by the continuation of less proportions of deciduous *Quercus*, high values of *Pinus* and by the appearance of sedimentary charcoal particles. The increase in Asteraceae (tubuliflorae and *Cirsium*-t) and Apiaceae is also remarkable. The maximum values of *Glomus*, the occurrence of spores of coprophilous fungi and high values of monolete and *Pteridium* spores occur in this zone.

- Sub-zone B2a (5.55‑5.25 cal ka BP): is characterized by the recovery of deciduous *Quercus* and arboreal pollen values (80‑85%) and a marked decrease in *Pinus* corresponding with a sedimentary charcoal peak. The beginning of the *Alnus* curve, the increasing trend of *Quercus ilex-coccifera*, and the appearance of *Fagus* are recorded. A significant decrease in fern spores and algae occurs in this zone.

- Sub-zone B2b (5.25‑5.1 cal BP): is marked by a fall in deciduous *Quercus* and arboreal pollen values (60‑65%), the continuation of low *Pinus* values and the appearance of high values of *Alnus*, as well as continuous curves of Salix and *Fraxinus*. Among the herbs not only Asteraceae liguliflorae values show an increase, but also Asteraceae tubuliflorae, Poaceae, *Plantago*, Apiaceae and *Paronychia*-t. The recovery of algae values is recorded in this zone.

- Sub-zone B2c (5.1‑3.35 cal BP): starts with the recovery of deciduous *Quercus* and *Pinus* values, the decrease of *Alnus*, a peak of sedimentary charcoal particles and a peak of Cyperaceae. Afterwards, the recovery of *Alnus*, the consolidation of *Salix* and *Fraxinus* values, the appearance of continuous curves of *Ulmus* and *Fagus*, and an increasing trend of *Quercus ilex-coccifera*, *Olea* and *Phillyrea* is documented. In this zone, some peaks of monolete spores and algae, a continuous curve of *Glomus* and semi-continuous slight values of coprophilous fungal spores occur.

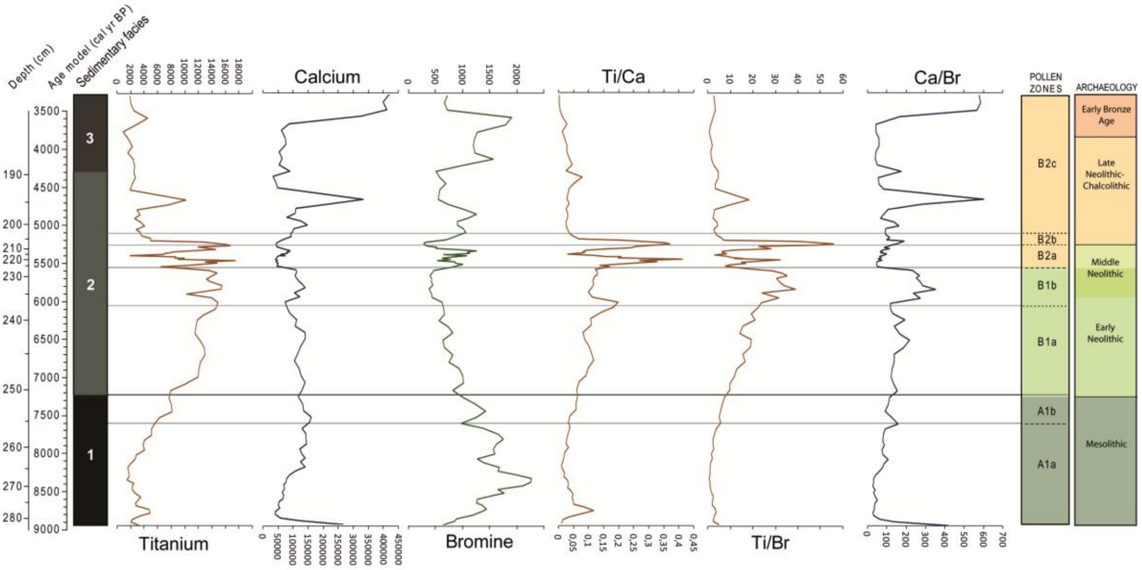

Figure 3. X-ray fluorescence (XRF) scanner data of the Lake Banyoles SB2 core. Element concentrations (Ti, Ca and Br), expressed as counts per second (CPS), and Ti/Ca, Ti/Br and Ca/Br ratios are indicated. Sedimentary facies/subunits, pollen zones and archaeological cultural periods are also included.

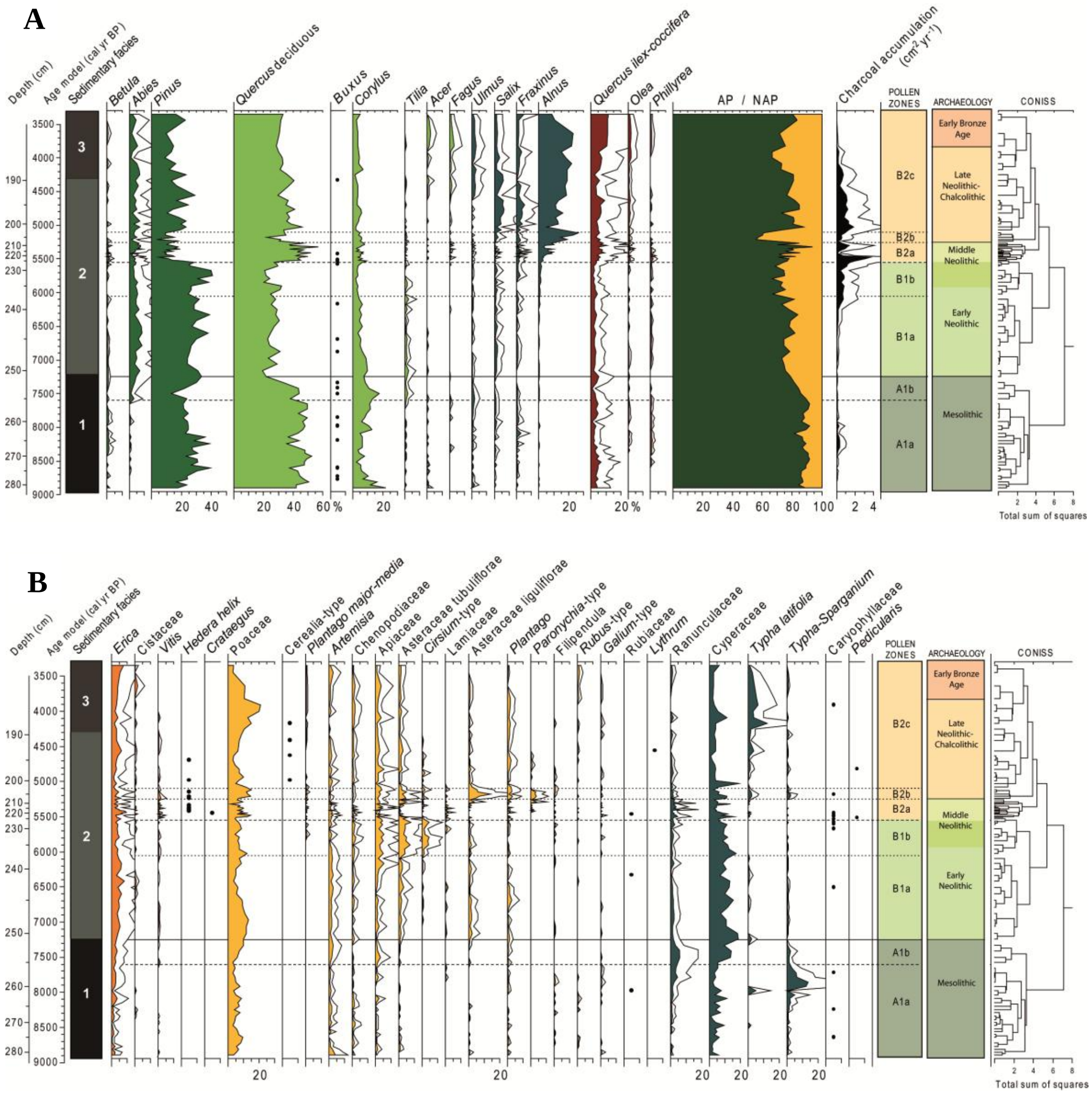

Figure 4. A. Percentage pollen diagram. Selected arboreal pollen taxa and sedimentary charcoal accumulation rate from the SB2 core (Lake Banyoles) are plotted to a calibrated year cal BP scale. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points (also in Figs. 4B and 6). B. Percentage pollen diagram. Selected non-arboreal pollen taxa from the SB2 core (Banyoles) plotted on a calibrated year cal BP scale.

4.4. Macro-remains analysis

Results of macro-remains analysis are plotted in absolute frequencies in Fig. 5. The diagram shows that the evolution of local plants in the lake margin follows the same trends as the pollen zones:

- Zone A. *Cladium mariscus*, and other lakeshore plants (*T. latifolia*, *Juncus* sp., *Juncus articulatus*-type and *Juncus effuses*-type) are present. Local aquatic plants and algae were *Potamogeton* cf. *coloratus* and Characeae.

- Zone B1. *Mentha aquatica*, *Lycopus europaeus* and *L. salicaria* appear, while *J. articulatus*-type increases, and *T. latifolia* disappears.

- Sub-zone B2a. *J. articulatus*-type shows a peak, Characeae disappear and some taxa occur exclusively in this zone: *Potentilla* sp., *Ranunculus* sp., *Ranunculus flammula*, *Carex* sp., Cyperaceae (roots and epidermis). The first evidence of macro-remains of *Alnus* sp. is remarkable.

- Sub-zone B2b. *Alisma* sp., appears and *J. articulatus*-type decreases, *T. latifolia* and Characeae reappear, and some non-lakeshore plants were recorded: *Linum* cf. *catharticum* and Asteraceae. Charcoal particles of *Alnus* sp. were observed for the first time.

- Sub-zone B2c is characterized by the presence of woodland taxa: *Alnus* sp., *Alnus* sp. charcoal, undetermined catkins, suberized leaf scars, *Eupatorium cannabinum*, *Rubus fruticosus* L.s.l., *Brachytecium* sp. and the presence of other non-lakeshore plants like *Aster* sp., *Galium* cf. *aparine*, cf. *Solanum* sp. The appearance of *Ranunculus* subgenus *Batrachium* and the presence of *Mentha* cf. *aquatica*, *Alisma* sp. and *Potamogeton* cf. *coloratus* and *Plumatella*-type (Bryozoa) show continuing local wet conditions.

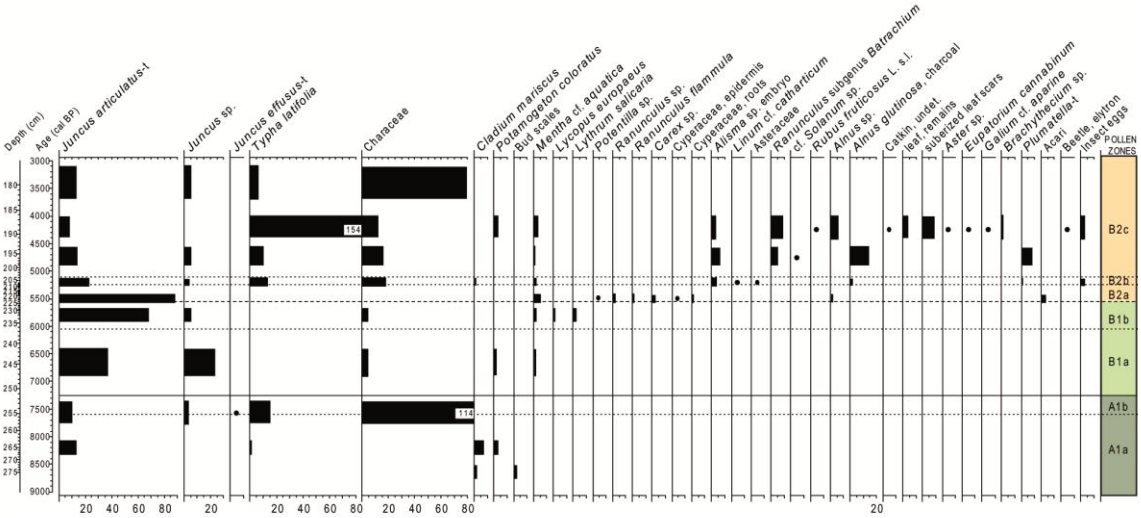

Figure 5. Macro-remain diagram of absolute frequencies plotted to a calibrated year cal BP scale. Individual occurrence of taxa is represented by points.

5. Discussion

5.1. Climatic, geomorphologic and anthropogenic controls on Mid-Holocene vegetation evolution

5.1.1. Broadleaf deciduous tree forests and subaerial swamp formation in the Holocene Climate Optimum (zones A1a and A1b: 8.9–7.25 cal ka BP)

The pollen spectra at the base of the SB2 sequence reflect the dominance of dense forests (see the AP/NAP ratio in Figs. 4A, 6 and 7), specifically of broadleaf deciduous trees (deciduous *Quercus* and *Corylus*). Furthermore, the presence of *Pinus* in the surrounding mountains is noteworthy. The dominance of broadleaf deciduous tree forest is consistent with the prevailing climate conditions, the vegetation cover in other regions of the Western Mediterranean during the same period (Sadori and Narcisi, 2001; Carrion et al., 2010; de Beaulieu et al., 2005; Jalut et al., 2009; Pérez-Obiol et al., 2011) and with previous palaeoecological studies in the area (Pérez-Obiol and Julià, 1994).

Despite the supposedly wet conditions in this period, the low values of riparian trees (*Ulmus*, *Fraxinus*, *Salix*) is remarkable, probably because of the absence of appropriate geomorphologic conditions for the development of these taxa; the relatively high water level in Lake Banyoles would prevent the existence of plains with water-rich vadose soils along the lakeshore. In that sense, the high-water level in the lake promoted the presence of a narrow water-saturated subaerial swamp in the margins of Lake Banyoles evidenced by the macro-remains results that would not have permitted the aforementioned trees to grow. The lake shore probablywas poor in nutrients and rich in calcium as indicated by the presence of *C. mariscus*.

The start of the sequence coincides with peat formation along the lakeshore about 9.0 cal ka BP, due to water-level regression, expressed by the sedimentological change from shallow water lacustrine carbonate facies to palustrine peaty wetland. This trend represents a lowering of the lake level and a transition from a shallow lacustrine charophyte rich platform sub-environment to a vegetated lakeshore margin. Drying eventswere previously attested in lacustrine records in Siles Lake, in the south-eastern Iberian Peninsula (9.3 cal ka BP) (Carrión, 2002), in Fuentillejo Maar (9.2‑8.6 cal ka BP) (central Iberian Peninsula; Vegas et al., 2009), in Basa de la Mora (9.3 and 8.8 cal ka BP) (Pyrenees; Pérez-Sanz et al., 2013), in Lake Cerin (9.0 cal ka BP) (Jura Mountains, France; Magny et al., 2011) and Lake Accesa (9.0 cal ka BP) (central Italy;Magny et al., 2007). This lowering in lake water level corresponds with one of the main rapid Holocene climate changes (Mayewski et al., 2004) that is globally detected as a phase of decreasing fluvial activity in Mediterranean areas (Magny et al., 2002), dry episodes detected in the Mediterranean Sea (Fletcher et al., 2010, 2013), episodes of reduced rainfall measured in $\delta^{18}O$ values Katerloch Cave (southeastern Alps) (Boch et al., 2009) and Soreq Cave (Israel; Bar-Matthews et al., 1999).

The relative stability of the characteristic wet climate during the early Holocene, was also disrupted by the 8.2 cal ka BP cooling event (Alley et al., 1997; Bond et al., 1997, 2001). This phenomenon has been characterized in different sequences in the Iberian Peninsula (Riera, 1993; Davis and Stevenson, 2007; Carrión and van Geel, 1999; Carrión, 2002; Carrión et al., 2001a, 2001b; Pantaleón et al., 1996, 2003; López Sáez et al., 2007) by a decrease in broadleaf deciduous trees and AP values, and the expansion of xerophytic taxa (Tinner and Lotter, 2001). In the SB2 core (Fig. 4A and B), at 8.2-8.1 cal ka BP there is a small decrease in deciduous *Quercus* values, the presence of sedimentary charcoal, the onset of increasing input of allochthonous terrigenous fine sediment to the lake, aswell as a slight increase in mountain taxa like *Pinus* and *Betula* and sclerophyllous trees like *Olea* and *Phillyrea*. Nevertheless, despite this slight evidence of drier conditions and the subsequent susceptibility to burning, the AP decline after the fire episode is smaller than expected during such an arid event.

Therefore, in the northern peninsula this dry event was detected in pollen records from Mediterranean coastal areas (Riera, 1993), in regions with more continental climates (Davis and Stevenson, 2007; González-Sampériz et al., 2008) and in high mountain areas (Pyrenees) (González-Sampériz et al., 2006; Pérez-Sanz et al., 2013). On the other hand, in regions influenced by a wetter sub-Mediterranean climate, where deciduous broadleaf formations prevail, like Lake Banyoles (Pérez-Obiol and Julià, 1994 and this study), and Olot (Pérez-Obiol, 1988), the 8.2 cal ka BP event impact would have been low or nonexistent. This situation is consistent with the fact that this cooling phenomenon would correspond with a wetter climate in European middle latitudes, locating the southern limit about 38‑40° N (central Iberian Peninsula) (Magny et al., 2003, 2013).

Afterwards, the most remarkable phenomenon in the zone A1b is the appearance of Abies (*ca*. 7.6 cal ka BP), which was recorded at the same time in previous studies (Pérez-Obiol and Julià, 1994). The first presence in the north-eastern Iberian Peninsula is in the Olot region at *ca*. 10.2 cal ka BP (Pérez-Obiol, 1988), and, later, other sequences register its presence in nearby mountain and inter-mountain areas (Burjachs, 1994; Pérez-Obiol and Julià, 1994). *Abies* cf. *alba* arrived in accordance with its dynamics of migration and colonization since the Late Glacial from refugia on the southern slopes of the Pyrenees (Terhürne-Berson et al., 2004; Liepelt et al., 2009; Sadori, 2013).

Several studies seem to locate an abrupt cold event in this period that could have affected the woodland cover around Lake Banyoles (Mayewski et al., 2004). Short cold and arid phases are detected in other Iberian lacustrine records (Jalut et al., 2000; Vegas et al., 2009; Pérez-Sanz et al., 2013) and Frigola et al. (2007) have documented an abrupt cold event between 7.4‑6.9 cal ka BP in a marine core from the western Mediterranean, that could be related with a period of dryness in the Iberian Peninsula. Stalagmite records in Soreq Cave (Israel) and Antro del Corchia (Northern Italy) also show a decrease in rainfall from *ca*. 7.4 cal ka BP onwards (Bar-Matthews et al., 1999; Zanchetta et al., 2007). This cooling event and decrease in rainfall would have coincided with the onset of a decrease in the values of broadleaf deciduous trees in Lake Banyoles (Figs. 4A, 6, 7), consistent with discrete intervals of reduced forest development detected in marine records in the Mediterranean Sea (Fletcher et al., 2010, 2013).

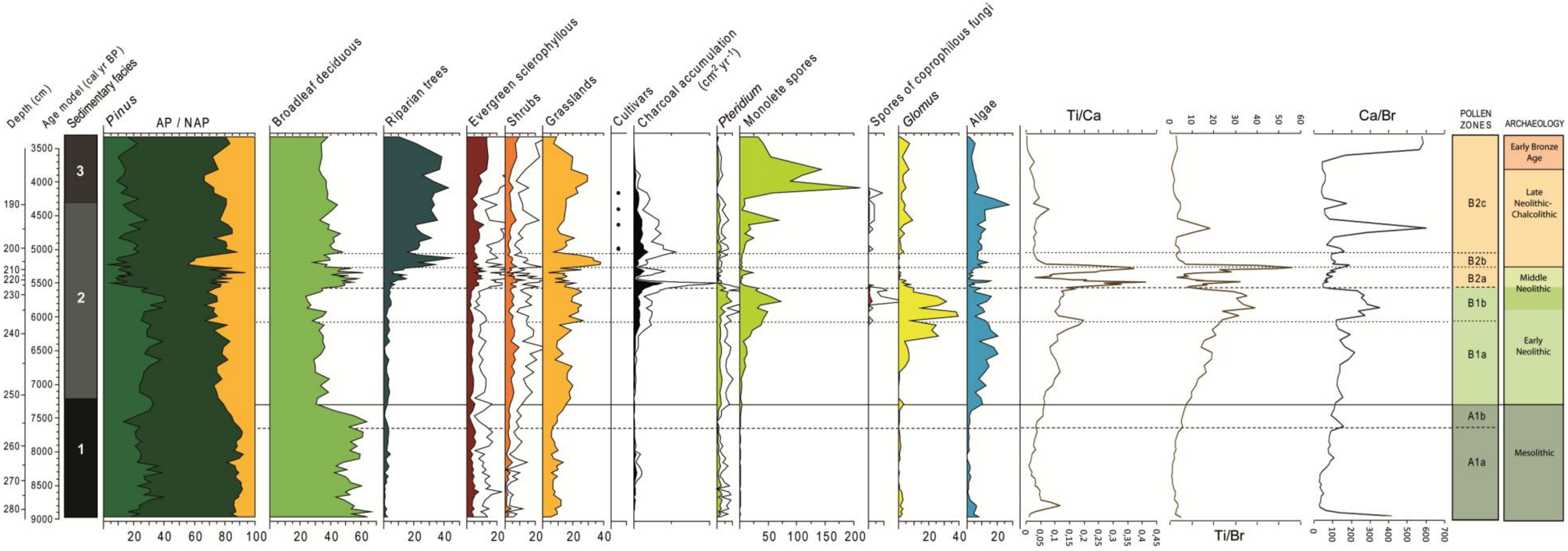

Figure 6. Pollen categories compared with non-pollen palynomorphs categories, sedimentary charcoal and geochemical data. Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*), riparian forest (*Ulmus*, *Fraxinus*, *Salix*, *Alnus*), evergreen sclerophilous trees (*Quercus ilex-coccifera*, *Olea*, *Phillyrea*), shrubs (*Erica*, Cistaceae, *Vitis*, *Hedera helix*, *Crataegus*), Grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Plantago*, Chenopodiaceae, Lamiaceae), Cultivars (Cerealia-type), Spores of coprophilous fungi (*Sordaria* type, *Podospora* type, *Cercophora* type, *Rhytidospora*), and Algae (*Spirogyra*, *Zygnema*, *Closterium*, *Mougeotia*).

5.1.2. Landscape transformation caused by the first farming societies (zones B1a and B1b: 7.25–5.55 cal ka BP)

The pollen record shows that the abrupt decrease in deciduous *Quercus* values which started about 7.6–7.4 cal ka BP consolidated at much lower percentages by 7.3–7.2 cal ka BP, suggesting an important process of landscape transformation after the establishment of the first farming communities at La Draga (7.27–6.75 cal ka BP; Bosch et al., 2012). From7.15 cal ka BP onwards, the deciduous *Quercus* forest deforestation consolidated, leading to the proliferation of grasslands (Fig. 6). This is the time of the *Tilia* maximum and an increase in *Pinus* spp. and heliophilous shrubs (*Erica* spp.), which probably occupied the space after oak forest clearance. It is important to note the low values of sedimentary charcoal, which suggests that the oaks were cut down and not burnt. The main arboreal taxa in this phase would be *Pinus*, developed in lowlands favoured by the oak decline. Nevertheless, part of the *Pinus* pollen may have come fromtrees located in the mountains, accompanied there by *Abies alba*, that arrived from nearby mountains. Previous pollen analysis undertaken in Lake Banyoles and La Draga Neolithic archaeological site also showed a fall in oak values coinciding with the settlement of La Draga (Pérez-Obiol, 1994; Pérez-Obiol and Julià, 1994; Burjachs, 2000).

Additionally, climate oscillations about 7.4 cal ka BP could affect oak forests, either contributing to their decline or to the maintenance of clearances made by the Neolithic communities. Nevertheless, due to resilience of deciduous broadleaf species in wetter sub-Mediterranean regions (as shown in the case of the 8.2 cal ka BP event), this cooling period cannot be the single cause of a decrease of oak as evidenced in the SB2 sequence about *ca*. 7.25 cal ka BP. Therefore, the climate shift linked to a slight decrease in GISP2 18O, documented ca. 7.6–7.4 and 7.3–7.2 cal ka BP (Fig. 7), seems unlikely to have caused an abrupt decline of oak and deciduous broadleaf forest at the site.

The importance of deforestation activities is attested by charcoal and wood analyzed from La Draga. About one thousand oak trunks have been recovered in the 800 m^2 of the excavated area. Considering the fact that the total extension of the site is about 8000 m^2, thousands of poles were cut for the construction and maintenance of the settlement over the period of occupation (Gassman, 2000; Revelles et al., 2014). These trunks were cut with adzes, as shown by traces on the tools (Bosch et al., 2008), and dragged to the settlement. According to the charcoal record, the increase in shrubs (*Buxus* cf. *sempervirens* and Rosaceae/Maloideae), and the decrease in deciduous oak and riparian taxa, in the most recent phase of occupation indicates that these taxa had expanded as a result of the above-mentioned forest perturbation (Piqué, 2000; Caruso-Fermé and Piqué, 2014).

Although the first evidence of husbandry practices are documented in this phase at La Draga site (Saña, 2011; Navarrete and Saña, 2013; Antolín et al., 2014), no spores of coprophilous fungi are documented at this time, due to their short distance dispersal.

Later, the main feature of the first half of the 6th millennium cal BP (sub-zone B1b) is the stabilisation of decreased pollen percentages of deciduous *Quercus* and the co-occurrence of sedimentary charcoal, pointing to clearances in the oak forest by Early Neolithic communities. Grazing by herbivores was probably linked with this maintenance, given the occurrence of spores of coprophilous fungi (Fig. 6). In fact, forest clearance maintenance could be the cause for the frequency of fire episodes at *ca*. 6.0 cal ka BP, in the context of a trend towards the spread of fire caused by increased aridity in the Mediterranean area of Iberian Peninsula after 6.0–5.0 cal ka BP (Reed et al., 2001; Carrión, 2002; Mayewski et al., 2004; Wanner et al., 2011; Pérez-Sanz et al., 2013; Morales-Molino and García-Antón, 2014). The occurrence of *Salix* sp. charcoal in the adjacent core S96, dated 6.0–5.9 cal ka BP, points to the burning of local riparian vegetation. Also maximum values of *Pteridium* spores are associated with these fire episodes (compare Tinner et al., 1999).

The beginning of continuous curves of monolete spores (ferns) and *Glomus* spores in this phase could be related with soil erosion events (Dimbleby, 1957; van Geel, 1986; van Geel et al., 1989; López-Merino et al., 2010; Gelorini et al., 2011; van Geel et al., 2011), evidenced in the increasing input of terrigenous allochthonous fine-grained sediments to the lakeshore detected in the core (Ti/Ca curve in Fig. 3), caused by deforestation during this zone. The high values of *Glomus* chlamydospores recorded in lakeshore swampy deposits may indicate the local occurrence of these mycorrizal mycelia (Kołaczek et al., 2013). But the co-occurrence of maximum values of Asteraceae and Apiaceae and the change in sedimentation dynamics due to a major input of allochthonous fluvial fine sediment and a relative reduction in peat formation in lakeshore areas detected in SB2 core showthe importance of *Glomus* as an indicator of soil erosion (Anderson et al., 1984; van Geel et al., 1989; López Sáez et al., 2000) (Figs. 3 and 6). Sedimentation as a consequence of soil erosion in deforested areas should not be dismissed as the cause of the arrival (together with terrigenous material) of charcoal particles and spores of coprophilous fungi.

The increase in algae and Cyperaceae and the presence of macroremains of *J. articulatus*-type, *Juncus* sp., and *Mentha* cf. *aquatica* point to the presence of a humid lakeshore environment at a local level.

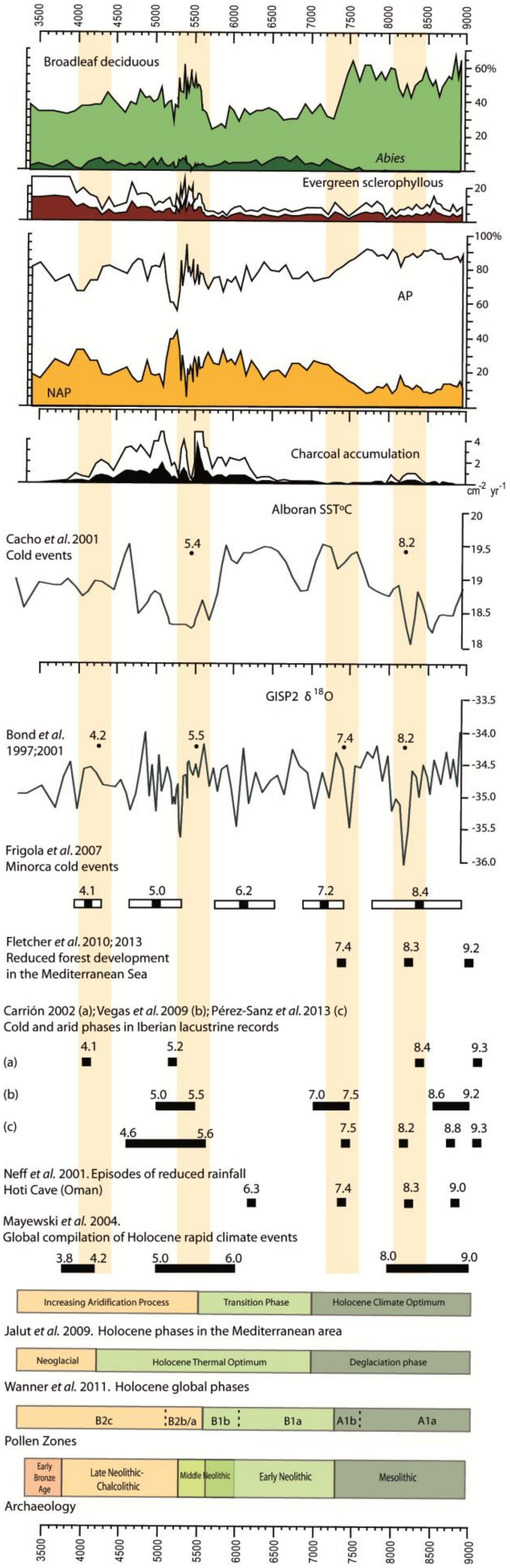

Figure 7. Pollen categories compared with climate data. Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*) and evergreen sclerophylous trees (*Quercus ilex-coccifera*, *Olea*, *Phillyrea*).

5.1.3. Human impact on riparian lakeshore environments and oak forest resilience in 6th–4th millennium cal BP (zones B2a, B2b and B2c: 5.55–3.35 cal ka BP)

In 5.55–5.25 cal ka BP (zone B2a), coinciding with the onset of the Subboreal period, oak forest and arboreal pollen recovered, while several pollen types and NPP taxa commonly associatedwith anthropogenic disturbance (ruderal herbs, coprophilous fungi, *Glomus*, ferns) declined. Equally, this phase saw an increase in *Alnus*, the first more or less continuous curve of *Fagus*, even thoughwith lowvalues, and higher values of *Betula*. The main sedimentary charcoal peaks in the sequence that coincide with major peaks in the terrigenous input to the lake occurred in *ca*. 5.5 cal ka BP (Figs. 3, 6). An increasing terrigenous input until *ca*. 5.3 cal ka BP and the maximum input peaks at *ca*. 5.5, 5.3 and 4.3 cal ka BP would point to a gradual increasing terrigenous erosion in fluvial basins surrounding the lake, punctuated by short duration, *ca*. 100 year, maximum peaks of terrigenous input that could denote increased soil erosion events related to, for example, more intense deforestation due to fires and/or cropland management. Despite the impact on the lakeshore environment cannot be discarded, fire episodes documented in *ca*. 5.5 cal ka BP could be related with climate changes causing a significant decline in *Pinus*, so the burning would have affected the regional mountain vegetation. In that context, the increase in *Betula* could be explained as colonization of spaces degraded by fire in mountain areas.

The changes in vegetation and sedimentation dynamics should be considered in the context of climate change. Many palaeoclimaticrecords show changes in precipitation seasonality starting from *ca*. 5.5 cal ka BP, coinciding with Bond event 4 (Bond et al., 1997, 2001), with the establishment of drier conditions in Mediterranean areas (particularly in summer), associated with a decrease in insolation maxima and general reorganization of atmospheric circulation (Jalut et al., 2009; Magny et al., 2012). In the NE Iberian Peninsula this hydrological change is well represented in Lake Estanya (Morellón et al., 2009), but also in marine sediments in the Balearic Sea (Frigola et al., 2007), as well as in Western Mediterranean pollen diagrams (Jalut et al., 2000; Pérez-Obiol et al., 2011; Aranbarri et al., 2014).

About 5.25 cal ka BP a major decline in oak and AP values and expansion of grasslands (Asteraceae, *Plantago* and Poaceae) occurred, related with a significant input of terrigenous sediments (Fig. 6) probably linked with a new deforestation process. Peaks of Asteraceae liguliflorae, Asteraceae tubuliflorae, *Plantago*, *Paronychia*-type, the presence of Caryophyllaceae, and evidence of macro-remains of Asteraceae, *Linum* cf. *catharticum* may have been linked with open herbaceous vegetation and upland soil erosion, as shown in Ti/Ca and Ti/Br curves (Fig. 3).

The mid-Holocene aridification trend lowered the lake water level and this process, combined with the high sedimentation rate related to soil erosion events during this zone, createdwidely exposed swampy plains close to the lakeshore. This process of infill of the lakeshore by allochthonous terrestrial sediments is also evident from the decline in algal spores (*Zygnema*, *Spirogyra*, *Mougeotia*, *Closterium*).

The progressive trend from broad swamp lakeshore areas to subaerial drier vadose substrates would explain the colonization by *Alnus*, resulting in the establishment of a larger riparian forest in the newly emerged lands, a process consolidated from *ca*. 5.25 cal ka BP with the expansion of other riparian trees (*Salix*, *Ulmus* and *Fraxinus*). The immigration of *Alnus*, which reached NE Iberia in 7.0‑6.0 cal ka BP from LGM refugia in the Pyrenees (Douda et al., 2014), should be considered. The predominance of alder in the riparian forest from *ca*. 5.5 cal ka BP, reaching high values from *ca*. 5.25 cal ka BP, is consistent with previous studies in Atlantic-influenced sequences (Rius et al., 2012; Morales-Molino and García-Antón, 2014).

Despite the larger productivity of pollen grains should be considered, the cause of the dominance of *Alnus* rather than other riparian trees such as *Salix* spp., *Corylus*, *Fraxinus* or *Ulmus*, can also be explained by the advantage of *Alnus* in lakeshore environments thatwere seasonally flooded, as shown by laminated sediment at this time (see Table 3), and also by its capacity to grow in degraded environments, related to its positive response to fire (Tinner et al., 2000; Connor et al., 2012) or to changes in local hydrological conditions (Morales-Molino et al. 2014).

Important fire episodes occur between *ca*. 5.0 and 4.3 cal ka BP, burning that may not necessarily have affected the regional vegetation, as shown in the presence of *Alnus* sp. charcoal in the period from 5.25 to 4.6 cal ka BP (Fig. 3). Local occurrence of *Alnus* is evident, confirmed by the presence of *Alnus* sp. seeds during 5.55‑5.45 cal ka BP and 4.4‑4.0 cal ka BP. Coincidently, from 5.05 cal ka BP to 4.65 cal ka BP *Alnus* values decline, recovering after 4.6 cal ka BP. Therefore, the fires affected the riparian forest, specifically the alder, probably provoked by human frequentation of this territory during the Late Neolithic ‑ Chalcolithic period. This hypothesis is reinforced by the documentation of *Salix* sp. charcoal in another core extracted 250 m to the south (S76) from 5.47 to 5.29 cal ka BP. The charcoal-rich levels detected in this zone create a very subtle increase in the terrigenous input to the lake (Fig. 3), pointing to lower related soil erosion due to the smaller extent of these deforestation events, probably very localized in nearby riparian forests and not affecting fluvial drainage basins significantly.

The establishment of riparian forest in newly emerged areas (regression ofwetland) would explain the decrease in values of some lakeshore herbs, such as Cyperaceae and Ranunculaceae, that reach maximum values in the phase 7.6 ‑ 5.5 cal ka BP, the appearance of riparian lianas and shrubs (*Vitis*, *Hedera helix*, *Galium*), woodland herbs (*Filipendula*, *Rubus*-type) and the presence of some macro-remains indicative of riparian woodland areas: *Alnus* sp., *Alnus* sp. charcoals, unidentified catkins, suberized leaf scars, *E. cannabinum*, *R. fruticosus* L.s.l., *Galium* cf. *aparine* and *Brachytecium* sp. The appearance of *Ranunculus* subgenus *Batrachium* and the presence of *Mentha* cf. *aquatica*, *Alisma* sp. and *Potamogeton* cf. *coloratus* indicate the presence of a swampy lakeshore.

The general water level regression, soil erosion and openings in the forest in this phase (from *ca*. 5.5 cal ka BP) is reinforced by the evidence of Cerealia pollen, which could have grown in the surroundings, known the local indicator that supposes Cerealia pollen (Heim, 1970; de Beaulieu, 1977; Diot, 1992). Due to the water level regression, the new geomorphologic conditions would have permitted the creation of crop fields in the emerged plains near the shore of Lake Banyoles (occupied by riparian trees: *Alnus*, *Fraxinus*, *Ulmus*, *Salix*). It is noticeable that between 5.0 and 3.35 cal ka BP the cereal crop fields would be nearer to the western lakeshore than in the Early Neolithic, corroborating that, in general, during the first half of the Holocene the lakeshore areas of Lake Banyoles would have been more swampy, and not suitable for agricultural practices. Co-occurrence of maximum values of ferns (monolete spores), coprophilous fungi, increase in grasses and the presence of Cerealia-type are recorded in the period 4.2‑4.0 cal ka BP, pointing to deforestation and evidence of farming activities. From *ca*. 4.5 cal ka BP, the onset of a continuous curve, with low values, of *Fagus*, is consistent with other studies (Parra et al., 2005; Rius et al., 2009).

In this phase, sedimentary Subunit 2 displays an organic peat layer formed in a wet environment favourable for the development of alder forest that could be seasonally dried, as shown by high values of monolete spores, which can also be interpreted as an aeration indicator in peat deposits (Dimbleby, 1957). The sedimentological and geochemical data show a change that denotes the onset of a vegetated lakeshore with increasing organic matter (Br, Fig. 3) and carbonate sedimentation without any significant allochthonous terrigenous input (Ti/Ca, Fig. 3). These changes could be related with the 4.2 event cal ka BP (Bond event 3; Bond et al., 1997), whose consequences are evident in arid climate conditions reconstructed in Lake Zoñar (4.0‑2.9 cal ka BP; Martín-Puertas et al., 2008), Lake Siles (lake desiccation in 4.1 cal ka BP; Carrión, 2002), and in Lake Estanya (4.8‑4.0 cal ka BP; Morellón et al., 2009). Nevertheless, there is no evidence of such a dry event in the vegetation history recorded at Lake Banyoles.

From *ca*. 4.2 cal ka BP onwards, an increase in *Quercus ilex-coccifera*, *Olea* and *Phillyrea* is recorded, consistent with the succession process from deciduous broadleaf tree forests to sclerophyllous evergreen forests across the northern Iberian Peninsula (Carrion et al., 2010; de Beaulieu et al., 2005; Jalut et al., 2009; Pérez-Obiol et al., 2011). The start of this succession is registered in the SB2 sequence, so a trend of a decline in deciduous trees and an expansion in evergreen trees is documented. However, the end-result of this succession is not recorded, as the sequence ends at *ca*. 3.35 cal ka BP, and it would probably have occurred several centuries later. The reason for this later succession could be the south‑north orientation of the process, starting in the south-eastern Iberian Peninsula in the early Holocene and reaching the north (41° N) around 2.87 cal ka BP (Jalut et al., 2000). As shown in this study, in sub-Mediterranean areas of the north-eastern Iberian Peninsula, the resilience of broadleaf deciduous forests prevailed during the Early andMiddle Holocene. From the data presented here, the origin of the current vegetation in the Lake Banyoles area should be seen in the context of the transition from the Sub-boreal to Sub-Atlantic periods (drier conditions in the Late Holocene) and in the multiplication of anthropogenic impact since Roman times.

5.2. Land use and human impact during Late Prehistory in the Lake Banyoles area

Available radiocarbon chronologies from archaeological contexts in the surroundings of the Lake Banyoles suggest that there is a gap in human presence in the region during the first half of the 8th millennium cal BP, with very few dates corresponding to the 9th millennium cal BP (Merkyte, 2003; Estévez, 2005; Weninger et al., 2006; Barceló, 2008). Indeed, no evidence of human occupation has been documented in the area immediately before the Neolithic, so vegetation changes before *ca*. 7.3 cal ka BP are considered to have been influenced by natural processes. The predominance of broadleaf deciduous tree forests, maximum values of arboreal pollen and the lack of anthropogenic modifications of the vegetation are consistent with this gap of settlement in the Mesolithic period.

The results from the SB2 core show an abrupt decline in oak forest coinciding with the early Neolithic settlement of La Draga. A slight climatic cooling episode may have affected broadleaf deciduous trees immediately before the arrival of farming societies to Banyoles. Nevertheless, climate cannot have been the main cause of this abrupt change, and the establishment of Neolithic communities apparently was a significant factor of disturbance in vegetation evolution. The intensive exploitation of oak forest to obtain firewood (Piqué, 2000; Caruso-Fermé and Piqué, 2014) and raw materials for the construction of dwellings was responsible for the major impact on vegetation dynamics (Revelles et al., 2014). The opening of farming plots, which were probably small and intensively managed (Antolín, 2013; Antolín et al., 2014), and without use of fire, had a relatively minor impact on the landscape.

Human impact is not only expressed as a deforestation process. The maintenance of the clearances in oak forests is also important. After La Draga was abandoned, oak forest recuperation would be expected, but in contrast, the maintenance of the clearances is documented, probably using fire, as the charcoal data shows.Without discarding the possibility of finding more recent phases in La Draga (only 10% of the site has been excavated), the archaeological record in the surroundings of Lake Banyoles suggests that Neolithic communities remained in the area in the Late Early Neolithic period (6.7-5.55 cal ka BP).

From 5.55 cal ka BP, despite the lakeshore being affected by short duration soil erosion events at *ca*. 5.5 and 5.3 cal ka BP, oak pollen attains similar values as prior to La Draga occupation, and the evidence of human impact on the vegetation cover is very limited. These data are consistent with settlement dynamics in the area: in Pla de l'Estany the Middle Neolithic period (5.95-5.25 cal ka BP) is characterized by scarce archaeological remains. In general, very few archaeological sites are documented for this phase in north-east Iberia, and particularly in this pre-Pyrenean area. Most of the Middle Neolithic archaeological sites consist of pit burials and open-air sites located in lowlands in prelittoral valleys and plains in the central area of this region (Bòbila Madurell, Martín et al., 1996; Mines de Gavà, Villalba et al., 2011; Can Gambús, Roig et al., 2010; Ca n'Isach, Tarrús et al., 1996; Serra del Mas Bonet, Rosillo et al., 2012).

From 5.25 cal ka BP the opening of forests and the increase of Poaceae and Asteraceae can be interpreted as new evidence of anthropogenic impact on oak forest. However, these vegetation changes should be interpreted in relation to new climate conditions established with the transition to the Subboreal period and in the context of lake water-level changes and environmental dynamics in the lakeshore area, influenced by natural processes. In the Late Neolithic/Chalcolithic period (5.25‒4.0 cal ka BP), prehistoric communities settled again on the lakeshore (Mas Castell de Porqueres, 500 m from the core location) and also in the caves located in the surroundings of Lake Banyoles. Local burning episodes documented (charcoal macro-remains of alder in 5.25‒4.6 cal ka BP) confirm human frequentation in this period.

Nevertheless, anthropogenic impact was less than during the Early Neolithic, at a time when greater impact on the landscape might be expected, given the fact that in the Late Neolithic less intensive agriculture is documented in north-east Iberia (Antolín, 2013) with the expansion of hulled barley, the reduction of cultivated legume diversity and the probable introduction of the plough. In the Late Neolithic-Chalcolithic, the dynamics of human disturbance of the landscape move to the highlands, from the 6th millennium cal BP, with the start of forest openings, fire episodes and the generalization of high concentrations of spores of coprophilous fungi documented in high mountain areas, on the southern slopes (Pèlachs et al., 2007; Cunill, 2010; Ejarque, 2010; Miras et al., 2010; Cunill et al., 2012) and northern slopes of the Pyrenees (Galop, 2006; Galop and López Sáez, 2002; Vannière et al., 2001). This might indicate higher mobility in settlement dynamics or even the start of transhumance practices. In the context of communities based on extensive economic practices, higher mobility may have been a solution to the fast depletion of cultivated land and the search for pastures for ever-larger flocks (and probable increase in importance of cattle herding), making grazing impracticable in still densely forested lowland areas, as shown in the present study.

In that context, short episodes of vegetation disturbance, fire episodes and lower impact of husbandry around Lake Banyoles could be explained in these terms: given higher mobility and the start of more extensive herding practices, the footprint of husbandry in the lowlands would be reduced and the effect of agriculture would be expressed in short-duration intervals of grassland expansion and arboreal pollen reduction, as seen in the periods *ca*. 5.25-5.1 cal ka BP, *ca*. 4.98-4.8 cal ka BP, *ca*. 4.63-4.41 cal ka BP and *ca*. 4.17-3.9 cal ka BP. Therefore, evidence of agriculture near the lakeshore, expressed in the presence of crops (Cerealia-t pollen) and weeds (*Plantago major-media*), is documented in *ca*. 4.98 cal ka BP, *ca*. 4.63 cal ka BP, *ca*. 4.41 cal ka BP and *ca*. 4.17 cal ka BP. In that sense, the coincidence of short deforestation processes, presence of cultivars and weeds and burning of local riparian vegetation point to the practice of slash and burn agriculture.

Despite the assumption of the Bronze Age as a period characterized by intensification in the human impact on the landscape (related in part with the emergence of metallurgy), the apparent invisibility of human impact in the Lake Banyoles record in the early Bronze Age is noteworthy, in part due to less evidence of human occupation in the area at that time (Tarrús, 2000), before new settlements in the Late Bronze Age. This situation is not consistentwith the main Bronze Age societies in southern Europe, where one of the features linked with the social change occurring in this period is the large-scale impact on the landscape, as at El Argar in the south-eastern Iberian Peninsula (Castro et al., 2000; Carrión et al., 2007), and other European regions like central Italy (Sadori et al., 2004), northern Italy (Valsecchi et al., 2006) and north-eastern Bulgaria (Marinova and Atanassova, 2006). This invisibility of Bronze Age communities could be due to the scarce archaeological record belonging to this phase in the surroundings of Lake Banyoles, and also to the fact that Bronze Age communities did not base their economy on metallurgical production, which may have been a secondary activity (Rovira, 2006). This low anthropogenic impact of Bronze Age communities is consistent with other regions like southern France (Carozza and Galop, 2008; Jalut et al., 2009; Rius et al., 2009) where the major impact took place in the Iron Age and Roman period.

6. Conclusion

High-resolution pollen and geochemistry analysis of the SB2 core from Lake Banyoles describes a mid-Holocene vegetation succession and related geomorphologic processes, reacting to both climatic and anthropogenic causes. Broadleaf deciduous forests were resilient during mid-Holocene cooling oscillations but human activities affected the natural vegetation development in the Early (7.25‒5.55 cal ka BP) and Late Neolithic (5.17‒3.71 cal ka BP). Neolithic land-use represented a turning point in the scale of human impact on the landscape. The impact on the landscape by the first farming societies is not only expressed in the deforestation process, the clearance maintenance between 7.25 and 5.55 cal ka BP may be more important, showing long intensive exploitation of the landscape in the Early Neolithic period. Afterwards, in the Late Neolithic, short deforestation processes linked with fire episodes are documented, showing higher mobility in settlement patterns and the practice of the slash and burn farming model. Deforestation processes affected sedimentation dynamics, expressed in soil erosion events (shown in inputs of terrigenous sediments at the coring site), progressively in 7.25‒5.55 cal ka BP and rapidly in *ca*. 5.5, 5.3 and 4.3 cal ka BP. On the other hand, these sedimentation processes affecting the vegetation, in terms of the consolidation of a larger riparian forest in the newly emerged lake border areas. This was confirmed by the macro-remains analysis which allowed us to reconstruct local vegetation evolution, in a transition from swampy areas with lakeshore and aquatic plants to a riparian woodland environment, with the local presence of *Alnus*.

The SB2 mid-Holocene sequence shows the resilience of broadleaf deciduous tree forests during cooling phases (8.2 cal ka BP, 7.4 cal ka BP, 5.5 cal ka BP, 4.2 cal ka BP), only causing slight decreases in AP and deciduous forests in 8.2 and 7.4 cal ka BP, with no evident effects during the 5.5 and 4.2 cal ka BP cooling/arid phases. Nevertheless, the progressive process of lake water-level regression from the start of the sequence coincides with similar processes in other regions around 9.0 cal ka BP

(Carrión, 2002; Magny et al., 2007, 2011) and around 5.5 cal ka BP (Frigola et al., 2007; Morellón et al., 2009). The start of the deciduous-evergreen oak succession documented at the end of the sequence, is consistent with the start of increasing aridification in the Western Mediterranean (Jalut et al., 2009).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi: http://dx.doi.org/10.1016/j.palaeo.2015.06.002. These data include Google maps of the most important areas described in this article.

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4.1.2. Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia).

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Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia).

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Abstract

The analysis of non-pollen palynomorphs (NPP) provides useful information about local environmental conditions. The study of a core from Lake Banyoles (Girona, NE Iberia) enabled the reconstruction of ecological changes and assessment of human impact in a lakeshore environment during the Mid-Holocene. This work aims to fill the gap in knowledge about the ecological significance of NPP in lowland areas in NE Iberia, and provides descriptions and illustrations of new types documented.

Deforestation induced by Early Neolithic communities caused the proliferation of lignicolous fungi in decaying wood and an increase in soil erosion. The input of allochthonous mud led to higher turbidity in the lake water, causing a succession in aquatic organisms, from cyanobacteria to green algae. In that context, a group of erosion-associated fungal spore types were recorded. Indicators of soil disturbance and coprophilous fungi were recorded from 5000 to 4200 cal BP, linked with local habitation during the Late Neolithic-Chalcolithic. The NPP analysis reflects the significant human impact that caused changing local environmental conditions, consistent with the signals based on pollen analysis.

Keywords: Non-pollen palynomorphs, Lakeshore environment, Iberian Peninsula, Neolithic land-use, Mid-Holocene, soil erosion

1. Introduction

Interest in the study of palaeo-environmental evolution during the Mid-Holocene lies in the interaction between cooling and arid/moist climatic oscillations and a substantial increase in anthropogenic impact following the adoption of the farming lifestyle (Ruddiman, 2003; Ruddimann, 2013; Carrión et al., 2010a; Sadori, 2013; Smith and Zeder, 2014; Ruddiman et al., 2015; Revelles, in press). The study of human-environment interactions and palaeo-environmental evolution can be carried out with different proxies on different scales. Palaeoecological research provides data on a regional basis through pollen analysis, but in addition strictly local data can be obtained, based on the analysis of macrofossils and non-pollen palynomorphs (NPP).

This paper focuses on the potential contribution of NPP analysis to the reconstruction - at a local scale- of the palaeo-environmental development of the Banyoles lakemargin during the Mid-Holocene. Previous work concentrated on vegetation changes on a more extra-local scale (Revelles et al., 2014, 2015). This paper expands the information obtained by pollen analysis, by using detailed knowledge based on NPP in order to comprehend the formation processes of the cored deposit and the climatic, sedimentary or anthropogenic factors that may have affected the various recorded changes. This approach has been successfully applied in a nearby archaeological context, at the site of La Draga, dated in the Early Neolithic (7270‑6970 cal BP) (Revelles et al., 2016).

NPP analysis provides useful information about local environmental conditions, such as changes in hydrology and trophic conditions, soil erosion episodes, fire occurrence and the presence of dung (van Geel et al., 2003, 2006). In the Iberian Peninsula, to date over thirty studies have considered NPP analysis (López Sáez et al., 1998, 2000, 2002, 2006, 2007; López-Sáez et al., 2009a, 2009b; Carrión and van Geel, 1999; Carrión et al., 2000, 2001a, 2001b, 2001c, 2003, 2004, 2005, 2007, 2010a, Carrión et al., 2010b; Carrión, 2002; Navarro et al., 2002; López-Merino et al., 2006, 2010a, 2010b, 2011; Riera et al., 2006; Valero-Garcés et al., 2006; Danielsen, 2008, 2010; Ejarque et al., 2010; Miras et al., 2010; Moreno et al., 2011; Rull et al., 2011; Orengo et al., 2014; Expósito et al., in press). However, only one paper included ‘new’ types with descriptions and illustrations (Carrión and van Geel, 1999). The scarcity of palaeorecords providing descriptions and illustrations of palynomorphs in the Iberian Peninsula is further accentuated in NE Iberia, where the only study providing new non-pollen palynomorphs refers to modern samples (López-Vila et al., 2014). In addition, in NE Iberia NPP studies have mainly focused on high mountain areas (the Pyrenees), both for palaeorecords (Riera et al., 2006; Ejarque et al., 2010; Miras et al., 2010; Rull et al., 2011; Orengo et al., 2014) and for surface samples (Ejarque et al., 2011; López-Vila et al., 2014). In that context, the present work attempts to address the lack of knowledge about the ecological significance of NPP in lowland areas in NE Iberia, and to provide descriptions and illustrations of newly recorded NPP types, which is an essential step in order to make progress in NPP research.

Previous palynological studies on the same core allowed the reconstruction of vegetation history and human impact during the Mid-Holocene, showing the predominance of deciduous forests (deciduous *Quercus* and *Corylus avellana*) and the importance of conifers in the nearby mountains (*Pinus* sp. and *Abies alba*; Revelles et al., 2015). Pollen, sedimentary charcoal, sedimentological proxies and selected NPP succeeded in characterizing the impact of changes in land-use management. Deforestation processes affected oak forests and riparian forests in the Early Neolithic (7250‑5550 cal BP) and Late Neolithic-Chalcolithic (5170‑3710 cal BP), in the context of broadleaf deciduous forest resilience against cooling and moisture/dryness fluctuations. Furthermore, changes in sedimentation dynamics and lake water level caused the emergence of dry land along the lake margin where a dense riparian forest was established from 5550 cal BP onwards (Revelles et al., 2015). The present study compares detailed NPP results with previous data, in order to obtain a better understanding of changing local environmental conditions and to comprehend the formation of this Mid-Holocene record and assess anthropogenic and natural processes at a local scale.

Therefore, the main objectives of this paper are:

- To evaluate the ecological significance of documented NPP.

- To assess the relationship between the NPP record, vegetation changes and sedimentation dynamics at a local scale.

- To assess human impact and identify anthropogenic indicators among the NPP.

2. Study area

2.1. Environmental settings

The study area is located in the north-east of the Iberian Peninsula, 35 km from the Mediterranean Sea and 50 km south of the Pyrenees (Fig. 1). Lake Banyoles is a karst lake associatedwith a large karst aquifer system located in a tectonic depression, fed by underground water. The lake is approximately 2100 m long and 750 m wide, with an average depth of 15 m, reaching up to 46 m at several locations (Julià, 1980; Casamitjana et al., 2006; Höbig et al., 2012). The lake water is supersaturated in calcite, causing precipitation, and thus constituting the main component of the lake sediments (Bischoff et al., 1994). Lake Banyoles is defined as oligo-mesotrophic, andwater temperatures range between 8-25 °C on the surface and 8-17 °C in deep water (Serra et al., 2002).

The climate in the Banyoles region is defined as humid Mediterranean, with an annual precipitation of 750 mm and amean annual temperature of 15 °C. The average maximum temperature during July and August is 23 °C, and the minimum average is 7 °C in winter. The minimum monthly precipitation (ca. 10 mm) occurs during summer and in December.

The current vegetation is dominated by a mixed forest with evergreen oak (*Quercus ilex*, *Quercus coccifera*, *Rhamnus alaternus*, *Phillyrea media*, *Ph. angustifolia*), deciduous oak forest (*Quercus humilis*, *Buxus sempervirens*, *Ilex aquifolium*) and pine forest (*Pinus halepensis*). In this context, shrublands (*Erica arborea*, *Rosmarinus officinalis*) are well represented. Along the lakeshore, there are helophytic communities represented by *Phragmites australis*, *Typha angustifolia*, *Lythrum salicaria* and several cyperaceous species (Gracia et al., 2001) and a riparian forest with *Fraxinus angustifolia*, *Alnus glutinosa* and *Salix atrocinerea*.

2.2. Archaeological background

Considering the limited evidence of settlements in the area during the Mesolithic (lack of radiocarbon dates during the first half of the 8th millennium cal BP and only a few dates during the 9th millennium cal BP; Barceló, 2008; Bogdanovic et al., 2015), the establishment of the first farming societies is supposed to represent the first appearance of Holocene human societies causing landscape transformation and disruption of the natural environmental conditions in the region.

The Early Neolithic was one of the most remarkable periods in this area given the notable occupations along the lakeshore and in the near surroundings. On the eastern shore of Lake Banyoles (Fig. 1), the site of La Draga has provided an exceptional archaeological record and detailed knowledge of Neolithic communities (Cardial Neolithic, 7270‑6750 cal BP), owing to excellent preservation in waterlogged conditions (Bosch et al., 2012; Palomo et al., 2014; Bogdanovic et al., 2015; Terradas et al., in press). At a regional scale, some Early Neolithic occupations were recorded in Serinyà Caves (4-5 km away from Lake Banyoles), dated in both the Cardial Neolithic and the Epicardial and Postcardial Neolithic (6900‑5550 cal BP) (Tarrús, 2000). After scarce evidence of occupation during the Middle Neolithic (5950‑5250 cal BP), in the Late Neolithic‑Chalcolithic the lakeshore was occupied at the same time as occupations recorded in the Serinyà caves and in the Esponellà caves (10 km away). However, most of this evidence comes from decontextualised finds or old archaeological excavations and dating is indirect, based on ceramic styles.

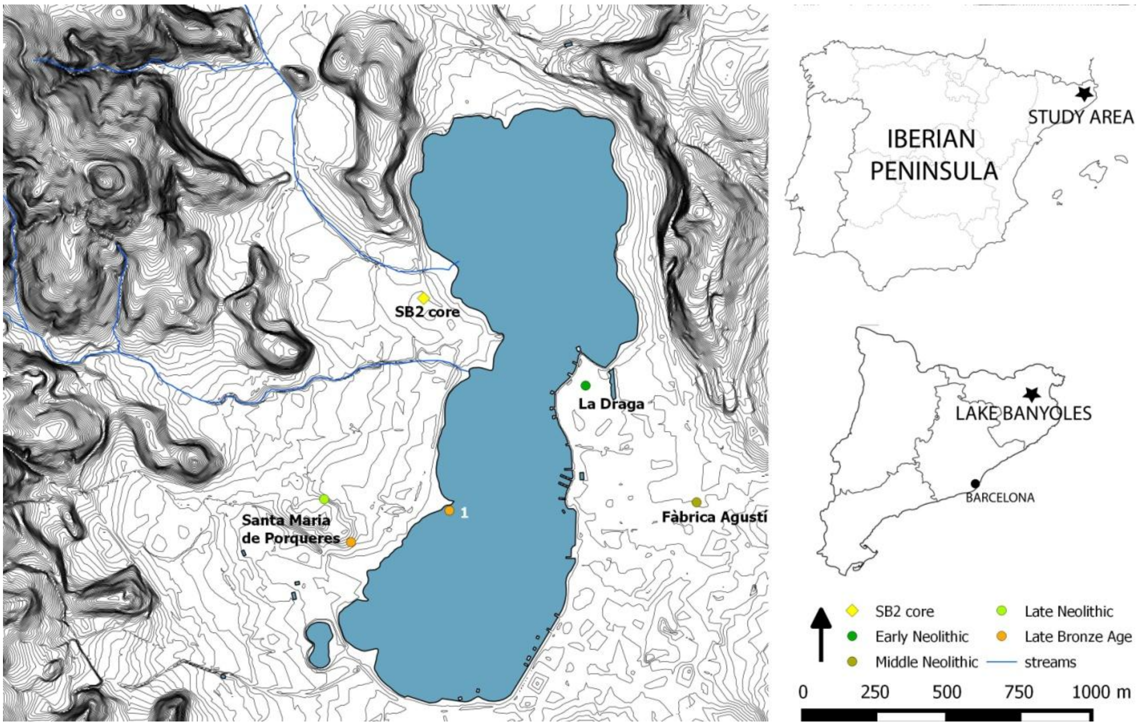


Figure 1. Location of the coring site and surrounding archaeological sites. Isolines indicate 1mdifferences in altitude. 1)Workedwooden remains, probably a canoe, recovered by underwater surveying, and dated in 3200‑3180 cal BP (Bosch et al., 2012).

3. Material and methods

3.1. The SB2 core (Lake Banyoles)

The present study is based on the same samples formerly used for pollen analysis (see Revelles et al., 2015 for more details in sampling and other interdisciplinary data). The age-depth model based on six Accelerator Mass Spectrometry (AMS) radiocarbon dates (Table 1) shows that the studied organic unit, 107 cm in depth, spans the time between *ca*. 8900 and 3300 cal BP, providing information about changing environmental conditions from the late Early Holocene to the early Late Holocene. This organic unitwas divided in three subunits: peaty organic facies on top of shallowcarbonate lacustrine sands (8900-7200 cal BP); less organic peaty facies with an increasing content of siliciclastic mud (7200-4200 cal BP); and a peaty layer with fine carbonate sedimentation (4200-3300 cal BP; Revelles et al., 2015).

3.2. NPP analysis

The preparation of the samples followed standard methods (Burjachs et al., 2003) using treatment with HCl, NaOH, flotation in dense Thoulet liquor, HF and final mounting in glycerine. NPP were counted using an Olympus Bx43 microscope fitted with 10× eyepiece lenses and 40/60× objective lenses and the percentages correspond to NPP/300-350 pollen sums of terrestrial taxa. NPP identification followed van Geel (1978, 2001), van Geel et al. (2003), Gelorini et al. (2011) and Cugny (2011). Some NPP were described for the first time and named using a code with the prefix UAB (Universitat Autònoma de Barcelona) and a sequential number (see Appendix A). Some of the recorded UAB types were previously described and illustrated by Revelles et al. (2016).

Table 1. Radiocarbon dates, SB2 core (Lake Banyoles) (fromRevelles et al., 2014, 2015). Calibration to years cal. BPwas performed with Clam 2.2 (Blaauw, 2010) based on the data set IntCal13.14C (Reimer et al., 2013).

Sample depth (cm)	Lab. code	Type	AMS radiocarbon date BP	Cal. yr BP (2σ range) 95% prob.	Cal. yr BP in diagram
173	SUERC-38761 (GU26454)	Bulk sediment	2590± 30	2732–2876	2759
201	Beta-325839	Charcoal	4480± 30	4836–5171	5030
215	SUERC-38760 (GU26453)	Bulk sediment	4650± 30	5292–5452	5383
237	SUERC-49224 (GU31929)	Bulk sediment	5148± 30	5948–6239	6024
253	SUERC-49225 (GU31930)	Bulk sediment	6645± 31	7171–7518	7418
276	SUERC-38759 (GU26452)	Bulk sediment	7855± 30	8609–8947	8685

4. Results

4.1. NPP analysis

The NPP analysis (in pollen slides) shows the changing records of different fern spores, vegetative botanical remains, fungal spores, algae, cyanobacteria, zoological remains and other, unclassified types through the Mid-Holocene. NPP percentage curves are presented in Fig. 2A, B and C (NPP taxa) and in Fig. 3 (selected NPP taxa and categories compared with other palaeoecological proxies) using Tilia software (Grimm, 1991-2011). Two main NPP zones and six subzones were defined using stratigraphically constrained cluster analysis CONISS (Grimm, 1987):

- Sub-zone A1a (8900–8140 cal BP): low values of ferns and algae, some evidence of Cyperaceae roots, presence of *Glomus* and occurrence of clusters and high values of HdV-361. Continuous curve and highest values in UAB-20 and in HdV-224, high values in UAB-22 and UAB-23 and occurrence of *Pseudoschizaea* and UAB-24.

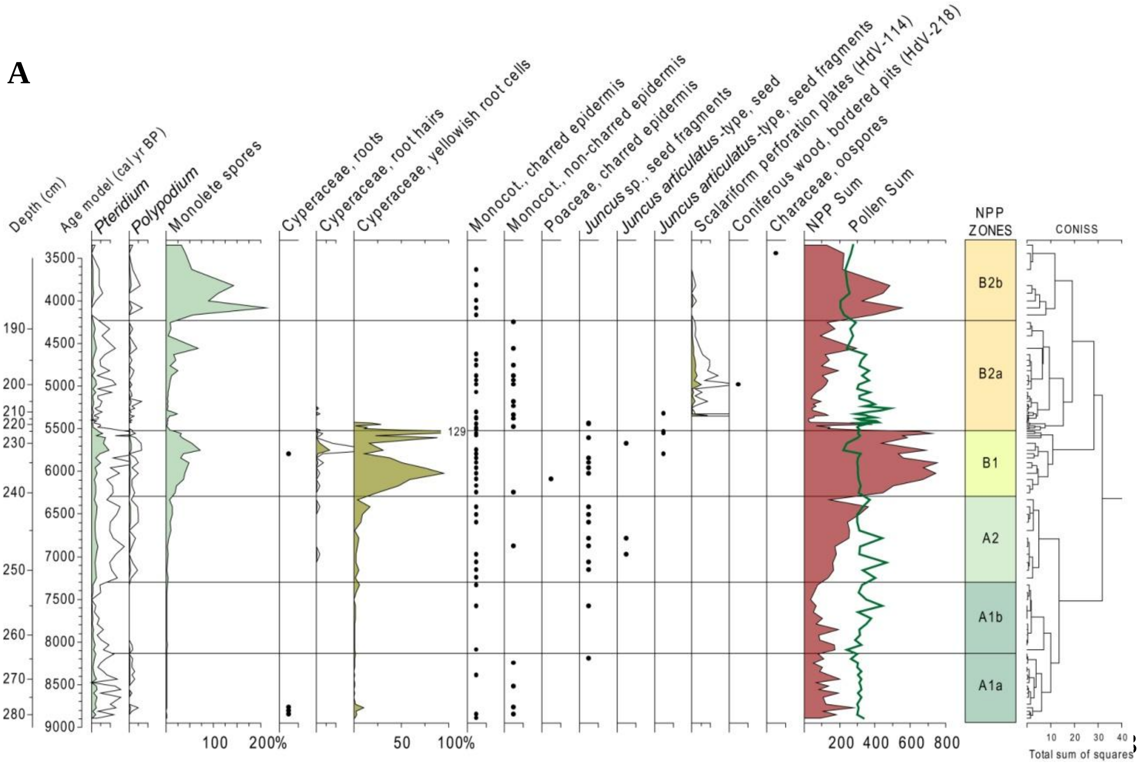
- Sub-zone A1b (8140–7250 cal BP): high values in *Gloeotrichia* and the presence of *Rivularia*-type correspond with the decrease in HdV-224. Continuation of low values of ferns and algae and decrease in fungal spores.

- Sub-zone A2 (7250–6300 cal BP): increase in values of ferns and zoological remains, appearance of a continuous curve of yellowish root cells of Cyperaceae and occurrence of *Juncus* sp. seeds. An increase in algae, especially *Spirogyra* and *Mougeotia*, a decrease in *Gloeotrichia*, the disappearance of *Rivularia*-type and the appearance of HdV-128 undiff. occur in this sub-zone. Among fungal spores, the presence of *Coniochaeta* cf. *ligniaria*, *Glomus*, UAB-7 and UAB-8.

- Sub-zone B1 (6300–5550 cal BP): high values ofmonolete fern spores and highest values of *Pteridium*, Cyperaceae root hairs and yellowish root cells. Highest values of *Glomus* and HdV-361. Occurrence of spores of coprophilous fungi (*Sordaria*-type, *Cercophora*-type, *Podospora*-type, *Rhytidospora*), eggs of parasites (*Trichuris* sp.) and highest values of carbonicolous/lignicolous fungi (*C*. cf. *ligniaria*, *Gelasinospora* and *Kretzschmaria deusta*). Some 'new' types showing their highest values or exclusive appearance in this sub-zone: UAB-1, 2, 3, 4, 5, 10, 11, 12, 13, 17, 18A, 18B. Continuation of the high values of algae, highest values of HdV-128 undiff., HdV-182, UAB-26 and UAB-27, and occurrence of Type 988 (Carrión and van Geel, 1999) and *Pseudoschizaea* at the end of the sub-zone.

- Sub-zone B2a (5550–4250 cal BP): decrease in fern spores and highest values in scalariform perforation plates. Disappearance of *Juncus* spp. seeds and the presence of bordered pits of coniferous wood. Among fungi, the presence of *Cercophora*-type, *Gaeumannomyces* and UAB-21, decrease in *Glomus* and HdV-361 and exclusive occurrence of *D. rhizophila*, UAB-14 and UAB-29. Decrease in algae at the onset of the sub-zone and slight recovery afterwards, the highest values of *Closterium* and presence of *Gloeotrichia*, *Rivularia*-type, HdV-128 undiff. and UAB-25.

- Sub-zone B2b (4250–3350 cal BP): the highest values of monolete fern spores and presence of scalariform perforation plates. Presence of *Glomus* and HdV-361 and high values of UAB-30A and UAB-30B. Decrease in algae values and the highest values of *Gloeotrichia*, *Rivularia*-type and UAB-25 (Plate II). Occurrence of HdV-224 and UAB-24 and high values in UAB-22.



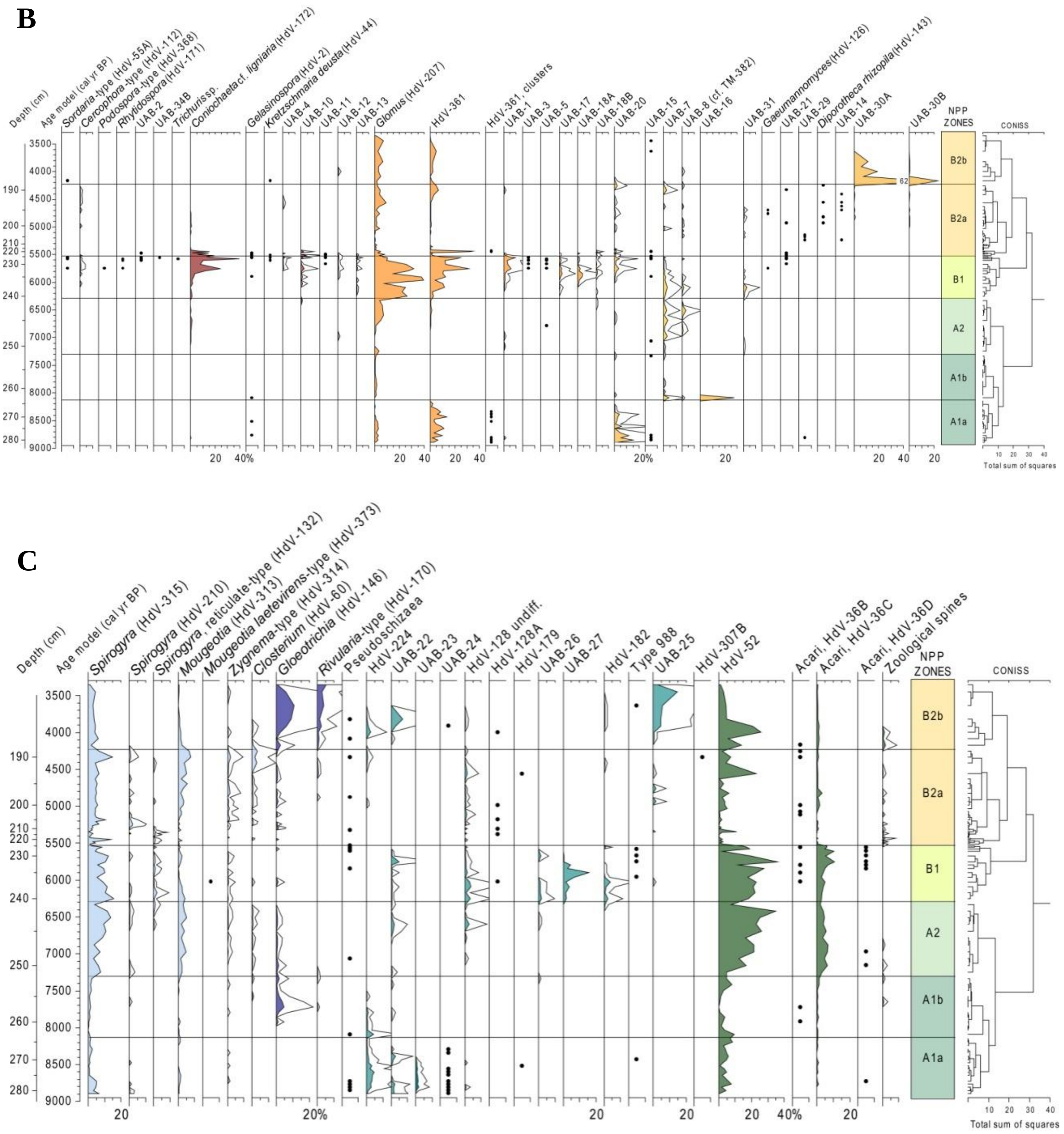


Figure 2. A. Percentage NPP diagram. Fern spores and plant remains are plotted to a calibrated year BP scale. Hollow silhouettes showvalues exaggerated ×5. Values below 1% are represented by points (also in Figs. 2B, C and 3). B. Percentage NPP diagram. Fungal spores are plotted to a calibrated year BP scale. C. Percentage NPP diagram. Aquatic organisms, unidentified palynomorphs and zoological remains are plotted to a calibrated year BP scale.

5. Discussion

5.1. Palaeo-environmental changes as recorded in the Mid-Holocene

5.1.1. Transition from lacustrine to palustrine environment and vegetated lakeshore formation (A1a and A1b, 8900–7250 cal BP)

The start of the sequence coincides with the transition from a carbonate lacustrine facies to carbonate-rich peaty silts with some plant remains (Revelles et al., 2015). Peat formation about 8900 cal BP is due to a water-level regression, a process also attested in other Mediterranean areas during this period (Carrión, 2002; Magny et al., 2007; Vegas et al., 2009; Pérez-Sanz et al., 2013). This lowering process leads to the colonization of the lakeshore by vegetation, constituting a subaerial swamp with Cladium mariscus (as shown in the macrofossils record and the evidence of Cyperaceae roots and yellowish root cells, Figs. 2A and 3), pointing to the existence of an alkaline substrate, poor in nitrogen. Maximum values in UAB-20 are consistent with this type of environment as shown in previous works in the area (Revelles et al., 2016), as well as the maximum values in HdV-224 (and the morphologically similar UAB-23 and UAB-24, Plate III), characteristic of sandy layers with plant debris (van Geel et al., 1989).

This transition to a palustrine environment coincides with the frequent occurrence of *Pseudoschizaea* at the onset of the sequence, a palynomorph often associated with seasonal drying or the prolongation of the summer drought (Scott, 1992; Carrión and Navarro, 2002), or with soil erosion (Pantaleón Cano et al., 1996). In that context, the presence of *Glomus* and HdV-361, and the occurrence of clusters of HdV-361 would be related with the increasing allochthonous terrigenous silt sedimentation in this part of the sequence (Revelles et al., 2015).

From *ca*. 8000 cal BP onwards, the decline in HdV-224, UAB-23, UAB-24 and UAB-20 coincides with the onset of a continuous curve of *Gloeotrichia* and the presence of *Rivularia*-type. These cyanobacteria could play a pioneer role in nutrient poor conditions, fixing nitrogen and opening up local conditions for other aquatic plants (van Geel et al., 1984). In that context, a succession in lakeshore vegetation occurs from *C. mariscus* to *Juncus* spp., *T. latifolia* and a noticeable presence of Characeae (Fig. 3).

5.1.2. Soil erosion episodes in a swampy lakeshore environment (A2 and B1, 7250–5550 cal BP)

The process of nitrogen fixation by cyanobacteria leads to suitable conditions for freshwater algae (*Spirogyra*, *Mougeotia*, *Zygnema*-type, *Closterium*) that reach high peaks in their absolute concentration from *ca*. 7200 to 6300 cal BP, and for *Mentha* cf. *aquatica* from 7250 cal BP onwards (Figs. 2C and 3). The increasing inputs of terrigenous mud to the shore is reflected in the appearance of a continuous curve of *Glomus* and the occurrence of Cyperaceae root remains, indicating increasing soil erosion (Anderson et al., 1984; van Geel et al., 1989; López Sáez et al., 2000). The rise in ferns (*Pteridium*, *Polypodium* and monolete spores) could be understood in the context of deforestation processes occurring in the area during the Early Neolithic (Revelles et al., 2014, 2015), due to the intensive exploitation of oak woodlands in order to collect firewood (Caruso-Fermé and Piqué, 2014) and timber (López, 2015).

The sediment from the period 6300-5550 cal BP contains the highest diversity and amount of non-pollen palynomorphs (Fig. 2A, B, C), and this is linked to soil erosion and fire episodes (Fig. 3). Upland soil erosion in deforested areas leads to high values of *Glomus*, HdV-361, monolete spores and Cyperaceae root remains in the sediment at the sampling site. In the context of increasing fire activity, the highest values of carbonicolous/lignicolous fungi are recorded, especially of *C.* cf. *ligniaria* (Fig. 2B), often associated with deforestation and fire episodes (López Sáez et al., 1998). The landscape transformation by Neolithic communities is also reflected by spores of coprophilous fungi (*Sordaria*-type, *Cercophora*-type, *Podospora*-type, *Rhytidospora*, UAB-2 and UAB-34B), as well as by evidence of intestinal parasites (*Trichuris* sp.). The input of allochthonous silts in this period is strongly linkedwith anthropogenic disturbance in nearby upland areas. Fire and domesticated herbivores may have played a role in the maintenance of forest clearances from *ca*. 6000 cal BP onwards, evidencing a reiterative Neolithic impact in the area and suggesting a permanent settlement during the whole Early Neolithic period (7300‑5550 cal BP).

The existence of a wet swampy lakeshore environment is reflected in the continuation of high values of algae occurring in shallow freshwater and the occurrence of HdV-182 and Type 988 (Fig. 2C), which are palynomorphs characteristic of stagnant shallow water (van Geel et al., 1983; Carrión and van Geel, 1999; Carrión and Navarro, 2002). Short interruptions by strong inflows of allochthonous matter caused a sharp decrease in the concentration of algae between *ca*. 6000‑5400 cal BP (Fig. 3).

5.1.3. Agricultural impact in an alder carr (B2a and B2b, 5550-3350 cal BP)

The evidence for soil erosion ends *ca*. 5400 cal BP, resulting in the disappearance of NPP previously attested. But an important local environmental change is recorded, caused by the infill of the lakeshore by terrestrial sediments and the lowering of the lake water level in the context of the Mid-Holocene aridification process in the Mediterranean region (Jalut et al., 2009; Carrión et al., 2010a). The newly exposed swampy plains close to the lakeshore were colonized by *Alnus* and other riparian trees (Fig. 3), a process consolidated from *ca*. 5250 cal BP, resulting in the establishment of a larger riparian forest on a vadose substrate (Revelles et al., 2015). The presence of some macrofossils indicative of riparian woodland areas (*Alnus* sp., *Alnus* sp. charcoal, unidentified catkins, suberized leaf scars, *Eupatorium cannabinum*, *Rubus fruticosus* L.s.l., *Galium* cf. *aparine* and *Brachythecium* sp.) and of a swampy lakeshore (*Ranunculus* subgenus *Batrachium*, *Mentha* cf. *aquatica*, *Alisma* sp. and *Potamogeton* cf. *coloratus*) suggest the existence of an alder carr environment. Among the NPP the same dichotomy is recorded, shown by the highest values and exclusive appearance of scalariform perforation plates (HdV-114) (probably belonging to *Alnus*, considering the great abundance of rungs, Plate V) and *Diporotheca rhizophila* (HdV-143), a parasitic fungi previously found in alder carr environments (Prager et al., 2006), or in association with pollen of *Alnus* and *Salix* (Bos et al., 2005; Gelorini et al., 2006; Menozzi et al., 2010; Deforce, 2011). On the other hand, the continuation of high values of green algae points to the availability of water in spring and probable desiccation in summer (Fig. 3).

In the period *ca*. 5000‑4200 cal BP, short deforestation episodes, fire activity in riparian vegetation and the presence of Cerealia-type coincide with records of coprophilous fungi (*Cercophora*-type and *Sordaria*-type) (Fig. 2B) and an increase in monolete spores, revealing strong evidence of local human impact near the lakeshore. The presence of *D. rhizophila*, apart from pointing to the existence of eutrophic wetland conditions (Ramezani et al., 2008; Montoya et al., 2010; Wheeler et al., 2010), reinforces the hypothesis of nearby cultivation proposed in Revelles et al. (2015), as it is a parasitic fungus and indicator of eutrophic wet habitats combined with major soil disturbance (Hillbrand et al., 2012). The human modification of this alder carr is also reflected in the co-occurrence of charcoal and short regression phases of *Alnus* and presence of Cerealia-type.

From *ca*. 4200 cal BP, the greatest change recorded is the noticeable increase in cyanobacteria (*Gloeotrichia* and *Rivularia*-type), as well as the highest values of monolete fern spores, together with the decrease in green algae. After the end of the inputs of terrigenous mud to the lakeshore, authigenic fine carbonate sedimentation occurs (Fig. 3). The highest peaks of monolete fern spores could be related with oxidation in peat environments (Dimbleby, 1957), probably seasonally dried, and the increase in cyanobacteria would reflect excessive eutrophication, conferring a competitive advantage over green algae in environments with increased levels of phosphorus (van Geel et al., 1994). The detected eutrophication would have been the result of the combination of human impact and lake level lowering as recorded in other studies (Hillbrand et al., 2014). This local evidence of relative drier conditions would be consistent with palaeoclimatic evidence in the western Mediterranean from the 4200 event onwards (Bond et al., 1997; Denèfle et al., 2000; Jalut et al., 2000, 2009; Roberts et al., 2001; Sadori and Narcisi, 2001; Carrión et al., 2010a; Sadori, 2013), although no remarkable changes to drier conditions are recorded in upland vegetation, showing the resilience of broadleaf deciduous forests against climate oscillations during the whole Mid-Holocene and in the transition to the Late Holocene (Revelles et al., 2015).

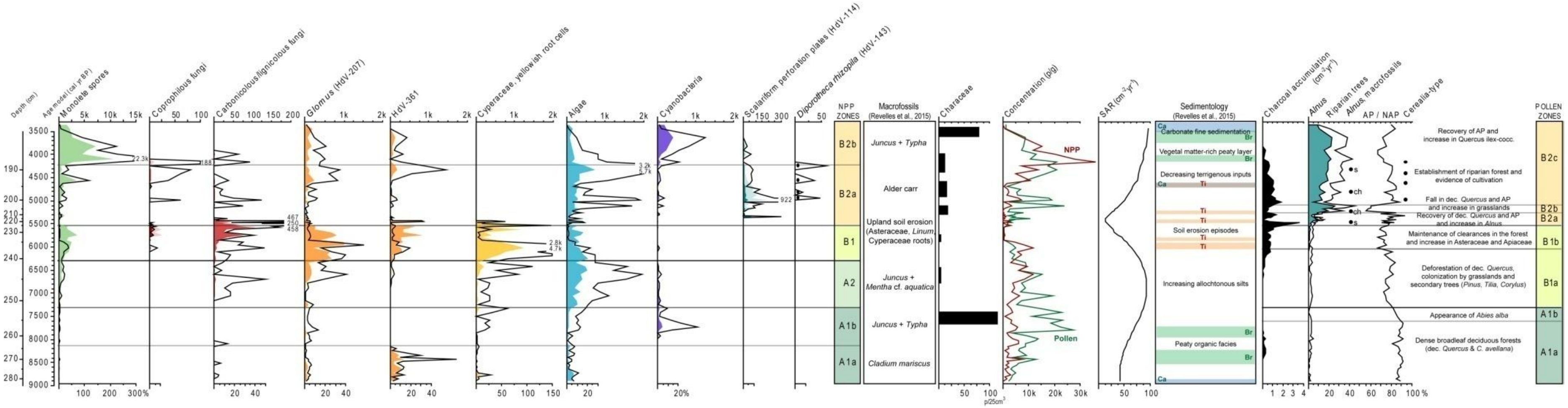


Figure 3. Synthetic diagram comparing selected NPP taxa and categories expressed in percentages (silhouettes) and absolute concentration (particles/g) (lines), with macrofossils, sedimentology and pollen data from a previous work.

5.2. Ecological interpretation of NPP and anthropogenic indicators

5.2.1. Neolithic husbandry and spores of coprophilous fungi

Spores of coprophilous fungi have become a key element when assessing human impact in terms of grazing pressure (Ralska-Jasiewiczowa and van Geel, 1992; Cugny et al., 2010; Gauthier et al., 2010). The adoption of farming practices involved the progressive occurrence of dung indicators inmicrofossil records in periods of deforestation and expansion of grasslands and ruderal taxa. This is extensively documented in Iberia during the Middle and Late Holocene, especially in high mountain areas (Carrión, 2002; Riera et al., 2006; Miras et al., 2007; Ejarque et al., 2010; López-Merino et al., 2010a; Miras et al., 2010; Orengo et al., 2014). But the local geomorphologic evolution of the analysed deposit should also be considered, because changes in lake level and in the distance between the coring site and the lakeshore may be very important factors in the representation of spores of coprophilous fungi in lacustrine records (Raper and Bush, 2009). Spores of coprophilous fungi are transported over relatively short distances and thus are merely local or extra-local (sensu Janssen, 1966) indicators for large herbivores.

Although the first farming societies in the Lake Banyoles area transformed the landscape noticeably, in terms of oak woodland deforestation, from 7300 cal BP, no impact of grazing has been detected contemporary with this phenomenon. The lack of spores of coprophilous fungi during the onset of the Early Neolithic could be understood in the context of the intensive farming system documented at La Draga (Antolín et al., 2014), where the flocks would have grazed in the immediate surroundings of the settlement (along the opposite shore) or in the upland crop fields (Revelles et al., 2016). Nevertheless, the geomorphologic conditions of the lakeshore must be considered in order to comprehend this lack of spores of coprophilous fungi. Considering the swampy lakeshore, the animals could not approach the area and there is no evidence of grazing pressure until the occurrence of the soil erosion bringing allochthonous material from uplands in the period from 6000 to 5500 cal BP. In that phase, ascospores of *Sordaria* (HdV-55A), *Cercophora* (HdV-112), *Podospora* (HdV-368) and *Rhytidospora* (HdV-171) were recorded, as well as egg shells of intestinal parasites (*Trichuris* sp.) and the new types UAB-2 and UAB-34B, that are ascospores previously documented in archaeological layers with evidence of dung (Revelles et al., 2016). In this way, transport and deposition of eroded material is able to reconstruct the range of the signal of grazing pressure during the Neolithic in the Lake Banyoles area. During the first centuries of the Early Neolithic, the grazing impact was restricted to the eastern lakeshore, as evidenced at La Draga (7270‑6750 cal BP) (Revelles et al., 2016), whereas in the late Early Neolithic (6000-5500 cal BP) grazing pressure is detected (indirectly) along the western lakeshore (Figs. 2B and 3), as a consequence of soil erosion episodes.

From 5550 cal BP onwards, the occurrence of spores of coprophilous fungi can be considered a local grazing pressure indicator, given the establishment of an alder carr environment providing a drier substrate comparedwith the previous swampy lakeshore. The local occurrence of coprophilous fungi, with their highest concentration values (Fig. 3) around *ca*. 5000 cal BP and from *ca*. 4600 to 4200 cal BP, is associated with evidence of local cultivation, soil disturbance and burning in the riparian forest.

5.2.2. Fire and carbonicolous/lignicolous fungi

The most direct evidence of fire is the sedimentary charcoal record, but fire episodes can occur at local or regional scales. Carbonicolous/lignicolous fungi have been proposed as indicators for local occurrence of fires near coring sites (Blackford et al., 2006). There is no direct correlation between fungi and host tree, although *K. deusta* (HdV-44) is linked with *Fagus* (van Geel et al., 2013) or other deciduous trees such as *Quercus*, *Fraxinus*, *Ulmus* or *Tilia* (Cannon et al., 1985; van Geel and Andersen, 1988; Innes et al., 2006). Relatively high quantities of ascospores of tree-infecting fungi could be expected in forest soils (van Geel et al., 2013), but in the SB2 record the highest values of carbonicolous/lignicolous fungi (dominance of *C.* cf. *ligniaria* and presence of *K. deusta* and *Gelasinospora*) are recorded in the phase of soil erosion (6300‑5550 cal BP). The ascospores probably reached the lakeshore due to the input of allochthonous muds from disturbed upland areas, a phenomenon consistent with results in van Geel et al. (2013), where *K. deusta* spores were apparently transported from the forest floor into the lake by strong winds and water during rainstorms. Likewise, López-Merino et al. (2012) attested maximum values of C. cf. ligniaria in a phase of soil erosion and grazing pressure on nearby deforested land.

Human impact, in terms of wood cutting and grazing pressure may have stimulated fungal infections of trees (van Geel et al., 2013). The cutting of oak trees may have provided the proper conditions for infection and rapid wood decomposition by lignicolous fungi. Thus, the reiterative human exploitation of forests during the Early Neolithic would have been the cause of their highest values. Fewer lignicolous fungi were documented in the Late Neolithic period, when burning in the riparian forest is evidenced, but in short phases thatmay have enabled the recovery of the alder carr environment after every short episode of human disturbance. In that sense, the presence of carbonicolous/lignicolous fungi may have been linked with decaying wood (transported to the lakeshore by runoffs) rather than the presence of charred wood or fire episodes. Thus, different land-use or woodland exploitation regimes may have influenced the different fungal records (Innes et al., 2010). Exclusive pyrophytic fungi are absent (*Neurospora*, HdV-55C) or scarcely recorded (*Gelasinospora*, HdV-2), and the best represented is *C.* cf. *ligniaria* (HdV-172), a fungus often associated with decaying wood. In addition, the new types classified in the carbonicolous/lignicolous category are morphologically similar to the genus *Coniochaeta* (UAB-10) and the family Xylariaceae (UAB-11, UAB-12, UAB-13) (Plate I, Appendix A), and this assemblage of spores of carbonicolous/lignicolous fungi has been previously documented in the same area in an archaeological deposit characterized by the collapse of oak structures (Revelles et al., 2016). In conclusion, the frequencies of ascospores of carbonicolous/lignicolous fungi in Lake Banyoles are probably related to the exploitation of forests by Neolithic communities rather thanwith the local or regional signal of fire episodes.

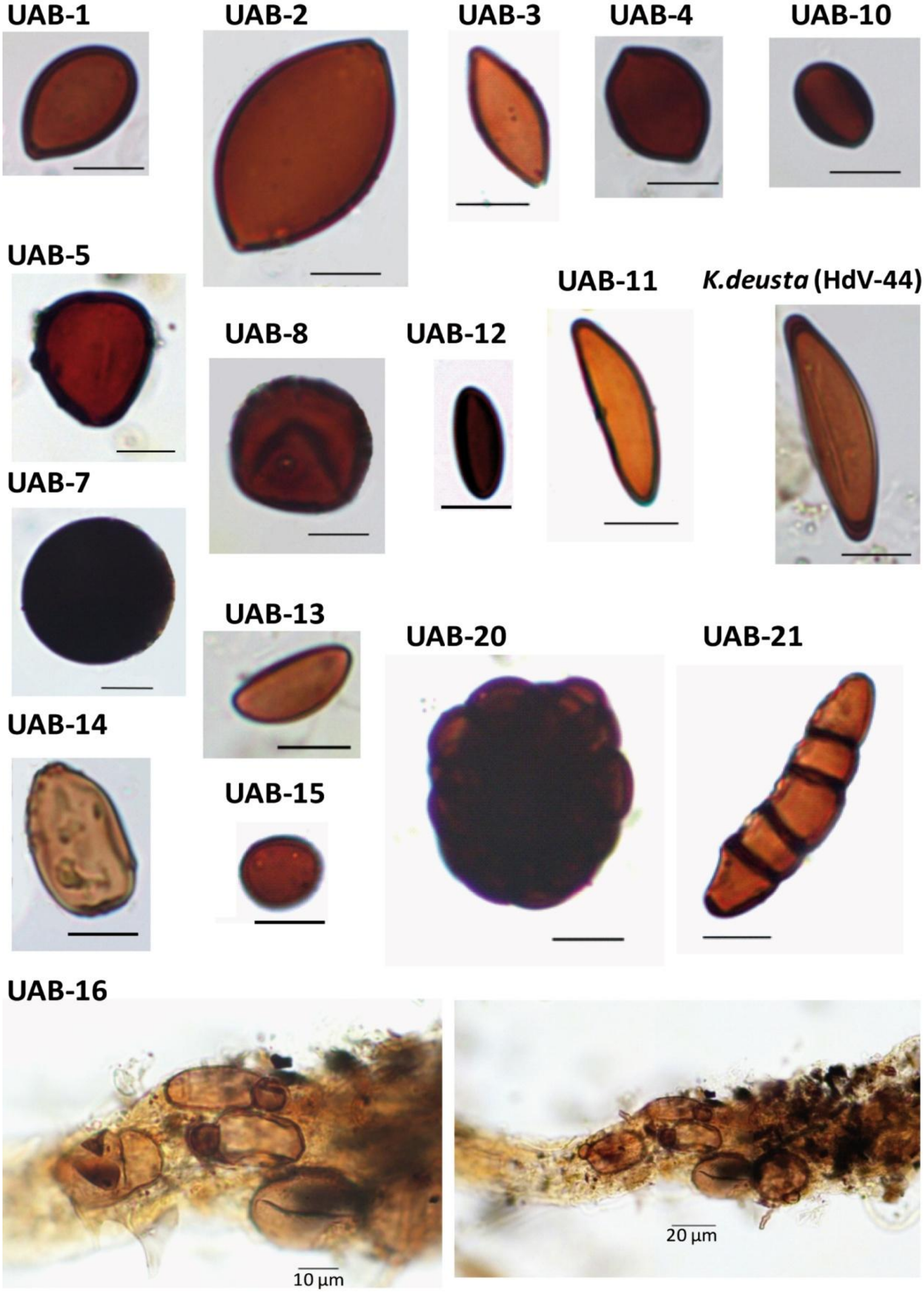


Plate I. Types UAB-1, UAB-2, UAB-3, UAB-4, UAB-5, UAB-7, UAB-8, UAB-10, UAB-11, *Kretzschmaria deusta* (HdV-44), UAB-12, UAB-13, UAB-14, UAB-15, UAB-16, UAB-20 and UAB-21. All scale bars are 10 µm.

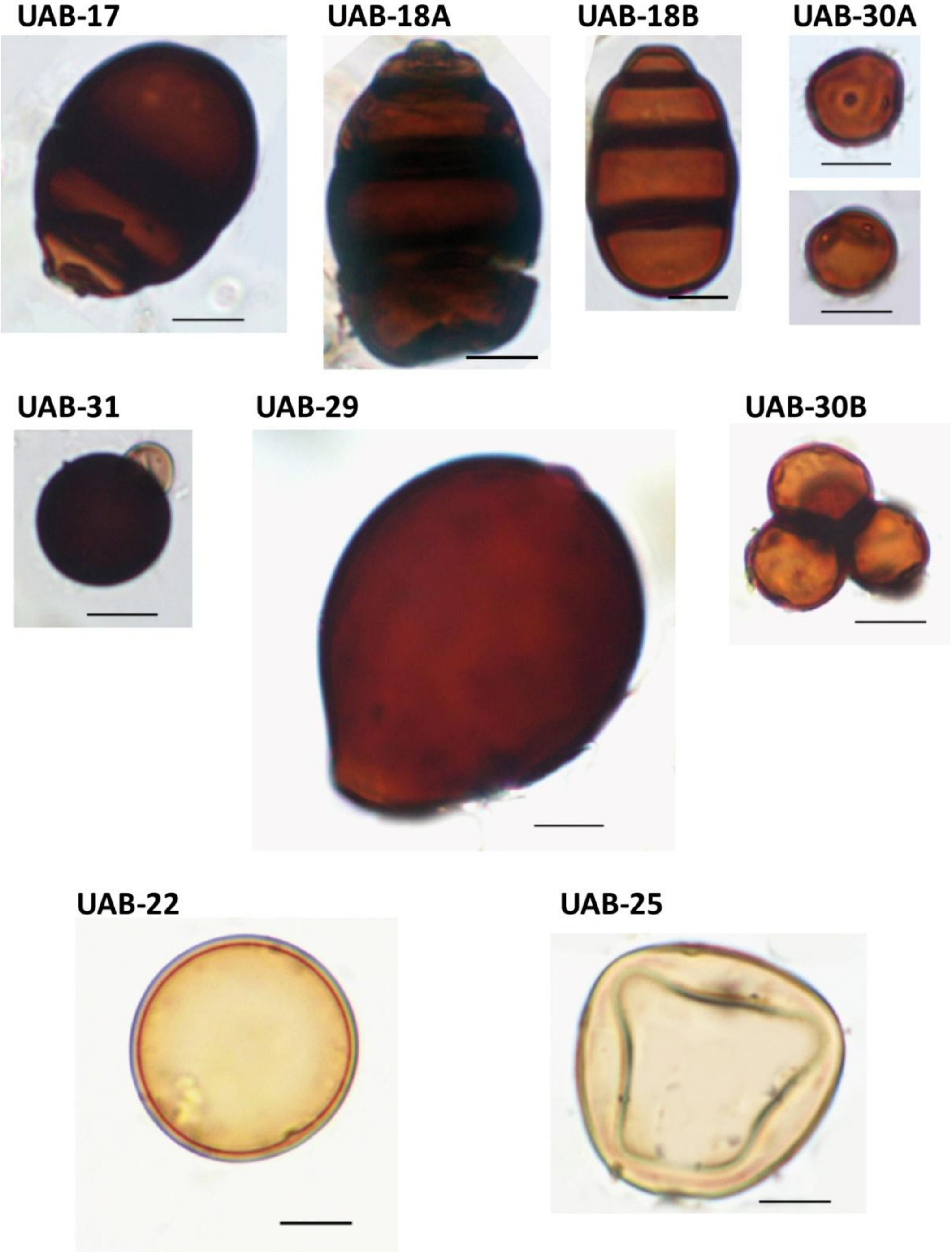


Plate II. Types UAB-17, UAB-18A, UAB-18B, UAB-22, UAB-25, UAB-29, UAB-30 A, UAB-30B, UAB-31.

5.2.3. Human impact and soil erosion indicators

Human impact has been widely proposed as the main cause of sedimentation of eroded soil material in lake deposits at different times in the Holocene (Dotterweich, 2008; Dusar et al., 2011; Simonneau et al., 2013; Notebaert and Berger, 2014). The adoption of farming activities and the intensive deforestation carried out since the Neolithic induced significant acceleration in soil erosion processes. Nevertheless the climatic factor should be considered as a possible amplifier of these erosion phases during the first half of the Holocene (Simonneau et al., 2013), when torrential episodes led to high hydrological activity causing erosion (Berger et al., 2016). Some characteristic NPP appeared to be good indicators for such processes, such as *Glomus*, *Pseudoschizaea* or HdV-361 (van Geel et al., 1983, 1989; Anderson et al., 1984; Pantaleón Cano et al., 1996; López Sáez et al., 2000). In addition to these typical indicators of soil erosion, the highest values or exclusive presence of UAB-5, UAB-7, UAB-8, UAB-26, UAB-31 and Type 988 appear in this phase, and these taxa have previously been documented in similar erosion processes in the site of La Draga (Revelles et al., 2016).

The open vegetation created after oak woodland deforestation during the Early Neolithic (7300-5550 cal BP) was linked to upland soil erosion in a climate context increasingly prone to torrential rainfall. The input of allochthonous mud to the lakeshore brought NPP indicative of grazing pressure and woodland infections caused by deforestation and farming practices in the surroundings of the lake. The taxa displaying their highest values or exclusive occurrence contemporary with the significant soil erosion episodes recorded between 6300 and 5550 cal BP appear to be indicators of human impact in the catchment area of the streams bringing material to the lakeshore. The most remarkable changes evidenced in the NPP record point to sedimentation dynamics as the main factor of alteration, as shown in the correspondence between major changes in NPP and contemporary changes in the sedimentary composition.

5.2.4. Limnological evolution in a lakeshore environment

The analysis of NPP contributes to the characterization of limnological responses to climate change and human impact. Information can be obtained about lake level changes, and changing trophic conditions. Nevertheless, changes in vegetation, aquatic organisms and in sedimentology do not always respond synchronously, evidencing different threshold responses of some microorganisms upon environmental changes. Resilience of aquatic microorganisms towards important palaeo-environmental changes was recorded at the beginning of the sequence in Lake Banyoles. Indicators of alkaline environments poor in nitrogen, characteristic of the previous lacustrine environment, were resilient from 8900 to 8100-8000 cal BP (Fig. 2C), contrasting with the established vegetated lakeshore from 8900 cal BP onwards.

During the 8th millennium cal BP, the cyanobacteria *Gloeotrichia* and *Rivularia*-type played a pioneer role in the abovementioned nutrient poor environment, fixing nitrogen and opening up local conditions for other aquatic plants (van Geel et al., 1984). In addition, the highest values of Characeae are recorded, pointing to the existence of calm, transparent waters near the lakeshore. The settlement of Neolithic communities in the immediate surroundings of the lake implied strong sediment changes. Soil erosion linked with deforestation led to the input of streams carrying terrigenous sediments, causing higher turbidity in the water and higher levels of phosphorous, induced by farming in upland areas. These new ecological conditions conferred an adaptative advantage to green algae against cyanobacteria, given that under high turbidity light becomes the limiting factor for nitrogen fixation (Zevenboom and Mur, 1980). Characeae decreased, as water transparency (Langangen, 1974) and phosphorous levels

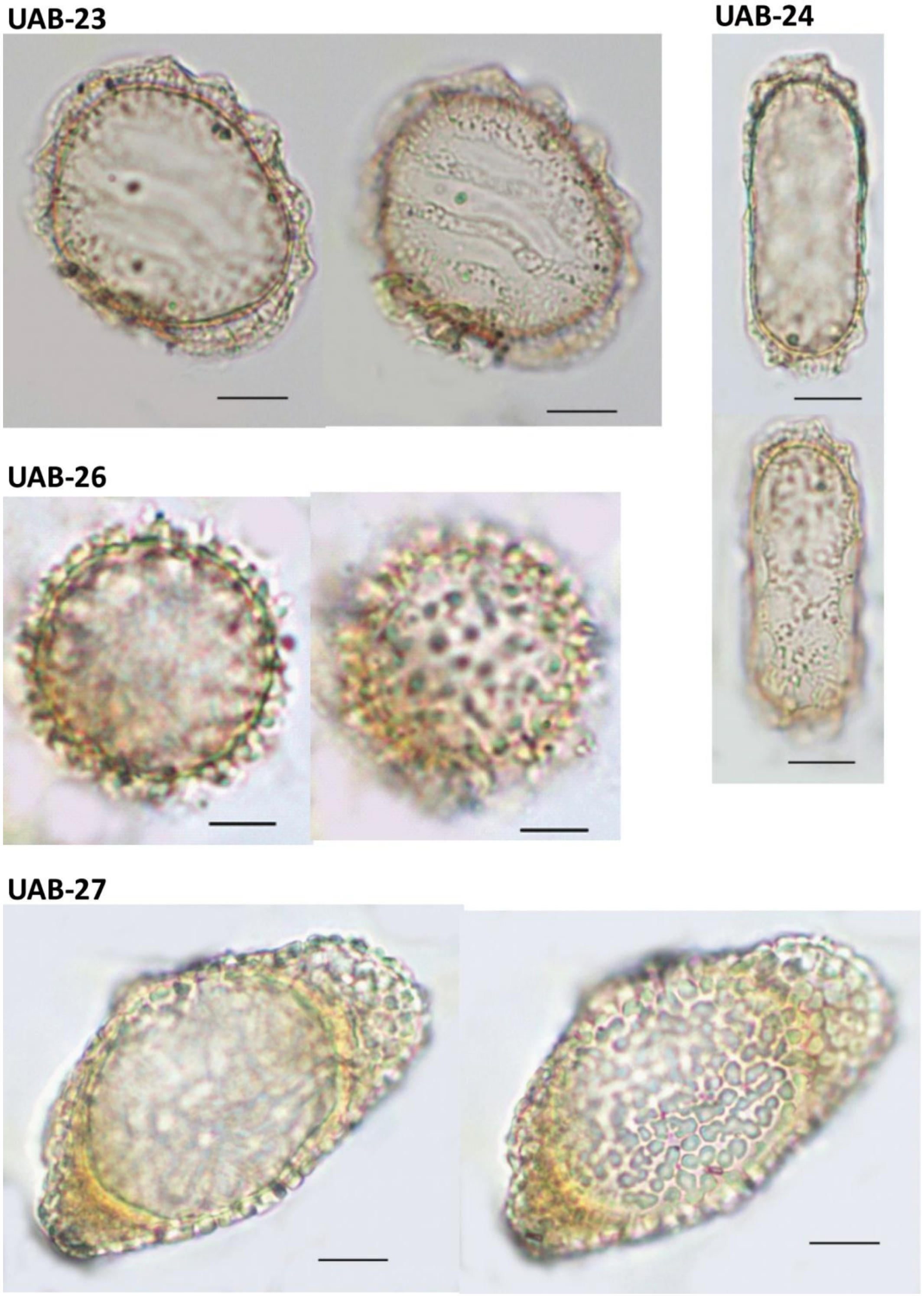


Plate III. Types UAB-23, UAB-24, UAB-26 and UAB-27. All scale bars are 10 µm.

are decisive for their distribution (Haas, 1994). The highest values of green algae (*Spirogyra*, *Mougeotia*, *Zygnema*, *Closterium*) and presence of HdV-128A and HdV-128 undiff. (Fig. 2B, Plate IV) showthe continuity of thismuddy-water swampy environment during the 7300 4200 cal BP period, when it was disrupted during short phases by the input of allochthonous matter as a consequence of upland soil erosion. Finally, from *c*. 4200 cal BP a new eutrophication phase is recorded, probably as a result of a combination of human impact (nearby crop cultivation from *c*. 5000 to 4200 cal BP) and lake-level lowering.

Different threshold responses of aquatic organisms were evidenced in the palaeo-environmental evolution of the Lake Banyoles shore. The limnological response to natural processes was slow and progressive, as observed in the transition from aquatic lacustrine to vegetated palustrine environments in the onset of the sequence. On the other hand, abrupt changes induced by human impact involved a rapid limnological response, as shown by the cyanobacteria-green algae succession after increased turbidity.

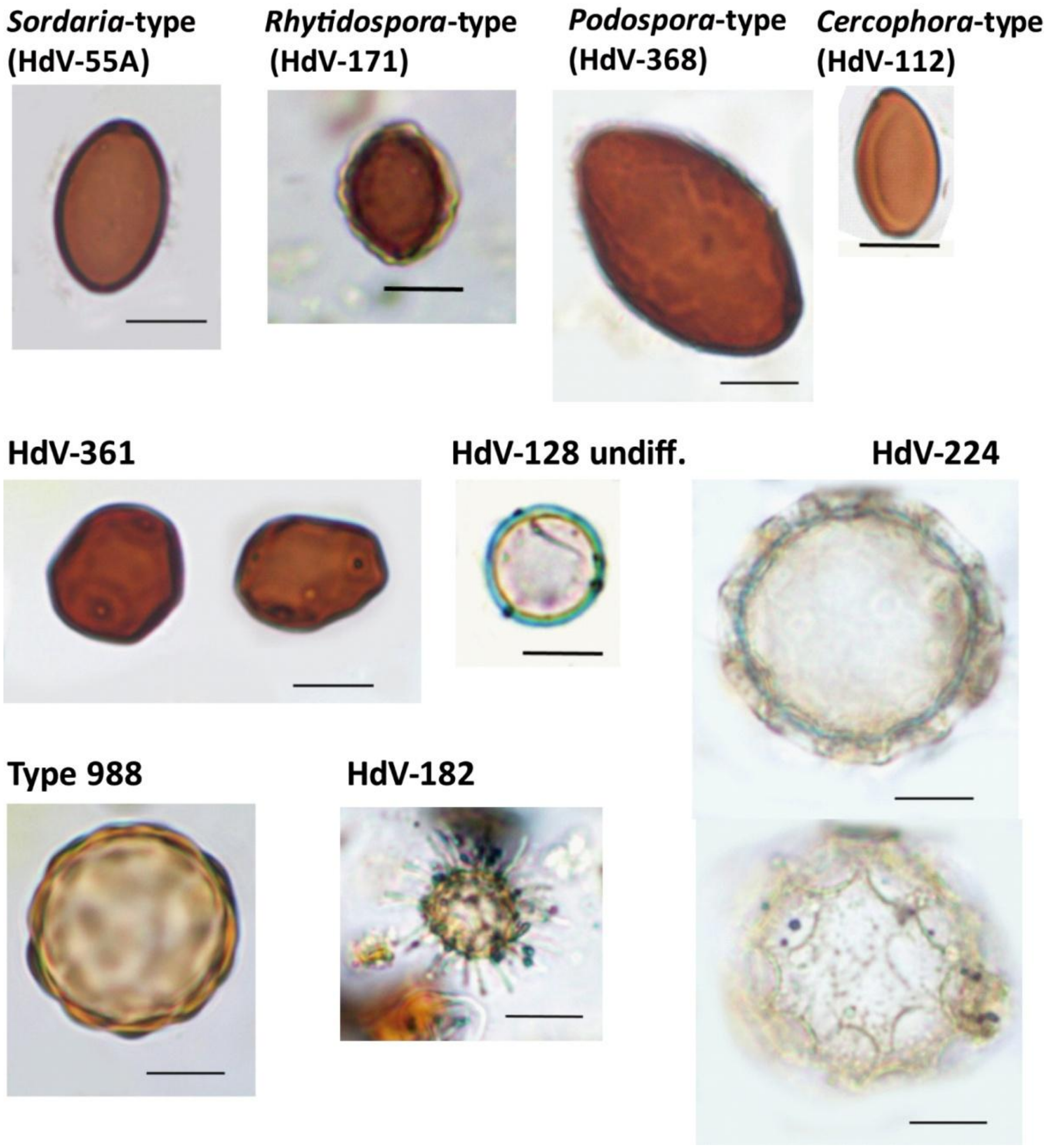


Plate IV. *Sordaria* (HdV-55A), *Podospora* (HdV-368), *Rhytidospora* (HdV-171), *Cercophora* (HdV-112), HdV-361, HdV-224, HdV-128 undiff., HdV-182 and Type 988. All scale bars are 10 µm.

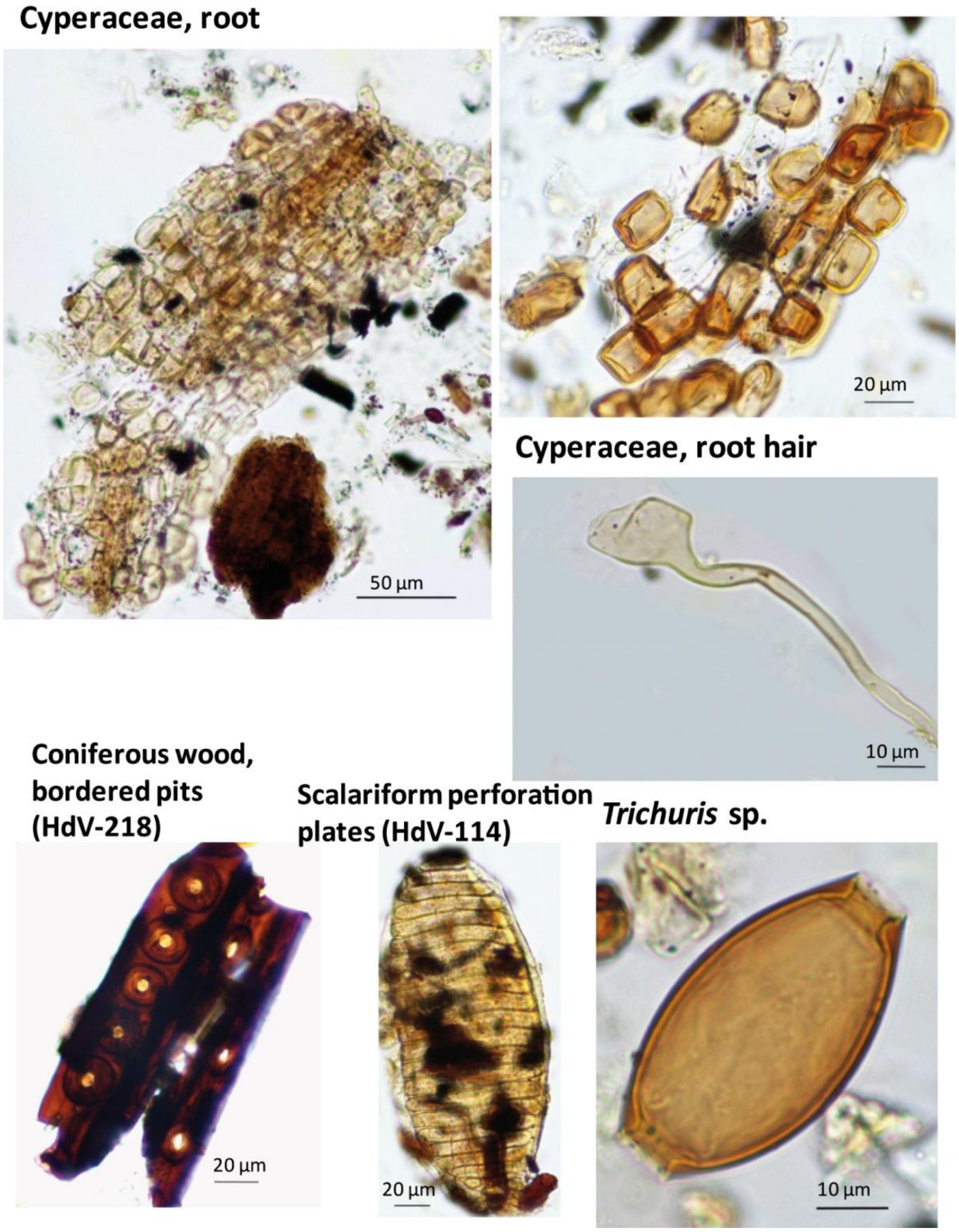


Plate V. Cyperaceae root, Cyperaceae root hair, bordered pits of coniferous wood (HdV-218), Scalariform perforation plate (HdV-114) and egg shale of *Trichuris* sp.

6. Conclusion

The analysis of NPP has provided detailed information about the palaeo-environmental evolution of the Lake Banyoles shore environment during the Mid-Holocene. Climate change influenced the vegetation composition on the lake margin from *c*. 9000 cal BP and contributed to a drop in the lake level after *c*.5500 cal BP. Neolithic land-use was the main agent of ecological changes occurring in this wetland environment, disrupting the natural vegetation. Major NPP fluctuations corresponded with vegetation changes as reflected by pollen analysis in the same core. Soil erosion induced by deforestation during the Early Neolithic (7300–5500 cal BP) caused major changes to the lakeshore, influencing the aquatic ecosystem and the fungal spectra. Decaying wood generated the proliferation of lignicolous fungi and increasing levels of phosphorous, and later water turbidity caused a cyanobacteria-green algae succession. During the Late Neolithic-Chalcolithic (5000–4200 cal BP) local human impact in the lakeshore area caused transformation of an alder carr environment, towards sediment with indicators of soil disturbance and dung. The results confirm that human transformation of the landscape was a key factor in changing environmental conditions during the Mid-Holocene.

Finally, the present study contributes to our knowledge of the ecological significance of some NPP and we provide illustrations and descriptions of ‘new’ NPP types. The integration of pollen, NPP and macrofossil data is evidently important for the reconstruction of local environmental dynamics, including responses to climate change and human impact.

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Appendix A. Descriptions, illustrations and interpretations of new types from Lake Banyoles (SB2)

A.1. UAB-1 (Plate I)

Fungal spore, one-celled, ovoidal, dark brown, 12.5–17.5(–20) × 7.5–12.5 µm. Rounded at one end and tapering at the other end, showing a small pore (Revelles et al., 2016).

Highest values in the soil erosion phase (subzone B1).

A.2. UAB-2 (Plate I)

Ascospores, one-celled, ellipsoidal, brown, (25–)27.5–35(–37.5) × (15–)17.5–22.5 µm, showing an apical pore (representative of Sordariales?) (Revelles et al., 2016).

Evidenced in the soil erosion phase (subzone B1) and co-occurring with spores of coprophilous fungi.

A.3. UAB-3 (Plate I)

Ascospores, one-celled, fusiform, light brown to brown, 20–27.5 ×7.5–10 µm, showing a small pore at both ends (Revelles et al., 2016).

Occurring in the soil erosion phase (subzone B1).

A.4. UAB-4 (Plate I)

Ascospores, one-celled, lemon-shaped, brown to dark brown, 18.75–22.5(–30) × 12.5(–15) µm, showing a small pore at both ends (Revelles et al., 2016).

Highest values in the soil erosion phase (subzone B1). Probably carbonicolous/lignicolous (Revelles et al., 2016).

A.5. UAB-5 (Plate I)

Fungal spores, one-celled, triangular with rounded corners, thick-walled, dark brown to black, 20–30 × 17.5–22.5 µm, showing one apical pore (Revelles et al., 2016).

Occurring in the subzone B1, may indicate inorganic clayish sediments formed by soil erosion episodes (Revelles et al., 2016).

A.6. UAB-7 (Plate I)

Globular black spores, 20–30 µm in diameter, without any further visible characteristics (Revelles et al., 2016).

Continuous curve and highest values in subzones A2 and B1, when higher input of allochthonous mud is recorded.

A.7. UAB-8 (Plate I)

Fungal spores, one-celled, globose to subglobose, dark brown, (17.5–)20–25(–27.5) µm in diameter. Some spores showing pores of *ca*. 2.5 µm in diameter (Revelles et al., 2016). Similar to type TM-382, as described by Cugny (2011).

Irregularly occurring along the sequence. Indicator of inorganic sediments formed by soil erosion episodes in previous analyses (Revelles et al., 2016).

A.8. UAB-10 (Plate I)

Fungal spores, one-celled, globose to ellipsoidal, 7.5–10 × 5–7.5 µm, dark brown with a longitudinal light brown zone. Representative of Coniochaetaceae? (Revelles et al., 2016).

Co-occurring with highest values of spores of *C.* cf. *ligniaria* (HdV-172) and other carbonicolous/lignicolous fungal spores.

A.9. UAB-11 (Plate I)

Ascospores, fusiform, 20–27.5 × 7.5 µm, light to dark brown. One side flattened and bearing a longitudinal germ slit. Similar to *K. deusta* (HdV-44), but smaller and without the characteristic wall thickenings at the ends. Representative of Xylariaceae? (Revelles et al., 2016).

Occurring in the soil erosion phase (subzone B1). Probably a carbonicolous/lignicolous fungus (Revelles et al., 2016).

A.10. UAB-12 (Plate I)

Ascospores, ellipsoidal, 12.5–17.5 × 5–7.5 µm, brown, showing a longitudinal light brown zone (germ slit?).(Revelles et al., 2016).

Occurring in the soil erosion phase (subzone B1). Probably a carbonicolous/lignicolous fungus (Revelles et al., 2016).

A.11. UAB-13 (Plate I)

Ascospores, 17.5 × 7.5 µm, light brown, with rounded ends, and one flat side.

Occurring in the soil erosion phase (subzone B1).

A.12. UAB-14 (Plate I)

Ascospores, one-celled, (21.25–) 22.5–25 × 10–15 µm, light brown, flattened at the basal side and rounded at the top, showing an apical pore (Revelles et al., 2016).

Occurring in an alder carr (subzone B2a), indicator of wet environments (Revelles et al., 2016).

A.13. UAB-15 (Plate I)

Fungal spores, globose-subglobose, brown to dark brown, 10–12.5 µm in diameter, with some small pores (Revelles et al., 2016). Similar to type TM-334 (Cugny, 2011).

Irregularly occurring along the sequence.

A.14. UAB-16 (Plate I)

Fungal spores, consisting of a brown large cell (18–25 µm in diameter) and a hyaline small cell (2.5–5 µm in diameter).

Clusters of this type occur on plant remains.

A.15. UAB-17 (Plate II)

Fungal spores, ellipsoidal, unequally and asymmetrically 3-celled, dark brown, 32.5–42.5 × 25–27.5 (–37.5) µm, basal cell pale. This type may be related to type UG-1085 (Gelorini et al., 2011).

Occurring in the soil erosion phase (subzone B1).

A.16. UAB-18A (Plate II)

Fungal spores, ellipsoid, unequally and asymmetrically 4-celled, 37.5–47.5 (–55) × 25–32.5 µm, thick-walled, slightly constricted at the septa, basal cell sub-hyaline and truncated (Revelles et al., 2016). This type is similar to UG-1091 (Gelorini et al., 2011), identified as *Bactrodesmium* type, found worldwide on wood and bark of various deciduous trees (Ellis, 1971).

Occurring in the soil erosion phase (subzone B1). Co-occurrence and similar morphology of types UAB-17, UAB-18A and UAB-18B may reflect the same origin, probably related with the input of decaying wood and the highest values of spores of carbonicolous/lignicolous fungi.

A.17. UAB-18B (Plate II)

Fungal spores, ellipsoid, unequally and asymmetrically 4-celled, brown, (26.25–)30–40 × (15–)17.5–22.5 µm, thick-walled, constricted at the septa, basal cell subhyaline (Revelles et al., 2016).

Occurring in the soil erosion phase (subzone B1).

A.18. UAB-20 (Plate I)

Globose clusters of fungal cells (each one *ca*. 7.5 µm). Pale brown to dark brown, 25–42.5 µm in diameter (Revelles et al., 2016).

Highest values in an alkaline environment poor in nutrients (subzone A1a).

A.19. UAB-21 (Plate I)

Ascospores, inequilateral (one side almost straight), 35–42.5 × 10–12.5 µm, brown, 5 celled, slightly constricted at the septa (Revelles et al., 2016).

Irregularly occurring along the sequence.

A.20. UAB-22 (Plate II)

Globose microfossils, pale yellowish, (22.5–) 27.5–30 µm in diameter.

Irregularly occurring along the sequence.

A.21. UAB-23 (Plate III)

Subglobose hyaline microfossils, (25–)30–37.5 (–42.5) × 25–30(–35) µm, inclusive of an external undulating velum, supported by spongy tissue.

Occurring in an alkaline environment poor in nutrients (subzone A1a).

A.22. UAB-24 (Plate III)

Ellipsoidal hyalinemicrofossils, 37.5–45 × 17.5–20 µm, inclusive of a reticulum formed by a thin undulating velum and supported by a spongy tissue.Wall structure similar to the globose HdV-224.

Occurring in an alkaline environment poor in nutrients (subzone A1a).

A.23. UAB-25 (Plate II)

Globose microfossils, 27.5–37.5 µm in diameter, yellowish. Often folded in a characteristic way.

Highest values in eutrophic waters, co-occurring with maximum values of *Gloeotrichia* and *Rivularia*-type.

A.24. UAB-26 (Plate III)

Globose hyaline microfossils, 25 µm in diameter, including *ca*. 2.5 µm long appendages (Revelles et al., 2016).

Highest values in the soil erosion phase (subzone B1).

A.25. UAB-27 (Plate III)

Microfossils of irregular shape, 45–65×30–50 µm.Walls showing an irregular pattern of thicker and thinner areas, with a characteristic structure between inner and outer layer (Revelles et al., 2016).

Occurring in the soil erosion phase (subzone B1).

A.26. UAB-29 (Plate II)

Ascospores?, one-celled, brown, 37.5–55 × 30–42.5 µm, truncated at the basal end and showing a *ca*. 1 µm wide apical pore.

Occurring in alder carr environment (subzone B2a).

A.27. UAB-30A (Plate II)

Fungal cells, subglobose, 12.5–15 µm in diameter, light brown, showing two flattened areas at relatively short distance, each one with a central pore, and darkerwalls around the pores. Often occur in clusters of 4 cells (Type UAB-30B) (Revelles et al., 2016).

Highest values co-occurring with local human impact in an alder carr environment.

A.28. UAB-30B (Plate II)

Spores consisting of 4 subglobose fungal cells, greatest diameter of the spores: 22.5 µm. These spores commonly split up in separate cells (see Type UAB-30A) (Revelles et al., 2016).

Highest values co-occurring with local human impact in an alder carr environment.

A.29. UAB-31 (Plate II)

Fungal spores, consisting of a dark-brown, large cell (17.5–25 µm in diameter) and a hyaline small cell (2.5–5 µm in diameter) (Revelles et al., 2016). Similar to Type UG-1138 (Gelorini et al., 2011).

Irregularly occurring along the sequence.

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.revpalbo.2016.05.004. These data include the Google map of the most important areas described in this article.

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4. 2. SOCIO-ECOLOGICAL CONSEQUENCES OF NEOLITHISATION IN THE LAKE BANYOLES AREA.

· Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain).

· Archaeoecology of Neolithisation. Human-environment interactions in the NE Iberian Peninsula during the Early Neolithic.

4.2.1. Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain).

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Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain).

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Abstract

This paper focuses on the high-resolution pollen analysis of one new pollen record from Lake Banyoles (Girona, Spain) and its contextualisation with other archaeobotanical records (charcoal, seed and wood remains) from the early Neolithic lakeshore settlement of La Draga. Around *ca*.7250 cal BP, coinciding with the first settlement phase of La Draga, a rapid fall of the pollen values of deciduous *Quercus* sp. is observed, and a stabilisation of these values is found until *ca*. 6000 cal BP. The causes for such changes in vegetation cover are discussed, taking into consideration environmental data to calibrate the role of climate in vegetation dynamics, as well as archaeobotanical data to evaluate impact of the management of vegetal resources on the landscape. The discussion of the data shows that climate could not have been the main cause for the decrease of broadleaf deciduous forests, and that the need of gathering raw material for the construction of dwellings played a major role in this change. The fact that these plant community does not recover during the occupation or after the abandonment of La Draga would confirm that human impact continued over time and that forest clearances were maintained for various purposes.

Keywords: Neolithic, Iberian Peninsula, La Draga, Pollen analysis, Archaeobotany

1. Introduction

The onset of farming is often associated with a significant change in the relationship between humans and environment in comparison to hunter-gatherer societies. Obtaining new land for agriculture and animal husbandry, as well as raw materials for building, firewood and goods production, caused a great impact on the landscape at a local level. Early farming societies were first established in the northeastern (NE) Iberian Peninsula at the end of the 8th millennium cal BP. This first occupation used caves: Bauma del Serrat del Pont (Tortellà, Girona) (7480–7280 cal BP, Alcalde and Saña 2008), Cova de Can Sadurní (Begues, Barcelona) (7430–7240 cal BP, Blasco et al. 2005; Edo et al. 2011), Balma Margineda (Sant Julià de Lòria, Andorra) (7860–7390 cal BP, Guilaine 1995) and Cova del Toll (Moià, Barcelona) (6949–6597 cal BP, Guilaine et al. 1982); as well as open-air settlements: La Draga (Banyoles, Girona) (7250–6950 cal BP, Bosch et al. 2012), Sant Pau del Camp (Barcelona) (7265–7075 cal BP, Molist et al. 2008) and Font del Ros (Berga, Barcelona) (7390–7260 cal BP, Bordas et al. 1995).

These open-air settlements were generally located in areas without evidence of earlier human occupation (Molist et al. 2003; Martín et al. 2010), although there are some exceptions e.g. Font del Ros. Available radiocarbon chronologies suggest that there is a gap in human presence in the region during the first half of the 8th millennium cal BP, with very few dates corresponding to the 9th millennium cal BP (Merkyte 2003; Estévez 2005; Weninger et al. 2006; Barceló 2008; Antolín 2013). The lack of evidence of previous occupation seems to support that the idea that neolithisation of the NE Iberian Peninsula was the result of a process of migration of farming populations to uninhabited territories (Zilhao 2000, 2011), in contrast to the interaction documented between indigenous Mesolithic communities and the arriving farming communities on the Eastern coast of the Iberian Peninsula, where hunter-gatherer societies eventually adopted the economic changes introduced by farming societies (Bernabeu 1997, 2002; Bernabeu et al. 2009).

First evidence of agriculture in NE Iberia is documented at Can Sadurní (7430–7240 cal BP, Blasco et al. 2005; Edo et al. 2011), with a predominance of hulled wheat (emmer and einkorn), together with naked wheat (Antolín and Buxó 2011a). Nevertheless, naked wheat and hulled barley are among the best represented crops in early Neolithic (Antolín 2013), which are also characterised by an important variety of crops (wheat, barley and some legumes), denoting, good, early knowledge of agricultural techniques and procedures (Antolín and Buxó 2012).

First farming societies dwelled in densely forested areas, with predominance of deciduous broadleaf tree forests, which were frequently dominant in the Mediterranean region of the Iberian Peninsula (Burjachs et al. 1997; Pérez-Obiol 2007; Carrión et al. 2010; Pérez-Obiol et al. 2011). In that context, deciduous *Quercus* (oak) was the main taxa exploited for firewood supply (Piqué 1996, 2005). Climatic and anthropogenic impact on the landscape during the early Neolithic has been reconstructed for parts of NE Iberia, e.g. the Pyrenees (e.g. Miras et al. 2007; Gassiot et al. 2012; Orengo et al.

2014) and the central Catalan coast (Riera et al. 2007; Antolín et al. 2011). Most of the studies focused on lowlands where a reduction of deciduous forest is observed. Although several causes are proposed by different authors, all of them agree that this change was largely the result of human intervention.

The opening of woodland for several purposes (mainly related to farming activities) in the Pyrenees is also observed from the earliest stages of the Neolithic, according to the above-mentioned authors. Nevertheless, only charred plant macroremains were available for all these areas and evidence of important uses of wild plant resources, such as the use of timber for construction were unavailable to include in these analyses. Therefore the permanent open-air settlement of la Draga (Banyoles, Spain) offered an exceptional opportunity to correlate archaeobotanical data of exceptional preservation with palaeoecological analysis from lakeshore peat deposits.

Recent excavations at the lakeshore site of La Draga have provided a detailed bioarchaeological record that is unique for the Iberian Peninsula thanks to the anoxic preservation conditions of the site. This paper focuses on the high-resolution pollen analysis of one new pollen record from Lake Banyoles and its contextualisation with other archaeobotanical records (charcoal, seed and wood remains) from La Draga, as well as the archaeological record from the area surrounding Lake Banyoles, in order to achieve a better understanding of landscape changes around the lake. The main goal of this paper is to characterise the environmental conditions in which Neolithic communities developed, and, at the same time, reconstruct the impact of the economic practices of these social groups on the landscape.

1.1. Research Background and Setting

Lake Banyoles

Lake Banyoles is located at 173 m asl (Fig. 1), 35 km from the Mediterranean Sea and 50 km south of the Pyrenees. It is a karst lake associated with a large karst aquifer system located in a tectonic depression being fed by underground waters. The lake is approximately 2100 m in length by 750 m in width with an average depth of 15 m that can reach up to 46 m in places (Julià 1980; Casamitjana et al. 2006; Höbig et al. 2012).

The climate of the Banyoles region is humid Mediterranean, with an annual precipitation of 750 mm and an annual mean temperature of 15°C. Current vegetation is dominated by a mixed evergreen oak, deciduous oak and pine forest (Gracia et al. 2001).

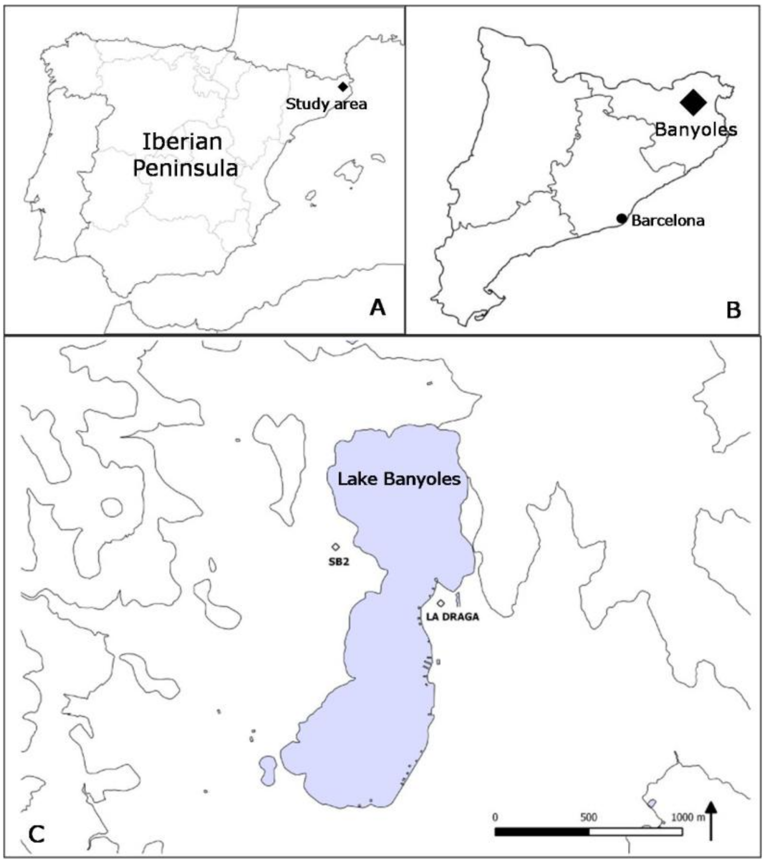

Figure 1. Map showing the location of the study area in the Iberian Peninsula (A), the location of Banyoles in Catalonia (B) and the location of La Draga site and the SB2 core in Lake Banyoles surroundings (C).

Previous palaeoecological analyses carried out in the study area focused upon the Pleistocene records (Pérez-Obiol and Julià 1994; Wansard 1996; Höbig et al. 2012). However, the pollen analysis undertaken in Lake Banyoles by Pérez-Obiol and Julià (1994) also presented data of the vegetation cover during the early Holocene, which was characterised by broadleaf deciduous tree forests, especially deciduous *Quercus* and *Corylus*, and a fall in oak values around 7000 cal BP. Nevertheless, this previous work is hindered by low chronological resolution and therefore the new sequence presented here is necessary in order to understand vegetation changes that occurred during the early Holocene.

The archaeological site of La Draga

The site of La Draga (Bosch et al. 2000, 2006, 2011) provides evidence of one of the earliest farming societies in open-air settlements in NE Iberia, dated to 7250–6950 cal BP (Bosch et al. 2012). The site is located half-way along the eastern shore of Lake Banyoles (Fig. 1). Despite occupying an area of over 8000 m^2 (Bosch et al. 2000), archaeological investigations to date have concentrated on an area of *ca*. 3000 m^2 (of which 825.5 m^2 have been excavated, in the northern part of the settlement, where the site is best preserved). Fieldwork was undertaken in multiple seasons from 1991 to

2012. From 1991 to 2005, the excavations concentrated on sector A, where the archaeological level is above the water table and hence waterlogging conditions have not continued until present. The archaeological level is in the phreatic layer in sector B and sector C is totally under water. New excavations from 2010 to 2012 focused on an area of 58 m^2 called sector D, which is located to the south of sector B and presented similar preservation conditions.

Two different phases of early Neolithic occupation with distinctive constructive traditions have been documented; both placed within the ending of the Cardial Ware Neolithic culture according to pottery style and in the last three centuries of the 8th millennium cal BP according to the radiocarbon dates. Phase I (7250–7050 cal BP) is characterised by the collapse of wooden structures (presumably dwellings), which have been preserved in an anoxic environment. Phase II (7150–6950 cal BP) presents several pavements of travertine stone. This archaeological level had less optimal conditions of preservation and the organic material is mainly found in a charred state, although some hard-coated uncharred material is found occasionally (Bosch et al. 2000, 2011; Antolín 2013; Palomo et al. in press). The waterlogged context of Phase I provided excellent preservation of the bioarchaeological record, constituting, by far, the richest assemblage from the early Neolithic period of the Iberian Peninsula. This allowed an interdisciplinary archaeobotanical work that can be used to reconstruct the management of vegetal resources and the human impact on the landscape.

Archaeobotanical macro-remains of La Draga

Abundant archaeobotanical data were obtained from La Draga, including charcoal data (Piqué 2000; Caruso-Fermé and Piqué 2014), uncharred wood remains (O. López, ongoing PhD; Bosch et al. 2006), seed and fruit remains (Buxó et al. 2000; Antolín and Buxó 2011b; Antolín 2013), and amorphous plant tissues, including tubers (Berihuete, unpublished), completing an extraordinary palaeoecological record for the region. A detailed description of the systematic sampling strategy applied for the recovery of plant macro-remains in sector D, can be found in previous publications (Antolín et al. 2013). Charcoal analyses identified 18 tree and shrub taxa (Caruso-Fermé and Piqué 2014). Taxa from deciduous forests were the best represented in both phases of occupation (Fig. 2). *Quercus* sp. deciduous was the most important taxa. Shrubs were only represented in very small percentages, although their importance increases in the most recent phase, with the dominant taxa being *Buxus sempervirens* (boxwood) and Rosaceae/Maloideae. Other taxa represented were Acer sp. and conifers including *Taxus baccata* (yew), *Pinus sylvestris-nigra* (pine) and *Juniperus* sp. (juniper). The best represented species from the riparian vegetation was *Laurus nobilis* (laurel). Other riparian taxa represented were: *Ulmus* sp. (elm), *Fraxinus* sp. (ash), *Corylus avellana* (hazel), *Salix* sp. (willow), *Alnus glutinosa* (alder), *Sambucus* sp. (elder), *Populus* sp. (poplar), *Clematis vitalba* (old man’s beard) and *Cornus sanguinea* (dogwood). Some of these species could also have grown in the deciduous forest. Finally, some evidence of Mediterranean vegetation was found: *Quercus ilex–coccifera* (holm oak) and *Arbutus unedo* (strawberry tree) were identified although in smaller proportions.

The study of timber also shows the importance of deciduous forest. *Quercus* is the dominant taxon in the record (around 95% of remains) (Fig. 2). It was used to make posts and boards for the huts. About 1000 posts have been documented up to now in around 800 m^2 excavated. Other taxa documented are *B. sempervirens, Cornus* sp., *C. avellana, Clematis* sp., *L. nobilis*, cf. Leguminosae, *Populus* sp., Rosaceae/Maloideae, Rosaceae/Rosoideae, *Rubus* sp., *Salix* sp., *Ulmus* sp. and *Vitis vinifera*, but they are scarcely represented (around of 5% of the remains). In Phase I 155 wooden tools have been recovered (Bosch et al. 2002; Palomo et al. 2013). Among them the handles of sickles and adzes, digging sticks, combs, spatulas, ladles, bows, vessels, beaters and projectiles have been identified. The use of 18 taxa for manufacturing wood was recorded. Deciduous *Quercus* sp. and *B. sempervirens* are the most often used raw materials, both being used to make a variety of tools. Other taxa collected in the deciduous oak forests were used more sporadically to make certain artefacts: *Acer* sp. (maple), Rosaceae/Maloideae and *Tilia* sp. (lime). Riparian forests were also exploited to obtain wood including dogwood *Cornus* sp., *C. avellana*, *L. nobilis*, *Populus* sp., *Salix* sp. and *Sambucus* sp. Three types of conifers: *T. baccata*, *Pinus* sp. and *Juniperus* sp. and some typically Mediterranean taxa: *A. unedo* and *Quercus* sp. Sclerophyllous were also used to manufacture wooden tools.

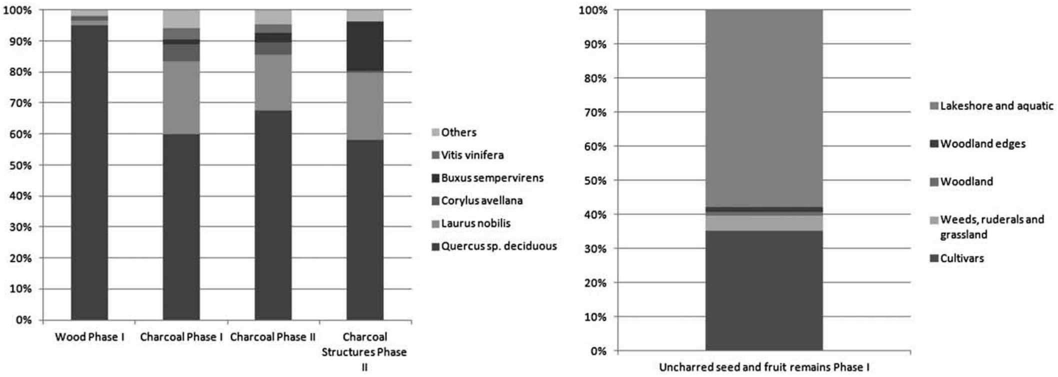

Figure 2. Relative proportions among the number of seed and fruit remains recovered in systematic samples from Phase I in sector D of La Draga (right). Percentage charcoal diagram of the two occupation phases (Caruso and Piqué 2014). Relative frequencies of the main taxa from wood and charcoal analysis (left). Taxa classified as others: *Salix* sp., *Populus* sp., *Clematis* sp., Rosaceae/Rosoideae, Rosaceae/Maloideae, *Rubus* sp., cf. Leguminoseae, Monocot, *Cornus* sp., *Populus* sp., *Juniperus* sp., *T. baccata*, *Acer* sp., *A. glutinosa*, *A. unedo*, *Fraxinus* sp., *Pinus* type *sylvestris-nigra*, *Prunus* cf. *avium-cerasus*, *Ulmus* sp.

A total of 18,334 charred and uncharred seed and fruit remains were recovered in 29.79 l of sediment processed systematically from the samples of Phase I of sector D of La Draga; *ca*. 4000 remains were recovered from the water-screened samples (Antolín 2013). Six cultivars were identified: *Hordeum distichum* (two-rowed hulled barley), *Triticum durum/turgidum* (tetraploid naked wheat), some spare finds of *Triticum aestivum* s.l. (hexaploid naked wheat), *Triticum dicoccum* (emmer), *Triticum monococcum* (einkorn) and *Papaver somniferum* (opium poppy). A total number of 65 wild taxa were identified from Phase I of La Draga in sector D: 23 belongings to the ecological group of weeds, ruderals, pastures and grasslands; 9 to woodland areas; 7

from woodland edges and clearings; and 20 from aquatic and lakeshore areas (Antolín 2013). Lakeshore and aquatic plants are the best-represented group in the uncharred record (Fig. 2): *Alisma plantago-aquatica* (common water plantain), *Cladium mariscus* (great fen sedge), *Lycopus europaeus* (gipsywort) and oogonia of Characeae are particularly abundant. They probably reflect local vegetation, which would indicate that the site was located on the shore of the lake. Potentially gathered wild plants are also relatively well represented, particularly *Quercus* sp. (oak) and *Rubus fruticosus* (bramble). Several amorphous charred objects were recovered. Among these, an underground vegetal structure was found during a preliminary evaluation. It is a small tuber that has anatomical features of monocotyledonous species. It constitutes the first evidence of the possible use of underground storage organs at La Draga. This part of the plant is thought to have constituted a source of food in the past, since they are very rich in starch, minerals and vitamins (Kubiak-Martens 2002). Finally, palynological data from La Draga show that the area was densely forested with deciduous *Quercus*, *C. avellana*, *Abies alba*, *Pinus* sp. and *Q. ilex–coccifera*. Pollen records also show a fall of oak values coinciding with La Draga occupation (Pérez-Obiol 1994; Burjachs 2000).

2. Material and Methods

2.1. Core extraction

A core of 370 cm of length (SB2 core) was extracted from the western shore of Lake Banyoles (Fig. 1). The coring location was chosen after taking into account the results coming from previous seasons of systematic exploration along the lake shores. One result of this exploration was the identification of some peat and organic clay deposits, allowing us to recover a complete sequence of Holocene sediments in order to develop more detailed environmental analyses. For this purpose, a Van Walt/Eijkelkamp mechanical drilling machine was used. SB2 core is now located 160 m away from the lake. The core includes some layers that are chronologically contemporaneous to the settlement of La Draga. Four sedimentary layers were distinguished: yellowish brown silt (0–158 cm), greyish silty clay (158–174 cm), dark silty clay (174–281 cm) and carbonated sands (281–370 cm). The succession of these sediments enabled us to reconstruct the evolution of lake margin depositional environments, which is expressed by the sedimentological change from carbonate layers to peat, therefore from shallow water to a palustrine wetland environment, with deposition of additional terrigenous material.

2.2. Accelerator mass spectrometry radiocarbon dates

Six AMS radiocarbon dates on bulk sediment were carried out. Calibration to years cal. BP was made using Clam 2.2 (Blaauw 2010) based on the data set IntCal13.14C (Reimer et al. 2013).

2.3. Pollen identification

Contiguous samples were retrieved at every 1 cm of the core. The preparation of the samples followed standard methods (Burjachs et al. 2003) using treatment with HCl, NaOH, HF and final mounting in glycerine. Between 300 and 350 terrestrial pollen grains were counted using a Nikon Eclipse 50i microscope fitted with ×10 oculars and ×50 objective. Cyperaceae and *Typha* have been excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according Reille (1992). Sedimentary charcoal results and selected pollen taxa between 8892 and 6094 cal BP are presented in a percentage pollen diagram using Tilia software (Grimm 1991–2011).

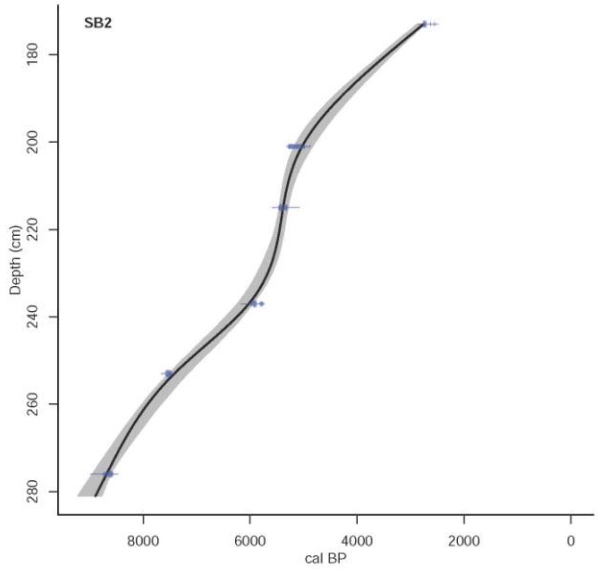

Figure 3. Age–depth model based on six AMS radiocarbon dates. Estimation of age along the entire profile by a smooth spline technique using Clam 2.2 (Blaauw 2010).

2.4. Sedimentary charcoal quantification

Contiguous samples of 1 cm^3 were retrieved at every 1 cm of the core, soaked in 10% NaOH solution for 24 h for peat digestion, then in 30% H^2O^2 solution for the same time to bleach non-charcoal organic material and thus make charcoal identification easier (Rhodes 1998). To reconstruct local fire history, a quantification of charred particles was made according to the sieving method (Carcaillet et al. 2001) with a 150 µm mesh (Clark 1988; Ohlson and Tryterud 2000). Charcoal concentrations (charcoal particles/cm^3) are expressed by the charcoal accumulation rate (charcoal particles/cm^2 yr) based on a sedimentation rate estimated using the depth–age model (Fig. 3).

3. Results

3.1. SB2 Core Chronology

The age model was based on six AMS radiocarbon dates, expressed as intercepts with 2σ ranges (Table 1). No reservoir effect correction has been applied to the radiocarbon dates because the analysed sediments consist of peat and organic clay and the presence of carbonates is minimal. Moreover, bulk sediment did not contain amorphous organic matter of lacustrine origin, so the deposit was formed terrestrially. To estimate ages along the entire profile, a smooth spline technique has been applied using Clam 2.2 (Blaauw 2010) (Fig. 3). The dated samples are located at 173, 201, 215, 237, 257 and 276 cm depth, but pollen and sedimentary charcoal were analysed up to 281 cm depth. Therefore, the age–depth curve was extended over the undated 5 cm, as it comprises the same sediment composition. As a result, the pollen analysis age model is established between 8892 and 2759 cal BP. Nevertheless, pollen analysis was focused on the samples belonging to the part of the record spanning the period before, during and immediately following the occupation of La Draga, between 8892 and 6094 cal BP.

3.2. Pollen Analysis

The pollen zonation carried out by CONISS analysis (Grimm 1987) distinguished two main pollen zones and four subzones (Table 2) (Fig. 4). As shown in the pollen diagram (Fig. 4), the phase corresponding to Mesolithic (subzones A1 and A2) is characterised by broadleaf deciduous trees and the presence of *Pinus*. Around 7250 cal BP, coinciding with the establishment of the Neolithic communities of La Draga, an abrupt decline of deciduous *Quercus* values is recorded. From 7150 to 7100 cal BP, deciduous *Quercus* values fall to a low point and Poaceae, Asteraceae, *Erica* and *Plantago* are recorded in much higher values. At this time *Tilia* reaches its maximum value and there is an increase in *Pinus* (the main arboreal taxa in this phase) and *Corylus* values. After the abandonment of La Draga, the low values of deciduous *Quercus* are more stable and coincide with the appearance of sedimentary charcoal particles.

Table 1. Radiocarbon dates, SB2 core (Banyoles). Calibration to years cal. BP was made using Clam 2.2 (Blaauw 2010) based on the data set IntCal13.14C (Reimer et al. 2013).

Sample depth (cm)	Lab. code	Type	AMS radiocarbon date BP	Cal. yr BP (2σ range) 95% prob.	Cal. yr BP in diagram
173	SUERC-38761 (GU26454)	Bulk sediment	2590± 30	2732–2876	2759
201	Beta-325839	Charcoal	4480± 30	4836–5171	5030
215	SUERC-38760 (GU26453)	Bulk sediment	4650± 30	5292–5452	5383
237	SUERC-49224 (GU31929)	Bulk sediment	5148± 30	5948–6239	6024
253	SUERC-49225 (GU31930)	Bulk sediment	6645± 31	7171–7518	7418
276	SUERC-38759 (GU26452)	Bulk sediment	7855± 30	8609–8947	8685

Table 2. Pollen subzones description.

Subzone	Chronology (cal BP)	Main features
A1	*ca*. 8900-7600	High values of arboreal pollen (AP), with the predominance of deciduous *Quercus* type, *Corylus* cf. *avellana* and *Pinus* spp. Around 8200 cal BP, the first sedimentary charcoal particles appear
A2	*ca*. 7600-7250	Starts with the beginning of the continuous *Abies* cf. *alba* and *Tilia* sp. curves. It corresponds with a decrease of deciduous *Quercus* and *Pinus* and with the last *Corylus* maximum. The increase of a slight non-arboreal pollen (NAP) expansion is noteworthy
B1	*ca*. 7250-6700	Characterised by the dramatic fall of deciduous *Quercus* values, the start of decreasing trend of *Corylus*, the increase of *Pinus* and *Abies*, the appearance of a continuous *Tilia* curve, and the expansion of non-arboreal pollen, mainly Poaceae, but also Asteraceae, *Artemisia* spp., Apiaceae, Chenopodiaceae and *Plantago* spp., as well as shrubs, especially *Erica* spp.
B2	*ca*. 6700-6090	Defined by the stabilisation of low values of deciduous *Quercus*, the decreasing trend of *Corylus* and Poaceae, and the occurrence of sedimentary charcoal particles.

4. Discussion

4.1. The Landscape around Lake Banyoles

The results from the pollen analysis show that an abrupt decrease of deciduous *Quercus* values started about 7600–7400 cal BP and had consolidated at much lower percentages by 7300–7200 cal BP. This important landscape transformation began at a time contemporary with the establishment of first farming communities at La Draga (7250–6950 cal BP). This is consistent with changes reconstructed at other pollen sites in Lake Banyoles and La Draga, which also showed a fall in oak values coinciding with the phases of human occupation at La Draga (Pérez-Obiol 1994; Pérez-Obiol and Julià 1994; Burjachs 2000).

The new pollen record suggests that the space left by oak forests was mainly colonised by herbs (Poaceae), shrubs (*Erica*) and secondary trees (*Pinus*, *Tilia*, *Corylus*). According to the charcoal record, the presence of box (*Buxus* cf. *sempervirens*), which colonises degraded areas, might indicate that this taxon had expanded, possibly as a result of the above-mentioned forest perturbation. Nevertheless, this taxon is not recorded at the pollen record due to the poor dispersal ability, causing an under-representation in the pollen diagrams. Besides this, the decline of deciduous *Quercus* values in the pollen record coincides with an increase of *Pinus* and the significant presence of *Abies* and, although presenting lower values, *Fagus* cf. *sylvatica*, which was probably an important forest constituent in the nearby mountains. The appearance of *Abies* for first time in this region is notable, arriving in accordance with its own dynamics of expansion since the Late Glacial from refuge zones in the southern slopes of the Pyrenees (Terhürne-Berson et al. 2004; Liepelt et al. 2009).

At a local level, the carpological assemblage from La Draga shows the presence of some weeds, ruderals and grasslands seeds, and also taxa from woodland edges and clearings. The impact of Neolithic communities surrounding the settlement also seems to be confirmed by the increased presence of shrub taxa in the charcoal assemblage during the latter phase of occupation of La Draga (Caruso-Fermé and Piqué 2014) (Fig. 3).

Nevertheless, despite the existence of a clear oak forest deforestation, the AP/NAP ratio (in Figs. 4 and 5) shows that the impact on the forest cover would have not been too dramatic. It is necessary to evaluate whether these changes in the landscape recorded at the western shore of the lake, at short distance from the site of La Draga, could be due to natural (climatic) or anthropogenic factors.

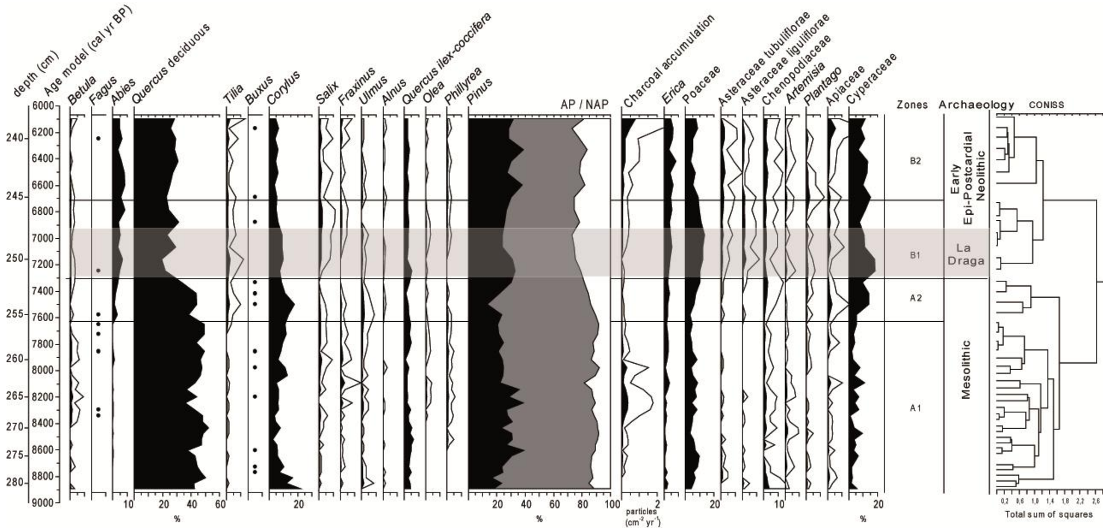

Figure 4 Percentage pollen diagram. Selected pollen taxa and sedimentary charcoal accumulation rate from SB2 core (Banyoles) are plotted to a calibrated year cal BP scale. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points. Pinus is AP overlayed. Valid for Fig. 5.

4.2. Climate Conditions and Vegetation History

In order to assess the relationship between the decrease of deciduous Quercus values and climatic conditions, selected pollen groups were compared with the climate evolution (Fig. 5). There are several palaeoclimatological records with which the results obtained at Lake Banyoles can be compared. On the one hand, some of these records do not locate any particular event that could be contemporary to the oak forest decline at Lake Banyoles. The SST °C from the Alboran Sea demonstrates that six short colder events (1–2°C) interrupted the general Holocene cooling trend (Cacho et al. 2001, 2006). Such atmospheric perturbations have been associated with a group of SST cooling events (2°C) in the North Atlantic Ocean (Bond et al. 1997). As can be observed in Fig. 5, none of these are contemporary with the occupation of La Draga.

Likewise, the oak forest decline does not coincide with any of the dry phases documented by the pollen ratio of deciduous broadleaf/evergreen sclerophyllous trees in the circum-Mediterranean area defined by Jalut et al. (1997, 2000, 2002, 2005, 2009). Furthermore, there is no cooling period recorded in the global compilation of events (Mayewski et al. 2004), which could be associated with the decrease in oak values at Lake Banyoles.

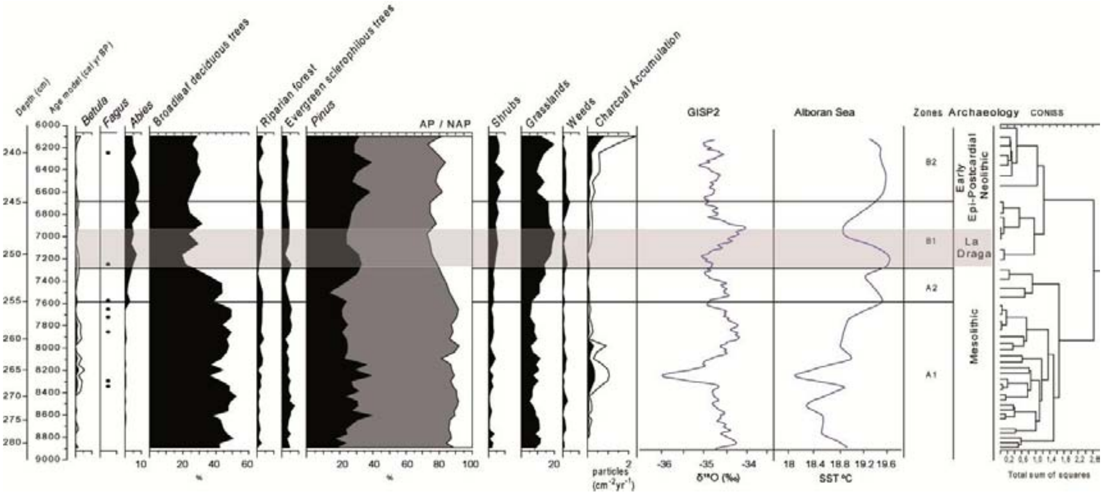

Figure 5. Pollen categories compared with climatic data (GISP2 and Alboran Sea). Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*), riparian forest (*Ulmus*, *Fraxinus*, *Salix*), evergreen sclerophilous trees (*Q. ilex–coccifera*, *Olea*, *Phyllirea*), shrubs (*Erica*, Cistaceae,*Vitis*), grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Urtica*), weeds (Chenopodiaceae, Brassicaceae, *Plantago* spp., *Plantago major-media*, *Rumex*). GISP2 values are 50-year smoothed.

On the other hand, other studies seem to locate an abrupt cold event which could have affected the woodland cover around Lake Banyoles. Frigola et al. (2007) have documented an abrupt cold event between 7.4 and 6.9 cal BP, that could be related with positive NAO (North Atlantic Oscillation), and therefore, with a period of dryness in the Iberian Peninsula and cold temperatures in Greenland isotopic records (Grootes et al. 1993), as well as with more persistent and stronger winter storms crossing the Atlantic Ocean (Hurrell 1995). These data are also consistent with GISP2 ^{18}O (Grootes and Stuiver 1997), which show a cooling event *ca*. 7600 cal BP, that would have coincided with the onset of a decrease in the values of broadleaf deciduous trees and the start of the continuous curve of *A. alba* (Fig. 5). Thereafter, around *ca*. 7250 cal BP, another cooling event is recorded in GISP2, coinciding with other palaeoclimatic records, such as stalagmite ^{18}O records of Antro del Corchia (CC26) (Northern Italy) and Soreq Cave (Israel), showing a decrease in ^{18}O values from *ca*. 7250 cal BP onwards (Zanchetta et al. 2007). These types of events could affect oak forests, either contributing to their decline or to the maintenance of the clearances made by the Neolithic communities.

In conclusion, the climate could have brought about a slight decline in deciduous broadleaf trees, and deciduous *Quercus* values specifically, from 7600 cal BP. Subsequently, the increase of *Pinus* and the appearance of *Abies* could suggest colder temperatures than today (Burjachs 2000). This hypothesis is reinforced by ^{18}O values obtained from archaeological wooden remains of Phase I of La Draga (Aguilera et al. 2011), where differences between sub-fossil and extant samples in Δ^{13}C and δ^{18}O records suggest slightly lower temperatures and higher plant water availability than at present during the establishment of agriculture at the site.

Moreover, the impact of other well-known climatic episodes, as the 8.2 cal BP arid and cold event on broadleaf deciduous trees is almost imperceptible in this area (Pérez-Obiol and Julià 1994; Pérez-Obiol 1988), probably due to the resilience of deciduous broadleaf trees in wetter sub-Mediterranean regions. In this context, the SB2 pollen record only shows a small decline in arboreal pollen and broadleaf deciduous trees, as well as the presence, albeit scarce, of sedimentary charcoal particles that could be associated with natural fires in the context of a higher aridity (Vannière et al. 2008), which is documented in other regions in NE Iberian Peninsula (Miras et al. 2007, 2010; Cunill 2010; Riera and Turu 2011) and of southern Iberian Peninsula (Berger and Guilaine 2009). In contrast, the 8.2 cal BP event has been documented in other regions of the Iberian Peninsula (Riera 1993; Pantaleón-Cano et al 1996, 2003; Carrión and van Geel 1999; Carrión et al. 2001a, 2001b; Carrión 2002; Davis and Stevenson 2007). Given the low impact of this cold event on broadleaf tree forests, the slight decrease in GISP2 ^{18}O documented *ca*. 7.3–7.2 cal BP seems to be an unlikely exclusive cause of such an abrupt change in the evolution of oak and deciduous broadleaf forest in the area. Thus, it is necessary to look for further potential causes for the decline of deciduous *Quercus* values in the pollen record. These might be related to human impact.

As mentioned above no evidence of human occupation has been documented in the area immediately before the Neolithic, so vegetation changes before *ca*.7300 cal BP are considered to have been influenced by natural processes. Subsequently, the arrival of the first farming communities could have affected the landscape in a significant way through farming, the deliberate burning of woodland areas for several purposes and woodland resource exploitation.

4.3. Intensive Farming Model and Vegetation Cover Evolution

The available zooarchaeological (Saña 2011; Navarrete and Saña 2013) and archaeobotanical (Antolín 2013) data recovered at La Draga suggest that a small-scale, labour-intensive cultivation and small-scale herding in an intensive mixed farming strategy were practiced (Antolín et al. 2014). An intensive cultivation system implies high yields due to high inputs of labour, through careful tillage, weeding and manuring (Bogaard 2004b, 2005).

The plots could not be in the immediate surroundings of the site, since it was established in a subaerial swamp unsuitable for cultivation. Crop fields would have been far enough away to prevent Cerealia pollen from reaching these deposits (given the short dispersion of this self-fertilisation taxon). Nevertheless, it is believed that plots were close enough to the site in order to make an intensive management strategy possible (Antolín 2013; Antolín et al. 2014). The farming system practiced at La Draga is consistent with results from other regions of the Mediterranean coast of the Iberian Peninsula (Pérez-Jordà and Peña-Chocarro 2013), as well as in south-east and Central Europe (Maier 1999; Halstead 2000; Bogaard 2004a; Hosch and Jacomet 2004; Bogaard and Jones 2007). Despite this apparent uniformity, other less intensive models are also proposed for some of these regions (see e.g. Kreuz 2012), for which the diversity of farming practices within the Neolithic period might be considerable.

The absence of burning episodes for land clearances is confirmed by the low values of sedimentary charcoal recorded in the SB2 sequence. The practice of intensive agriculture in small plots would have had a very limited impact on the pollen record. This could explain the low values of weeds observed in our record (see in Fig. 5). Therefore, farming practices cannot be the main reason for the decline in oak values in the pollen sequence.

4.4. Forest Resources Management and Anthropogenic Landscape Transformation

Other human activities could have had an impact on the landscape: the intensive and continued exploitation of oak forests for various activities (construction of huts, as fuel resource); or the use of leafy branches of certain trees to feed livestock during winter. According to the species identified in the charcoal analysis, the gathering of firewood took place in oak forests and the riparian vegetation surrounding the site. The results obtained (Fig. 3) show that no differences can be seen in the plant communities where firewood was collected during the two occupation phases of the site. Oak is the most frequently gathered species and was used as fuel and timber. River bank vegetation was also frequently exploited and in this case both arboreal taxa and the shrub and lianoid layer were used. The intensive use of oak forest for firewood supply is also documented in other sites in low altitudes in this region with similar chronologies (Piqué 2005; Obea et al. 2011).

Hundreds of oak trunks have been recovered in the 800 m^2 excavated in La Draga. Considering the fact that the total extension of the site is about 8000 m^2, probably thousands of oak trunks were cut for the construction and maintenance of settlement over the period of occupation. These trunks were cut with adzes, as shown by traces of these tools used in the wooden elements preserved and recovered in La Draga (Bosch et al. 2008), and dragged to the settlement.

The identification of several pathologies in *Bos taurus* methapods might indicate the exploitation of their labour for this purpose. In fact, it is unlikely that cattle were used in farming activities, considering the intensive farming model identified in the site. Instead, they would have been necessary for the transportation of all the wood that was needed for the construction of huts (Bosch et al. 2004; Saña 2011; Antolín et al. 2014).

On the other hand, deciduous *Quercus* exploitation could have been related to other complementary activities such as the collection of leaf fodder for livestock. *Quercus* is well known to have been gathered for leaf hay in winter due to the durability of its leaves in storage (Halstead and Tierney 1998), both through ethnographic work (Halstead 1998) and in the Neolithic settlements in Central Europe (Rasmussen 1993; Akeret et al. 1999; Delhon et al. 2008). To date there is no clear evidence of leaf foddering in La Draga so further analyses are necessary to identify this practice.

All these intensive activities must have had a significant impact on the landscape and they could be the reason for the oak forest clearance observed in the pollen diagram. The low values of sedimentary charcoal present in the pollen samples suggest that fires were not involved in the process of deforestation. After the abandonment of La Draga, oak forest regeneration would be expected, but the opposite occurred and the clearances were maintained by use of fire, as indicated by the sedimentary charcoal data. Fire episodes could have been human induced or natural, given the fact that the Early Neolithic activities would have caused the degradation of the surrounding forests and the shift to scrubland (more prone to burning) in the clearances. Once the forest was cleared, climatic conditions, along with continued human intervention in the landscape, would have been responsible for the maintenance of the clearings. For the moment, only early Cardial Neolithic occupations were detected at La Draga, but the possibility of finding more recent phases should not be discounted.

Archaeological sites surrounding Lake Banyoles, for example the Serinyà caves 4 km away, provide supporting evidence for a number of Epicardial and Postcardial Neolithic occupations (6500–5900 cal BP), such as Cova de L'Arbreda, Cova d'En Pau, Cova de Reclau Viver and Mollet III (Maroto et al. 2000), that suggest that Neolithic communities remained around Lake Banyoles. Similar dynamics are documented in other regions of the NE Iberian Peninsula during the same period, where first farming societies also adversely affected the development of the deciduous forests (Riera and Esteban-Amat 1994; Riera et al. 2004).

5. Conclusion

The analysis of a new pollen core from the surroundings of Lake Banyoles showed an abrupt decline of oak forest cover coinciding with the early Neolithic settlement of La Draga and a slight climate cooling episode. Several hypotheses were considered in order to explain the results. The aforementioned climate cooling, influenced vegetation cover, as shown by the decline of arboreal pollen immediately before the arrival of farming communities to La Draga.

Nevertheless, when examining the impact on the landscape of previous and more important cold episodes, we conclude that climate could have not been the main cause of the decrease in oak pollen shown in the SB2 pollen record. It seems that the intensive exploitation of oak forest to obtain raw materials for the construction of dwellings was responsible for the large impact on vegetation dynamics. The opening of farming plots, which were probably small and intensively managed, had a relatively minor impact in the landscape.

Deforestation is not the only anthropogenic feature documented. Equally important is the maintenance of the clearances opened in oak forests, either for the different organisational strategies involved in management of vegetal resources or for the productive processes implied in an intensive farming system.

Probably, the perpetuation of these clearances is the main anthropogenic impact on the environment, and also the essential factor for a real change in landscape evolution. The SB2 sequence points to the Neolithic as a turning point in vegetation and geosystem history in Lake Banyoles, given the absence of evidence of occupation prior to the settlement of Neolithic communities of La Draga. The onset of an economy based on agriculture and husbandry and the establishment of first farming communities in open-air permanent settlements had a great influence on the changes documented in the landscape.

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4.2.2. Archaeoecology of Neolithisation. Human-environment interactions in the NE Iberian Peninsula during the Early Neolithic.

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Archaeoecology of Neolithisation. Human-environment interactions in the NE Iberian Peninsula during the Early Neolithic.

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Abstract

The Neolithisation process involved significant socioeconomic and ecological transformations. Changes in food production, in natural resources management and in settlement patterns originated a new way in which humans and the environment interacted. The intensive farming systems in use during the Early Neolithic, implying small scale and labour-intensive cultivation resulted in a low impact of agriculture in off-site pollen records. Nevertheless, deforestation processes are well documented across Europe and, specifically, in the Iberian Peninsula. The review of intra-site and off-site pollen records from the Lake Banyoles area show the limited impact of farming activities, and the causality of deforestation is attributed to the intensive exploitation of oak forests to obtain firewood and raw materials for construction.

Keywords: Neolithisation, Archaeoecology, Lake Banyoles, Deforestation, Human impact, Pollen analysis, Iberian Peninsula.

1. Introduction

The spread of the farming lifestyle from western Asia to Europe had significant long-term social and ecological impacts. The changes involved in the adoption of this new mode of production have suggested different causal explanations, in terms of climate change (Berger and Guilaine, 2009; Childe, 1952; Gronenborn, 2009; Richerson et al., 2001; Weninger et al., 2006), disequilibrium between population and resources or productive capacity (Binford, 1968; Renfrew, 1973), demography (Bocquet-Appel, 2002; Cohen, 1981), transformation of mechanisms of social reproduction (Testart, 1982; Vicent, 1990), the appearance of a new ideology (Cauvin, 1994, 2000; Thomas, 1988) or a new system of values involving the social dominance of nature (Hodder, 1990). In any case, the transformation of subsistence strategies from hunting and gathering to farming involved significant changes in the economy, ideology and social organization, aswell as in the relationship between humans and the environment. In that sense, the study of the various environmental changes occurring during the Early and Mid-Holocene becomes especially important in order to characterise the environmental framework and possible constraints across Europe during the Neolithisation process.

The character of early farming in Europe has been widely discussed. Evolutionist proposals used to consider the first farming practices as extensive and characterised by a lowinvestment in labour, only becoming intensive after technological and demographic changes (Boserup, 1965). Another farming model proposed was shifting slash-and-burn cultivation as an adaptation by early farmers to the densely wooded landscape of central Europe (Clark, 1952). Nevertheless, bioarchaeological research carried out in recent decades has shown that intensive mixed farming (small-scale, labour-intensive cultivation integrated with small-scale herding) emerges as the most plausible model across Central and South-east Europe (Bogaard, 2004; Marinova, 2007), in North-west Europe (Bogaard and Jones, 2007) and in some areas of the Western Mediterranean (Antolín, 2013; Antolín et al., 2014, 2015; Pérez-Jordà and Peña-Chocarro, 2013). Archaeozoological research has also identified a small-scale intensive herding (Halstead, 1989). In fact, an intensive farming model would imply a close integration of agriculture and husbandry, with livestock kept within the settlements, the use of crops as fodder and the introduction of manuring (Bogaard et al., 2013).

The expansion of the first farming societies and the practice of an intensive agriculture implied limited impact on the landscape (Bogaard, 2004), in terms of small-scale forest modifications that can be traced across Europe following the chronological gradient associated with the Neolithisation process, starting in south-eastern Europe in the 9th millennium cal. BP (Kouli and Dermitzakis, 2008; Marinova et al., 2012) and reaching the opposite extreme of the continent at the beginning of the 6th millennium cal. BP (O'Connell and Molloy, 2001; Woodbridge et al., 2012). The arrival of the first Neolithic groups in the Iberian Peninsula is dated to 7650–7600 cal. BP, so this was the last region to adopt farming in the Mediterranean area. Their territorial expansion was discontinuous but rapid, extending over coastal regions and some inland areas following the course of the rivers in less than two centuries (Bernabeu et al., 2009, 2014).

Settlement patterns of the first farming communities in Iberia were characterised by the documentation of the first permanent open-air settlements, such as La Draga (Bosch et al., 2000, 2011), Mas d'Is (Bernabeu et al., 2003), Los Castillejos (Afonso et al., 1996), Los Cascajos (García Gazólaz and Sesma, 2001) or La Revilla del Campo and La Lámpara (Rojo et al., 2008). Considerable labour investment in the construction and maintenance of these large permanent open-air settlements and of certain structures (i.e. the large ditch documented in Los Cascajos, García Gazólaz et al., 2011) would imply a noticeable transformation of the landscape.

The first evidence of Neolithic occupation in NE Iberia is dated in the second half of the 8th millenniumcal. BP. The gap in human presence in the region during the first half of the 8thmillenniumcal. BP indicate that the Neolithisation of the NE Iberian Peninsula was the result of migration of farming populations to uninhabited territories (Zilhao, 2000, 2011), in contrast to the interaction documented between indigenous Mesolithic communities and the arriving farming communities on the Eastern coast of the Iberian Peninsula (Bernabeu, 1997, 2002; Bernabeu et al., 2009). The earliest dates of Neolithic occupations in NE Iberia correspond to caves and rock-shelters: Balma Margineda (Sant Julià de Lòria, Andorra) (7860–7390 cal. BP, Guilaine, 1995), Bauma del Serrat del Pont (Tortellà, Girona) (7480–7280 cal. BP, Alcalde and Saña, 2008), Cova de Can Sadurní (Begues, Barcelona) (7430–7240 cal. BP, Edo et al., 2011). Nevertheless, the main innovation in this period is the appearance of open-air permanent settlements: Font del Ros (Berga, Barcelona) (7390–7260 cal. BP, Bordas et al., 1995), Sant Pau del Camp (Barcelona) (7265–7075 cal. BP, Molist et al., 2008) and La Draga (Banyoles, Girona) (7270–6750 cal. BP, Bosch et al., 2012).

The latter, La Draga, located in the eastern shore of Lake Banyoles, should be highlighted because of the excellent preservation of the bioarchaeological record in waterlogged contexts (Bosch et al., 2000, 2006, 2011), constituting the richest assemblage from the early Neolithic period in the Iberian Peninsula. This particularity has allowed interdisciplinary bioarchaeological studies enabling the comprehension of farming activities (Antolín, 2013; Antolín et al., 2014; Navarrete and Saña, 2013; Saña, 2011), themanagement of natural resources involved in the reproduction of Neolithic communities (Caruso-Fermé and Piqué, 2014; Piqué, 2000) and a reconstruction of the environmental conditions in which they took place. This record has been obtained from both the archaeological site (Burjachs, 2000; Pérez-Obiol, 1994; Revelles et al., 2016) and from off-site pollen records (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015), providing information about past vegetation and Neolithic land-use. The Lake Banyoles area has become an outstanding place in the Iberian Peninsula to study humanenvironment interactions during the Neolithic, given the exceptional bioarchaeological record documented in over 20 years of interdisciplinary research at La Draga, and the extensive palaeoecological data available from Lake Banyoles (Bischoff et al., 1994; Casamitjana et al., 2006; Höbig et al., 2012; Julià, 1980; Morellón et al., 2014, 2015; Serra et al., 2002).

The study area is located in the NE Iberian Peninsula, 35 km from the Mediterranean Sea and 50 km south of the Pyrenees (Fig. 1). Lake Banyoles is a karst lake associated with a large karst aquifer system located in a tectonic depression and fed by underground waters. The climate in this region is defined as humid Mediterranean, with an annual precipitation of 750 mm and a mean annual temperature of 15 °C. The current vegetation is dominated by a mixed forest of evergreen oak (*Quercus ilex*, Quercus *coccifera*, *Rhamnus alaternus*, *Phillyrea media*, *Phillyrea angustifolia*), deciduous oak forest (*Quercus humilis*, *Buxus sempervirens*, *Ilex aquifolium*) and pine forest (*Pinus halepensis*). A review of palaeo-environmental data obtained from the site of La Draga and from Lake Banyoles is set in the context of the broad discussion about economic and social organization during the Early Neolithic in the Iberian Peninsula. In this context, the main purpose of this paper is to assess the ecological impact that the socioeconomic change involved in Neolithisation had in the NE Iberian Peninsula, and specifically to evaluate the scale of the impact of the different activities carried out by the first farming communities in the Lake Banyoles area.

Figure 1. Left) Location of the study area in the NE Iberia and location of sitesmentioned in Fig. 2: 1 - Besós (Barcelona), 2/5 - Bosc dels Estanyons, Forcat, Riu dels Orris and Planells de Perafita (Andorra), 6 - Monte Areo (Asturias), and 7 - Conquezuela (Soria). Right) Pollen records analysed around Lake Banyoles.

2. Humans, environment and Neolithic: a theoretical framework

The Neolithisation involved a significant change in the relationship between society and environment. The conceptualisation of "Neolithic" has aroused a long debate with definitions from diverse theoretical approaches. Firstly, Neolithic was considered one stage within human evolution towards civilization, overcoming the previous primitive savagery (Morgan, 1877), assuming a natural trend for humans to improve their life conditions and to seek increasingly-efficient organizational strategies. Thus, the Neolithic is conceived as a transcendental step forward from foraging to a productive economy, or an essential period in the History from the perspective of progress.

From the 1960's, the emergence of the so-called *New Archaeology* represented the onset of the integration of archaeological and palaeoecological data, and an increase in attention to environmental elements within the analysis of the archaeological record of early farmers (Sahlins, 1964; Wright, 1971). By adopting explicative premises from cultural ecology (Steward, 1955), human societies were considered as extrasomatic systems of adaptation to the environment (Binford, 1972), assuming a systematic relationship between the human organism and its environment in which culture is the intervening variable (Binford, 1962, 218). Nevertheless, based on a homeostatic relationship between society and environment, equilibriumwas considered the determining element of the adaptation, situating causalities of changes in external factors (i.e. demography or climate change), and thus omitting conflict within societies to comprehend social change. Humans, as social subjects, interact with the material world through labour (Marx, 1984), which makes sense in a physical support, the geosystem, consisting of biotic (plants and animals) and abiotic elements (lithosphere, hydrosphere and aerosphere) (Beroutchachvili and Bertrand, 1978). Social labour, aimed at the satisfaction of human existence conditions and social needs, and phenomenologically expressed by social practices (Castro et al., 1996, 1998), produces material changes in the geosystem. Based on social concepts, the environment should not be assumed as a pre-existent element determining human actions, and it is essential to consider modes of production and the productive systems depending on it, in order to comprehend the social needs that determine the human management of natural resources.

Thus, the geosystem is not used, felt or perceived, but exists in a relationship with productive forces and social categories (Beroutchachvili and Bertrand, 1978). In that sense, in the origins of Humanity, the physical space was a purely natural system, but, through history, physical space became progressively constructed by anthropogenic work, and the Neolithic represents a transcendental period since when anthropisation has grown exponentially. Thus, the landscape emerges as a historical product rejecting the original nature, becoming increasingly humanised (Bertrand and Bertrand, 2000, 54). According to an archaeoecological approach (Revelles, 2013), social organization must be understood as the product of the relationship between the environment and social recognition of needs, and not a passive adaptation to a given framework. The reality has to be analysed from the dialectical relationship between humans and geosystem, in order to assess the environmental conditions in which societies developed and to evaluate the effects of political and economic practices on the landscape.

The viewof the Neolithic as the appearance of newobjects and techniques and the onset of a productive economymust surely be overcome, in an approach to social relationships and material conditions in which the first farming societies developed. In that sense, economy should include not only the production involved in food procurement, but other productive processes and the maintenance of objects and subjects (Castro et al., 2005). Obtaining food by hunting and gathering should not be considered non-productive activities, because specific knowledge of the geosystem, the application of several techniques and technologies and an organization of labour and tasks are required and are involved in the global productive and reproductive process of hunter-gatherer societies (Piqué, 1999).

The Neolithic consists of the appearance of organizational strategies based on the inclusion of the appropriation of reproductive cycles of some plants and animals within mechanisms of social production and reproduction. In that sense, the shift from hunting and gathering to farming is viewed as a change in the way in which culture and environment interacted (Wright, 1971, 457). Domestication allowed human management of resources reproduction, making their availability artificial. Nevertheless, Neolithic research should not be focused only on domestication processes, but also on relationships established in labour organization and in the distribution, use and consumption of the goods produced. Moreover, these new productive processes are involved in the global productive process,where other tasks are included, such as subject production and the maintenance of both objects and subjects (Castro et al., 2005). Therefore, when referring to transformations from the hunter-gatherer to the farming mode of production, attention must be paid not only to changes in production, also to the social relationships that determine them (Vicent, 1990).

Aside from this debate on its causes and mechanisms, the Neolithic led to the economic and social foundations on which present-day societies are based, such as diversified food production and storage techniques, surpluses, sedentism, labour specialization, social complexity, and ultimately state institutions (Banks et al., 2013). These changes in food production, in natural resources management and in settlement patterns originated the onset of progressive human impact on the landscape that, together with climatic oscillations during the Holocene, caused considerable changes in the original geosystem. These changes place the Neolithisation process in the centre of the discussion on the origins of the Anthropocene, in terms of the human alteration of ecosystems (Ruddiman, 2003; Ruddimann, 2013; Ruddiman et al., 2015) and of human niche-constructing behaviour,modifying ecosystems through the domestication of plants and animals (Smith and Zeder, 2014).

3. Farming practices, vegetal resourcesmanagement and human impact during Neolithic in Iberia

3.1. Farming practices

The Early Neolithic in the Iberian Peninsula, as opposed to other European regions, featured an agriculture characterised by high crop diversity. Among the cereals, two types of hulled wheat are documented, einkorn (*Triticum monococcum*) and emmer (*Triticum dicoccum*), as well as two types of free-threshing wheat, macaroni wheat (*Triticum durum*) and bread wheat (*Triticum aestivum*), and two barleys, hulled (*Hordeum vulgare* var. *vulgare*) and free-threshing (*Hordeum vulgare* var. *nudum*). Legumes have also been attested: pea (*Pisum sativum*), lentil (*Lens culinaris*), fava bean (*Vicia faba*), bitter vetch (*Vicia ervilia*), common vetch (*Vicia sativa*) and grass peas (*Lathyrus sativus* and *Lathyrus cicera*). Finally, flax (*Linum usitatissimum*) and poppy (*Papaver somniferum*) have been also documented (Antolín, 2013; Antolín et al., 2015;

Buxó, 1997; Peña-Chocarro, 1999, 2007; Peña-Chocarro et al., 2005; Pérez-Jordà and Peña-Chocarro, 2013; Pérez-Jordà et al., 2011; Rovira, 2007; Zapata, 2007; Zapata et al., 2004). Recent studies in NE Iberia and Eastern Iberia have documented the practice of intensive agriculture (Antolín, 2013; Antolín et al., 2014, 2015; Pérez-Jordà and Peña-Chocarro, 2013), consistent with the European context (Bogaard, 2004; Bogaard and Jones, 2007; Bogaard et al., 2011; Marinova, 2007), an agriculture that included the cultivation of a large variety of cereals and legumes. Nevertheless, a transition towards an extensive form of agriculture based on the cultivation of a reduced number of cereal species is documented for theMiddle-Late Neolithic period (Antolín, 2013; Antolín et al., 2015; Pérez-Jordà and Peña-Chocarro, 2013). The large variety of crops, documented in the Early Neolithic in the Iberian Peninsula, with different requirements, processing and uses, implies that the first farmers quickly imported or acquired a wide range of agrarian knowledge. According to Halstead (1990, 1996), farmers can protect themselves against failure and climate instability by growing a diversity of crops with different growth requirements and tolerances. In that sense, the cultivation of small plots with a wide range of different crops may have been the result of a conscious strategy designed to minimize risk (Zapata et al., 2004).

3.2. Vegetal resources management

Social exploitation of woodland resources has been crucial since the origins of Humanity, as a source of food, through the practice of hunting-gathering strategies, firewood to obtain luminescent and calorific energy, raw materials to make tools and constructions…. But the first farmers had to deal with new forest management strategies adapted to new necessities associated with sedentary settlement patterns, more intensive productive activities (agriculture and husbandry) increasingly reiterated in the territory, growing population and new productive processes (i.e. ceramic technology).

The Iberian Peninsula encompasses a remarkable diversity of landscapes and ecological conditions, from the humid Atlantic climate in the north to the arid thermo-Mediterranean in the southeast. This situation is also reflected, although less markedly, in NE Iberia, where a humid Mediterranean climate with Atlantic influences is found in the northern part, the location of our study area, compared with the characteristic Mediterranean climate in the south. Climate conditions and landscapes at the beginning of the Neolithic were equally diversified. The vegetation the first Neolithic communities encountered on their arrival in Iberia influenced the availability of raw materials, although social necessities would have been the determining factor in planning timber and firewood procurement strategies. The first farming societies settled in densely forested areas, with a predominance of deciduous broadleaf tree forests in the humid Mediterranean northeast and in the Atlantic north of Iberia, a major importance of sclerophyllous trees and Mediterranean shrubland in eastern and south-eastern Iberia and the dominance of pine woodlands in high mountain and in some central continental areas (Burjachs et al., 1997; Carrión et al., 2010; Pérez-Obiol, 2007; Pérez-Obiol et al., 2011).

Timber, generally charred, constitutes the principal archaeological remains associated with the use of forest resources by Neolithic societies, mainly related to firewood combustion in the context of domestic or other productive activities. Forest management strategies to obtain firewood reflect the diverse vegetal landscape that existed in NE Iberia during the Neolithic, characterised in the north (pre-Pyrenean area) by the dominance of taxa from broadleaf deciduous forests (deciduous Quercus, Buxus sempervirens, Acer sp., Prunus sp., Corylus avellana, Rosaceae/Maloideae) and riparian forests (Ulmus sp., Fraxinus sp., Cornus sp., Laurus nobilis, Populus sp., Salix sp., Sambucus sp.) (Agustí et al., 1987; Buxó and Piqué, 2008; Piqué, 2000, 2002, 2005; Ros, 1995), consistentwith data fromthe Atlantic influenced northern Iberia (CarriónMarco, 2005; Zapata, 1999). On the other hand, in the southern part of NE Iberia evergreen Quercus formations dominated, a situation that can be extended through the eastern and southeastern Iberian Peninsula, where evergreen oak and Mediterranean shrublands were mainly exploited (Badal, 1988; Badal et al., 1994; Rodríguez-Ariza, 1996; Vernet et al., 1987). In sum, the first farming societies exploited deciduous oak and evergreen oak forests to acquire raw materials, depending on the geographic area and environmental availability.

The use of timber for the production of tools and for hut-buildings has been documented at an outstanding archaeological site in the Iberian Peninsula, the site of La Draga (Banyoles, Girona). The exceptional preservation of organic matter at La Draga has provided information about the use of timber, bark and lianas for making tools and building huts (Bosch et al., 2000, 2006, 2011; López, 2015; Palomo et al., 2011, 2013; Piqué et al., 2015). Raw materials were obtained in oak forests and riparian vegetation, as shown in the dominance of deciduous Quercus (96% of more than 1000 posts analysed), and the presence of *Cornus sanguinea*, *Corylus avellana*, *Laurus nobilis*, and Rosaceae/Maloideae (López, 2015, Revelles et al., 2014). For wooden tools (handles of sickles and adzes, digging sticks, combs, spatulas, ladles, bows, vessels, beaters and projectiles), deciduous *Quercus* and *Buxus sempervirens* are the most recurrent raw materials, together with other taxa from deciduous oak forests (*Acer* sp., Rosaceae/Maloideae, *Tilia* sp., *Corylus avellana*), riparian vegetation (*Cornus* sp., *Laurus nobilis*, *Populus* sp., *Salix* sp., *Sambucus* sp.), conifers (*Taxus baccata*, *Pinus* sp., *Juniperus* sp.) and sclerophyllous Mediterranean forests (evergreen *Quercus*, *Arbutus unedo*) (Bosch et al., 2006; Palomo et al., 2013).

3.3. Human impact

Anthropogenic impact on the landscape during the early Neolithic, involving deforestation, expansion of secondary woodland formations or pyrophilous and ruderal taxa has been documented in areas of NE Iberia, like the Pyrenees (i.e. Gassiot et al., 2012; Miras et al., 2007; Orengo et al., 2014), pre-Pyrenees (Revelles et al., 2014) and the central Catalan coast (Antolín et al., 2011; Riera and Esteban-Amat, 1994; Riera et al., 2007). The impact of the first farmers has also been documented in the rest of the Iberian Peninsula in different intervals between the second half of the 8th millennium cal. BP and the 7th millennium cal. BP: in north-western Iberia (Ramil-Rego and Aira, 1996; Ramil-Rego et al., 1994), in the north (Iriarte, 2009; López-Sáez and López-Merino, 2007; López-Merino, 2009; López-Merino et al., 2010; Peñalba, 1994), in central Iberia (Aranbarri et al., 2015; López-Sáez, 2002; López-Sáez et al., 2005); the Ebro valley (González-Sampériz, 2004; López-Sáez et al., 2006), eastern Iberia (Carrión and van Geel, 1999; Dupré et al., 1996; Yll et al., 2003); south-western Iberia (López-Sáez et al., 2007a, 2007b/2008; van der Knaap and van Leeuwen, 1995) and in southern Iberia (Carrión et al., 2001, 2007; Cortés et al., 2008; Fernández et al., 2007). Although several causes are proposed by different authors, all of themagree that these changeswere the result of human intervention, in which the woodland was opened up for several purposes. In some cases, evidence of fire has been found (Kaal et al., 2008; Martínez Cortizas et al., 2009; Riera et al., 2004) although this was not a general trend. Despite this evidence of landscape transformation during the early stages of Neolithisation in Iberia often being associatedwith farming activities, the low values or absence of Cerealia-type pollen and weeds in some sequences is noticeable (Carrión et al., 2007; Iriarte et al., 2007/2008; López-Merino, 2009; López-Merino et al., 2010; López-Sáez et al., 2007a, 2007b/2008; Peñalba, 1994; Pérez-Díaz et al., 2015; Ramil-Rego and Aira, 1996). On the other hand, concentrations of Cerealia-type pollen have been documented at many archaeological sites (Burjachs, 2000; Fernández-Eraso, 2007/2008; Iriarte, 2001; Iriarte et al., 2004, 2005; López-Sáez et al., 2006, 2007a, 2007b/2008; Pérez-Obiol, 1994), probably as the result of crop processing within the settlement, the practice of storage or the location of crop fields in the surroundings. This situation might be linked with the low impact of intensive farming in small plots at regional scale. The intensive and continued exploitation of forests for various activities, such as obtaining rawmaterial for tools or huts, as fuel in several domestic and communal productions or for grazing domestic animals, became themain cause for the anthropic transformations documented. In the next section, the case study of La Draga and Lake Banyoles will be used to approach to this problematic, where combined bioarchaeological research has provided an exceptional record to characterise palaeo-environmental evolution and human management of the landscape in the Early Neolithic at local and extra-local scales. Records from the Lake Banyoles area contribute newdata to the discussion about the social and ecological impact of Neolithisation in the Iberian Peninsula.

4. Landscape transformation during the Early Neolithic in the Lake Banyoles area

The settlement of the first farming societies in the Lake Banyoles area was the cause of major changes to the vegetation. This process has been documented in diverse records, from the Neolithic site of La Draga (Revelles et al., 2016) and from peat deposits on the western lakeshore (Revelles et al., 2014, 2015) (Fig. 1). Thus, the comparison between intra-site and off-site records allows us to assess vegetation, palaeo-environment and human impact both in the settlement surroundings and at an extra-local scale, in the area of Lake Banyoles. Furthermore, the comparison of the anthropic impact evidenced in these two different types of deposit enables an evaluation of the social use of space and the impact on the landscape of the different economic practices carried out in the settlement of La Draga during the Early Neolithic (7270–6750 cal. BP). Two different phases of early Neolithic occupation with distinctive constructive traditions have been documented; both dated within the late Cardial Neolithic according to pottery styles, and in the last three centuries of the 8th millennium cal. BP according to the radiocarbon dates. Phase I (7270–6930 cal. BP) is characterised by the collapse of wooden structures (carbonized in some points), which have been preserved in an anoxic environment. Phase II (7160–6750 cal. BP) consists of several pavements of travertine stone. The site lies on a carbonated clayish substrate (Layer IX); the sediments of the first phase (Layers VIa and VII) are characterised by high organic matter content and waterlogged conditions; levels in the second phase (III, IV, VI) are less organic as they are formed by allochthonous siliciclastic inputs in the context of soil erosion episodes; and the post-occupation layers (I, II) consist of peat. The off-site record (SB2 core, 107 cm) showed an alternation of peat and organic dark silty clay layers, covering the late Early Holocene-Late Holocene period (8900–3350 cal. BP) (Revelles et al., 2015).

The first farming societies settled in a humid and dense forested area, with the predominance of broadleaf deciduous forests (deciduous *Quercus* and *Corylus*) and conifers (*Pinus* and *Abies*) in the surrounding mountains (Fig. 2). At a regional scale, the presence of evergreen sclerophyllous taxa (*Quercus ilex-coccifera*, *Olea* and *Phillyrea*) is noteworthy. At a local level, riparian forests (*Ulmus*, *Fraxinus* and *Salix*) developed along the lakeshore, where hygrophyte (Cyperaceae, *Typha latifolia*, *Typha-Sparganium*, *Juncus articulatus* type, *Juncus effusus* type, *Cladium mariscus* and *Mentha* cf. *aquatica*) and aquatic plants (*Potamogeton coloratus*) were also present (Revelles et al., 2015, 2016).

Once they had settled at La Draga in *ca*. 7270 cal. BP, a fall in deciduous *Quercus* values is recorded at the site (Burjachs, 2000; Pérez-Obiol, 1994; Revelles et al., 2016) and in lakeshore peat deposits (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015). The space left by oak forests was colonised by herbs (Poaceae, Asteraceae and *Plantago*), shrubs (*Erica*, in the pollen record, and *Buxus* cf. *sempervirens,* as shown by its expansion in the anthracological record fromthe second occupation phase at La Draga; Piqué, 2000; Caruso-Fermé and Piqué, 2014) and secondary trees (*Pinus*, *Tilia* and *Corylus*). Part of the clearances would have been used for cultivation and grazing, but a large part of them remained unused and were colonised by secondary trees, resulting in only a slight decrease in AP (Fig. 2). Thus, Neolithic forest disturbance involved the expansion of light-demanding trees and shrubs in a more open landscape, defining woodland edges and clearings.

The low values of sedimentary charcoal recorded in the SB2 sequence (Fig. 2) suggest that burning was not involved in the deforestation process, thus confirming that the slash-and-burn farming model was not practiced in the Lake Banyoles area during Early Neolithic. In that context, the practice of intensive farming practices in small crop fields would have resulted in an almost imperceptible impact of agriculture in pollen records from off-site deposits, and deforestation would be linked with the need for firewood and raw material for construction (Revelles et al., 2014).

Despite the low impact of agriculture at extra-local level, small-scale, labour-intensive cultivationwas documented at La Draga,with six crops identified: *Hordeum distichum* (two-rowed hulled barley), *Triticum durum*/*turgidum* (tetraploid nakedwheat), some scarce finds of *Triticum aestivum* s.l. (hexaploid naked wheat), *Triticum dicoccum* (emmer), *Triticum monococcum* (einkorn) and *Papaver somniferum* (opium poppy) (Antolín, 2013; Antolín et al., 2014). The possibility of shifting agriculture was discarded in accordance with the weed spectrum and permanent cultivation of the fields and intensive soil perturbation was proposed, based mostly on the identification of annual taxa and the presence of vegetative reproduction plants (Antolín et al., 2014).

Therefore, a high concentration of Cerealia-type pollen is documented in both occupation phases at La Draga. Crop fields could not be in the immediate surroundings of the settlement, because it was established in a swampy area unsuitable for cultivation. The plots would have been far enough away to prevent Cerealia-type pollen from reaching the off-site peat deposits (Revelles et al., 2014) and high concentrations within the settlement have to be understood in terms of anthropic input of spikelets, either for storage of crops or by-products. This is consistent with the presence of mixed cereal grains and chaff within archaeological contexts, suggesting domestic storage (Antolín et al., 2014).

The impact of husbandry practices on the landscape show similar trends to the situation described for agriculture. At extra-local level, grazing pressure is imperceptible in off-site deposits, in terms of the absence of coprophilous fungi spores (Revelles et al., 2015). Nevertheless, high concentrations of coprophilous fungi spores are recorded at La Draga (Revelles et al., 2016), pointing to the keeping of flocks within the settlement and to a limited impact of grazing on the landscape at a regional scale. Deforestation processes affected more aspects than vegetation. Lack of plant cover implied high propensity to soil erosion in lakeshore environments, a phenomenon attested both within the site (2nd phase, *ca*. 7160–6750 cal. BP) and in natural peat deposits, progressively increasing from 7250 cal. BP, but clearly attested in the period *ca*. 6000–5550 cal. BP. These processes have been documented by the decrease in organic matter and inputs of terrigenous sediments and by some palynological indicators (rapid increase of grasslands, specifically Asteraceae, and high values of *Glomus* chlamydospores) (Revelles et al., 2015, 2016).

The clearances opened in oak forests were maintained during the Late Early Neolithic (6750–5550 cal. BP) by grazing (evidence of coprophilous fungi spores) and probably using fire (Fig. 2). Afterwards, in the Middle Neolithic, the Lake Banyoles area would have been less frequented, as shown by scarce archaeological remains and the recovery of oak forests due to the end of the Early Neolithic human pressure (Revelles et al., 2015). The clearest evidence of the impact of agriculture is documented in the Late Neolithic-Chalcolithic, when short deforestation processes occur throughout the period ca. 5250–3900 cal. BP, producing a combination of evidence of crops (Cerealia-type) and weeds (Plantago major-media, Chenopodiaceae) and local fire episodes affecting riparian forests, probably associated with slash-and-burn agriculture (Revelles et al., 2015).

Comparing intra-site and off-site pollen records has allowed an assessment of the intensity and scale of human impact. In that sense, coeval pollen records from natural and archaeological deposits are able to assess the representativeness of archaeopalynological analysis. Apart from the overrepresentation of crops and grasslands due to higher local impact and anthropic input of some taxa to the settlement (Fig. 2), the pollen record at La Draga shows the reliability of archaeological deposits in order to determine vegetal landscape evolution during several occupation phases. Nevertheless, the development of archaeoecological projects involving the integration of palaeoenvironmental data fromnatural and archaeological deposits becomes essential to comprehend the intensity of human activities on the landscape at local and extra-local levels. In that sense, the location of the site of La Draga on the shore of Lake Banyoles offered an exceptional opportunity in the context of the Iberian Peninsula to carry out an archaeoecological project comparing intra-site and off-site pollen records. The integration of bioarchaeological data from La Draga and from off-site pollen records provided significant data for the comprehension of human-environment interactions in the Iberian Peninsula during the Early Neolithic.

Human impact in the Early Neolithic has been recorded on both local and extra-local scales in the Lake Banyoles area. The signal of farming activities was only identified at intra-site level, indicating the limited impact of the intensive economic model practised by the first farmers. The precise location of the crop fields has still not been located, but the lakeshores were presumably not used for cultivation because of the swampy substrate. However, greater effortmust be made in this aspect, and it would be interesting to obtain new cores from the site surroundings in the future and carry out geomorphologic and palaeobotanical research. Nevertheless, the immediate surroundings of La Draga and, in general, of the lakeshore, can be excluded because of the geomorphologic conditions. The crop fields would have been on higher land, probably to the east of the settlement, in an area close enough to make an intensive management strategy possible (Antolín et al., 2014).

Landscape transformation at local and extra-local scale occurring from the time Neolithic communities settled in the area was mainly due to deforestation to obtain firewood and raw materials for construction. In that sense, the communities at La Draga intensively exploited oak forests, as shown in intra-site and off-site deposits, but also riparian vegetation, which displays a regression at local level. Nevertheless, the human transformation of landscape attested in the Lake Banyoles area during the Early Neolithicwas not definitive, as broadleaf deciduous forests regenerated after the end of human pressure.

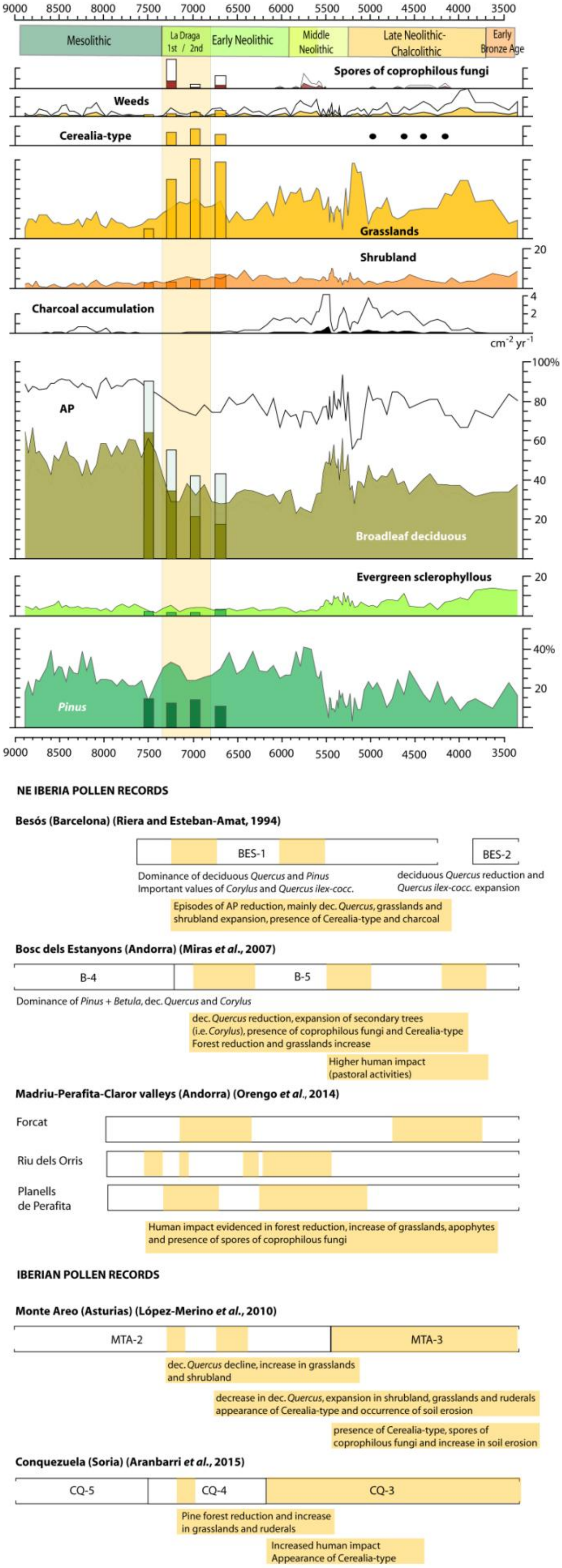

Fig. 2. Summary pollen diagram for SB2 (silhouette) and La Draga (histogram) and correlation with patterns of human impact in other pollen records in NE Iberia and in Iberian Peninsula. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points. Categories: shrubland (*Erica*, Cistaceae, *Heliathemum*, *Vitis*, *Hedera helix*, *Crataegus*, *Sanguisorba*, *Rhamnus*), grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Plantago*, Lamiaceae) and weeds (*Plantago major-media*, Chenopodiaceae, *Rumex*, Brassicaceae).

5. Conclusion

The Neolithisation implied the spread of a newlifestyle based on the inclusion of farming activities within organizational strategies, causing profound change in the relationship between humans and environment. Nevertheless, social practices involved in agriculture and husbandry should be understood in a global productive process. This economic change lead to social changes, including permanent settlement patterns, a growing population and more intensive productive activities increasingly reiterated in the territory. These socioeconomic changes started a progressive process of landscape transformation, involving deforestation to open clearings for agriculture, grazing or permanent open-air settlements.

In that context, archaeobotanical data becomes an essential key to assess the process of social change associatedwith the origin of farming societies, enabling vegetation history reconstruction and the characterisation of the impact of the exploitation of vegetal resources by Neolithic communities. The practice of intensive farmingmodels during the Early Neolithic, implying small-scale and labour-intensive cultivation, left little evidence of the impact of agriculture, in terms of absence or scarce values of crops andweeds in off-site pollen records.Nevertheless, deforestation processes or, at least, small-scale forest modifications, are well documented in several areas of the Iberian Peninsula, showing that social organization around farming societies implied significant landscape transformation. That process is clearly reflected in the case study of the Lake Banyoles area, where deforestation has been linked to intensive exploitation of oak forests to obtain firewood and building materials, as documented at La Draga. However, although the agricultural impact is not directly evidenced, permanent settlements should be considered a consequence of the adoption of agriculture. In that sense, the high labour and resources investment involved in the adoption of farming became as the backbone of the settlement of human communities in the territory since the Neolithic.

This model of human transformation of landscape is consistent with data from NE Iberia and, in general, from the whole Iberian Peninsula, where a sustainable small-scale and intensive farming system would have left scarce evidence of the impact of agriculture during the Early Neolithic. In any case, social changes linked with the adoption of farming can be considered the main cause of landscape transformation from the 8th–7th millennia cal. BP onwards. Thus, the establishment of permanent settlements and an intensive and reiterative exploitation of natural resources caused a noticeable modification of previous ecosystems.

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4. 3. POTENTIAL AND CONTRIBUTIONS OF ARCHAEOPALYNOLOGY IN LAKESIDE SETTLEMENTS RESEARCH.

· Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain).

· Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia).

4.3.1. Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain).

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Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain)

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Abstract

Pollen and non-pollen palynomorphs (NPP) from the Early Neolithic settlement of La Draga have provided new palaeoenvironmental data concerning the establishment of the first farming societies in NE Iberian Peninsula. The analysis of samples fromthe archaeological profiles allowed the comprehension of several processes involved in the formation of this archaeological site and the reconstruction of environmental conditions in the different phases of occupation, in addition to obtaining new data about the ecological significance of NPP in archaeological levels. New NPP have been described, illustrated, and discussed.

The first farming societies settled at La Draga in a humid and densely forested area, with the predominance of deciduous trees (deciduous *Quercus* and *Corylus*) and *Pinus* and *Abies* in the surrounding mountains. Following their establishment at the site, abrupt changes in vegetation are recorded, in terms of deforestation of oak and riparian forests. Sedimentation dynamics involved in the formation of the archaeological site influenced the composition of the NPP spectra, reflected in the contraposition between waterlogged and subaerial layers, but especially, between organic peaty layers formed at local level and sediments transported by erosive processes in the layers belonging to the second phase of occupation.

Keywords: La Draga, Neolithic, NPP, Pollen, Northeast Iberia, Archaeology

1. Introduction

In recent years our understanding of non-pollen palynomorphs (NPP) has grown considerably, and they have become an essential tool to improve our knowledge of Quaternary environmental conditions. NPP analysis provides information about specific ecological conditions (i.e. humidity/dryness), allows the reconstruction of certain geomorphologic processes such as soil erosion events (Anderson et al., 1984; van Geel et al., 1989; López Sáez et al., 2000), verifies local occurrence of host plants that can be invisible in pollen and macrofossil analyses (van Geel et al., 2006) and enables an assessment of human impact in terms of grazing pressure (Ralska-Jasiewiczowa and van Geel, 1992; López-Merino et al., 2009; Cugny et al., 2010; Gauthier et al., 2010), fire episodes (van Geel, 1978; Simmons and Innes, 1996; Innes and Blackford, 2003; Blackford et al., 2006) or the eutrophication of water (van Geel et al., 1994, 1996; Hillbrand et al., 2014). NPP analysis has also been applied in archaeological contexts, albeit less frequently, evidencing livestock presence within settlements or in the surroundings (van Geel et al., 1983, 2003); and determining the season of certain archaeological structures (Kvavadze and Kakhiani, 2010).

Nevertheless, the ecological requirements of many NPP are still under debate, while many new types are defined in every new published work. One of the main challenges of NPP research and, of course, of this paper is to obtain information about the ecological significance of these microremains. In that sense, this work attempts to shed new light on NPP documented in the archaeological site of La Draga (Girona, Spain), with special attention to 48 new types.

The first farming societies in NE Iberia settled in densely forested areas, with a predominance of broadleaf deciduous woodland, which was frequently dominant in the Mediterranean region of the Iberian Peninsula (Burjachs et al., 1997; Pérez-Obiol, 2007; Carrion et al., 2010; Pérez-Obiol et al., 2011). In the area of Lake Banyoles, deciduous forests were dominated by oak (deciduous *Quercus*) and hazel (*Corylus avellana*), with conifers in the nearby mountains, specifically pine (*Pinus* spp.) and fir (*Abies alba*), as shown by pollen analyses carried out on deposits from Lake Banyoles (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015).

The onset of an economy based on agriculture and husbandry and the establishment of the first farming communities in permanent open-air settlements greatly influenced the changes documented in the landscape. In NE Iberia there is evidence of the impact of Neolithic communities at a regional level from natural deposits (Riera and Esteban-Amat, 1994; Miras et al., 2007, 2010; Riera et al., 2007; Orengo et al., 2014; Revelles et al., 2014), and also at a local level, from archaeological sites (Burjachs, 2000; Antolín et al., 2011; Gassiot et al., 2012).

Human management of the landscape is an important element in the comprehension of formation processes of an archaeological site, as well as natural induced sedimentation dynamics. The integration of pollen and NPP can provide information about human impact on the local environment and generate new data about the use of space within the settlement.

In this context, the main objectives of this paper are:

- To evaluate the ecological significance of the NPP documented.

- To assess the environmental conditions in which Neolithic communities developed and the impact on the local environment of the economic practices documented at La Draga.

- To provide new data to comprehend the formation processes of this archaeological site.

2. Study area

2.1. Environmental setting

The study site is located in the north-eastern Iberian Peninsula, 35 km from the Mediterranean Sea and 50 km south of the Pyrenees (Fig. 1). Lake Banyoles is a karst lake associatedwith a large karst aquifer system located in a tectonic depression and fed by underground waters. The lake is approximately 2100 m long and 750 m wide with an average depth of 15 m that in several points can reach up to 46 m (Julià, 1980; Casamitjana et al., 2006; Höbig et al., 2012). The lake water is supersaturated in calcite causing precipitation, and constituting the main component of the lake sediments (Bischoff et al., 1994). Lake Banyoles is defined as oligo-mesotrophic and water temperatures ranges between 8–25 °C on the surface and 8–17 °C in deep water (Serra et al., 2002).

The climate of the Banyoles region is defined as humid Mediterranean, with an annual precipitation of 750 mm and a mean annual temperature of 15 °C. The mean maximum temperature during July and August is 23 °C, and the minimum mean is 7 °C in winter. The minimum monthly precipitation (10 mm) occurs during summer and December.

The current vegetation is dominated by a mixed forest of evergreen oak (*Quercus ilex*, *Quercus coccifera*, *Rhamnus alaternus*, *Phillyrea media*, *Ph. angustifolia*), deciduous oak forest (*Quercus humilis*, *Buxus sempervirens*, *Ilex aquifolium*) and pine forest (*Pinus halepensis*). Shrublands (*Erica arborea*, *Rosmarinus officinalis*) are also well represented. On the lakeshore, there are helophytic communities represented by *Phragmites australis*, *Typha angustifolia*, *Lythrum salicaria* and several Cyperaceae species (Gracia et al., 2001).

2.2. Archaeological background

Located half-way along the eastern shore of Lake Banyoles, the site of La Draga (Bosch et al., 2000, 2006, 2011) provides evidence of one of the earliest farming societies in open-air settlements in NE Iberia, with an Early Neolithic occupation (7270–6750 cal. BP) (Bosch et al., 2012; Palomo et al., 2014). Despite the site occupying an area of over

8000 m2 (Bosch et al., 2000), archaeological investigations to date have concentrated on an area of ca. 3000 m^2 (of which 825.5 m^2 have been excavated, in the northern part of the settlement, where the site is best preserved). Fieldwork was undertaken in multiple seasons from 1991 to 2014. From 1991 to 2005, the excavations concentrated on Sector A, where the archaeological level is above the water table and hencewaterlogged conditions have not continued until the present.

The archaeological level is in the phreatic layer in Sector B and Sector C is totally under water. New excavations from 2010 to 2012 focused on an area of 58 m^2 called Sector D, which is located to the south of Sector B and displayed similar preservation conditions. Two different phases of early Neolithic occupation with distinctive constructive traditions have been documented; both dated within the late Cardial Neolithic according to pottery styles, and in the last three centuries of the 8th millennium cal. BP according to the radiocarbon dates. Phase I (7270–6930 cal. BP) is characterized by the collapse of wooden structures (carbonized in some points), which have been preserved in an anoxic environment. Phase II (7160–6750 cal. BP) presents several pavements of travertine stone. The levels in Phase II enjoyed less optimal conditions of preservation and the organic material is mainly found in a charred state, although some hard-coated uncharred material is found occasionally (Bosch et al., 2000, 2011; Antolín, 2013; Palomo et al., 2014).

The waterlogged context of Phase I provided excellent preservation of the bioarchaeological record, constituting by far the richest assemblage fromthe early Neolithic period in the Iberian Peninsula. The available zooarchaeological (Saña, 2011; Navarrete and Saña, 2013) and archaeobotanical (Antolín, 2013) data recovered at La Draga are indicative of small-scale, labour-intensive cultivation and small-scale herding in an intensive mixed farming strategy (Antolín et al., 2014). The fields could not have been in the immediate surroundings of the settlement, since this was founded in a subaerial swamp unsuitable for cultivation. Crop fields would have been far enough away to prevent Cerealia pollen (given its short dispersion) from reaching the peat deposits analysed (Revelles et al., 2014).

According to the species identified in the charcoal analysis, firewood was gathered in oak forests and the riparian vegetation surrounding the site. Oakwas the most frequently gathered species andwas used as fuel and timber. River bank vegetation was also frequently exploited and, in this case, both arboreal taxa and the shrub and lianoid layer were used (Piqué, 2000; Caruso-Fermé and Piqué, 2014). The impact of Neolithic communities in the surroundings of the settlement also seems to be confirmed by the increased presence in shrub taxa in the charcoal assemblage during the latter occupation phase at La Draga (Caruso-Fermé and Piqué, 2014).

Previous pollen analyses undertaken in Lake Banyoles (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015) and La Draga (Pérez-Obiol, 1994; Burjachs, 2000) showed a fall in oak values coinciding with the Neolithic settlement, mainly caused by the intensive exploitation of oak forest to obtain raw materials for the construction of dwellings (Revelles et al., 2014).

Figure 1. Map with the location of the study area in the Iberian Peninsula, the position of Banyoles in Catalonia and the location of La Draga on the eastern shore of Lake Banyoles.

3. Material and methods

3.1. Sampling

In order to obtain information on the palaeo-environment of the Early Neolithic communities that occupied La Draga, two sequences (South and West) were collected from the profiles of the site (Fig. 2) for pollen, NPP andmacrofossil analyses during an archaeological excavation in 2012. Subsampling consisted of retrieving about 2–3 1 cm thick samples per layer (see Table 1 and Fig. 2) for LOI (loss on ignition) and pollen and NPP analyses, and one 25 cm3 sample per layer formacrofossil analysis (Fig. 2). During an excavation in 2014, one new sequence (West II) was subsampled in the field, retrieving samples every 5 cm for LOI, pollen and NPP analyses.

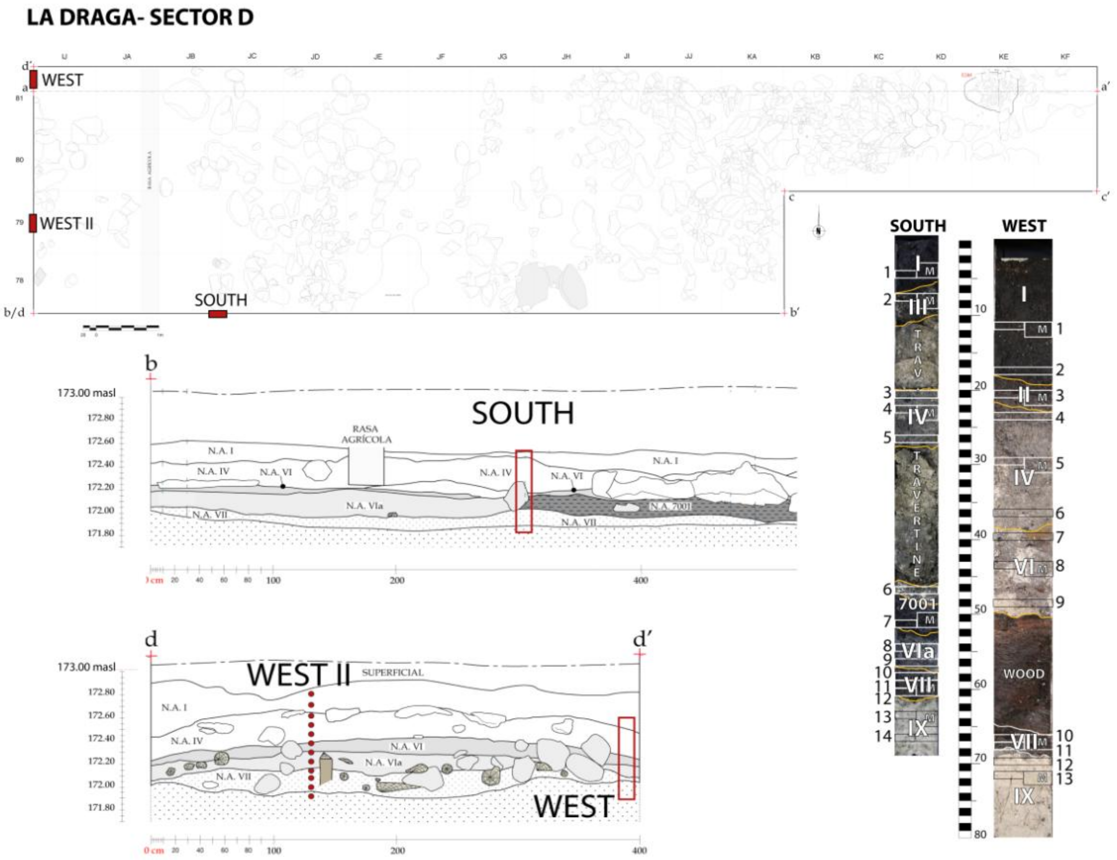

Figure 2. Plan view and cross section of Sector D at La Draga. Red rectangles in the plan view mark the spatial distribution of the three sequences analysed. In the cross section, red rectangles show columns of the West and South profiles; red points, subsamples retrieved in the field from West II profile.

Table 1. Sedimentological description of archaeological layers from the site of La Draga[2].

Phase	Layer	Description
Post-Neolithic	I	Peat, affected by modern agricultural works in some points of the site (i.e. south profile).
	II	Base of the peat layer, covering archaeological layers.
La Draga	III	Clay with abundant travertine inclusions, above travertine pavement.
2nd phase	IV	Greyish terrigenous clay among travertine stone structure.
	VI	Greyish terrigenous clay below travertine stone pavement.
La Draga	7001	Charred storage structure.
1st phase	VIa	Dark grey clay, with abundant charred particles, filling up the collapse of wooden structures.
	VII	Dark organic clay below collapse of wooden structures.
Pre-Neolithic	IX	Lake marl, natural sediments before Neolithic settlement.

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[2] A small change was done in Table 1 respect to the original paper, because structure 7001 and Layer VIa also correspond to the 1st phase.

3.2. Pollen and NPP analyses

The preparation of the samples followed standard methods (Burjachs et al., 2003) using treatment with HCL, NaOH, flotation in dense Thoulet liquor, HF and final mounting in glycerine. 300–500 pollen grains of terrestrial taxa were counted using an Olympus Bx43 microscope fitted with ×10 oculars and ×40/60 objectives. Cyperaceae, *Typha* latifolia and *Typha*/*Sparganium* have been excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Reille (1992) and Cerealia-type was defined according to themorphometric criteria of Faegri and Iversen (1989). Pollen concentration is expressed in pollen grains/gram of sediment following the volumetric method (Loublier, 1978).

Non-pollen palynomorph (NPP) identification followed van Geel (1978, 2001), van Geel et al. (2003), Gelorini et al. (2011) and Cugny (2011). Some NPP have been described for the first time and named using a code with the prefix UAB (Universitat Autònoma de Barcelona) and a sequential number (see Appendix A).

3.3. Macrofossil analysis

Samples of 25 cm3 were retrieved from every layer in two profiles (South and West), boiled in 5% KOH solution for peat digestion and sieved with a 150 μm mesh size. Then, macrofossils were transferred to a petridish and scanned using a stereoscopic microscope (10–50×). Only vegetal tissues, fungal macro-remains, bryozoans and insects have been identified, according to literature and reference collections (Mauquoy and van Geel, 2007). Seeds and fruits, charcoal and wooden remains from La Draga have already been widely analysed and published (Piqué, 2000; Bosch et al., 2006; Antolín, 2013; Caruso-Fermé and Piqué, 2014; Antolin and Jacomet, 2015; López, 2015).

3.4. Loss on ignition

Samples of 3 gwere retrieved for the application of the loss on ignition (LOI) method (Heiri et al., 2001). Firstly, samples are dried for 48 h at 60 °C. Afterwards, organic matter is oxidized for 4 h at 550 °C to carbon dioxide and ash. In a second reaction, carbon dioxide is evolved from carbonate for 4 h at 950 °C, leaving oxide. The weight loss during the reactions is measured by weighing the samples before and after heating and this weight loss is closely linked to the organic matter and carbonate content of the sediment (Bengtsson and Enell, 1986). A molecular conversion factor (weight loss at 950 °C × 2.27) was used to assess the proportion of carbonates (CaCO3) in the sediment (Dean, 1974), where 2.27 is the result of molecular weight of CaCO3 (100.088 g/mol)/molecular weight of CO3 (44.009 g/mol).

3.5. Principal component analysis

Multivariate analysis provides theoretical gradients that explain the structure behind the data. In that sense, even unknown NPP types can be classified according to their response to these gradients (Kramer et al., 2009). Firstly, the three profiles were individually analysed to explore ordination of samples (objects) considering the NPP percentages (variables) (Table 3). Afterwards, the relation between samples (variables) and NPP taxa (objects) and the integration of NPP taxa into groups of similar behaviour is shown through ordination with principal component analysis (PCA) using a variance-covariance matrix (Table 4 and Fig. 6), by Past 3.04 software (Hammer et al., 2001). The most representative layers at the site (I, IV, VI, VIa, VII) were selected for the PCA analysis. Only layers represented in marginal areas (II, III) or structures (7001) were rejected, aswell as very poor layers in abundance and diversity (IX). NPP percentages have been normalized considering the mean and standard deviation prior to ordination to reduce loading of dominant taxa.

4. Results

4.1. Pollen analysis

Samples fromthe three profiles allow the reconstruction of vegetation evolution in the moment prior, during and after the occupation of La Draga (Fig. 3). The highest values of AP (85–90%) are recorded before the establishment of farming societies on the shore of Lake Banyoles (Layer IX), when deciduous *Quercus*, *Corylus*, *Pinus* and *Abies* predominated. Other trees are recorded, although in lower values, such as Fraxinus, *Ulmus*, *Alnus* and *Quercus ilex-coccifera*. Once Neolithic communities settled at La Draga, a decrease in deciduous *Quercus* and, in general, in AP (40/55–65%) is documented. During the first occupation phase (Layer VII), the highest values of riparian trees (*Fraxinus*, *Salix*, *Ulmus*) and herbs (*Pedicularis*, Cyperaceae, *Typha-Sparganium*, Ranunculaceae) are recorded, as well as the appearance of Cerealia-type and the increase in Poaceae, Asteraceae and other ruderal herbs. After the collapse of wooden structures from the first phase (Layer VIa), a slight decrease in deciduous *Quercus* and an important increase in *Pinus* is recorded. In this layer, there is a decrease in riparian trees and Typha-Sparganium and an increase in *Vitis* and Asteraceae liguliflorae. Layers from the second occupation phase (III, IV, VI) display lower values of AP (30–45%), caused by the decrease in deciduous *Quercus*, *Corylus*, and an almost complete absence of riparian trees. On the other hand, this layer displays the highest values of Cerealia-type, Poaceae, Asteraceae and Apiaceae. After the abandonment of La Draga (Layers I and II), a slight recovery in AP is documented (35–55%), mainly caused by high values of Alnus. In these layers, the decrease in Cerealia-type, the increase in Asteraceae liguliflorae, Chenopodiaceae and very low values of Cyperaceae and *Typha-Sparganium* are are noticeable.

4.2. NPP analysis

The lacustrine sediment prior to the settlement of La Draga (Layer IX) is characterized by the scarcity of non-pollen palynomorphs, most of them appearing in very low values. In the first occupation phase (Layers VIa and VII), a wide variety of NPP is documented (Fig. 4A and B). NPP with the highest values are *Coniochaeta ligniaria* (HdV-172), *Coniochaeta xilariispora* (HdV-6), *Kretzschmaria deusta* (HdV-44), *Chaetomium* (HdV-7A), *Cercophora* type (HdV-112), UAB-4, UAB-11 and UAB-38. The presence of *Sordaria* type (HdV-55A), *Podospora* type (HdV-368), *Apiosordaria verruculosa* (HdV-169), cf. *Neurospora* (HdV-55B-2), *Glomus* and *Trichuris* sp. is also noteworthy.

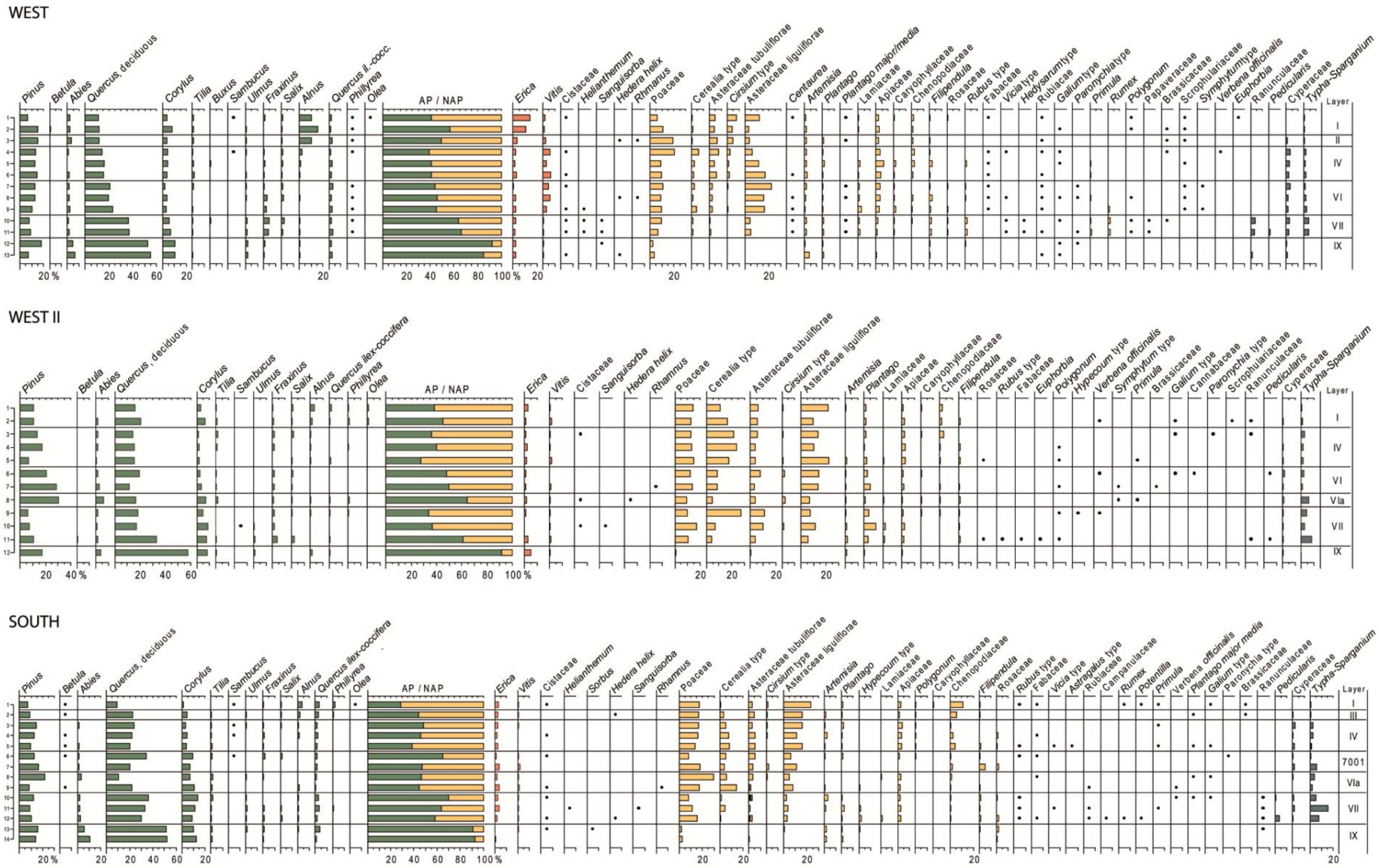
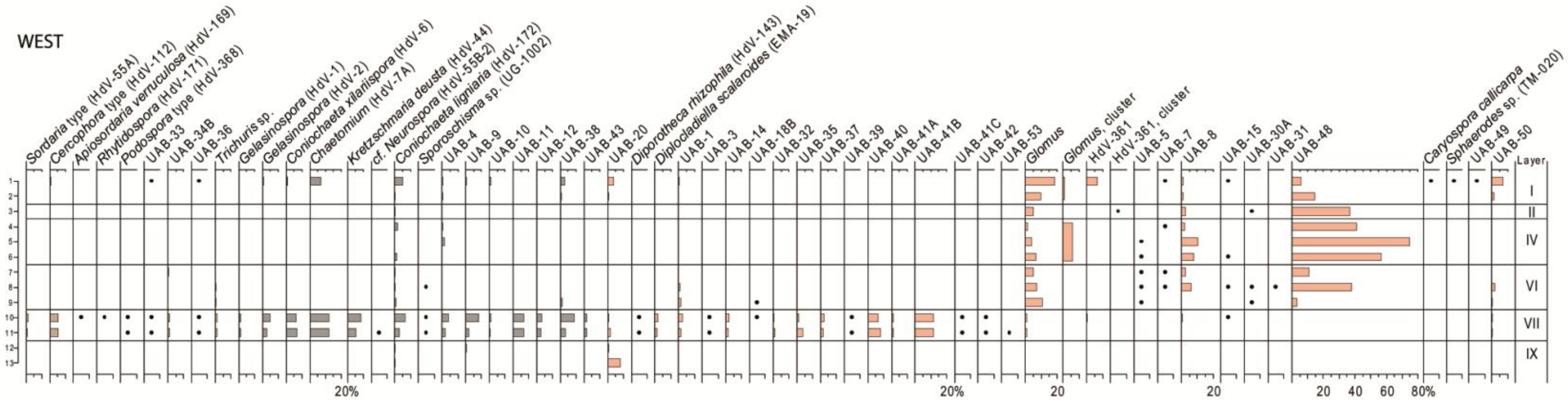
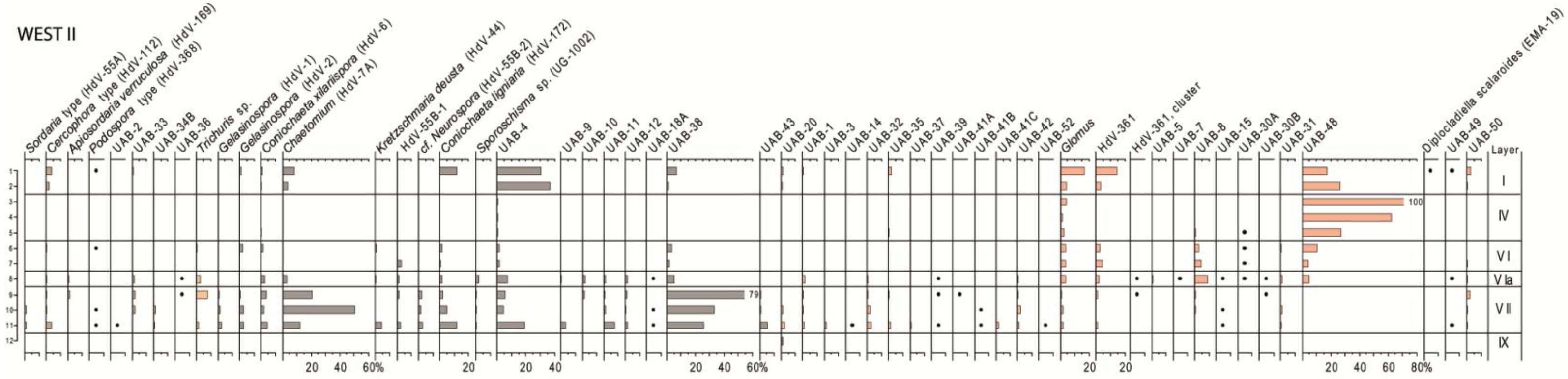


Figure 3. Percentage pollen diagram of the West, West II and South profiles. Values below 1% are represented by points.

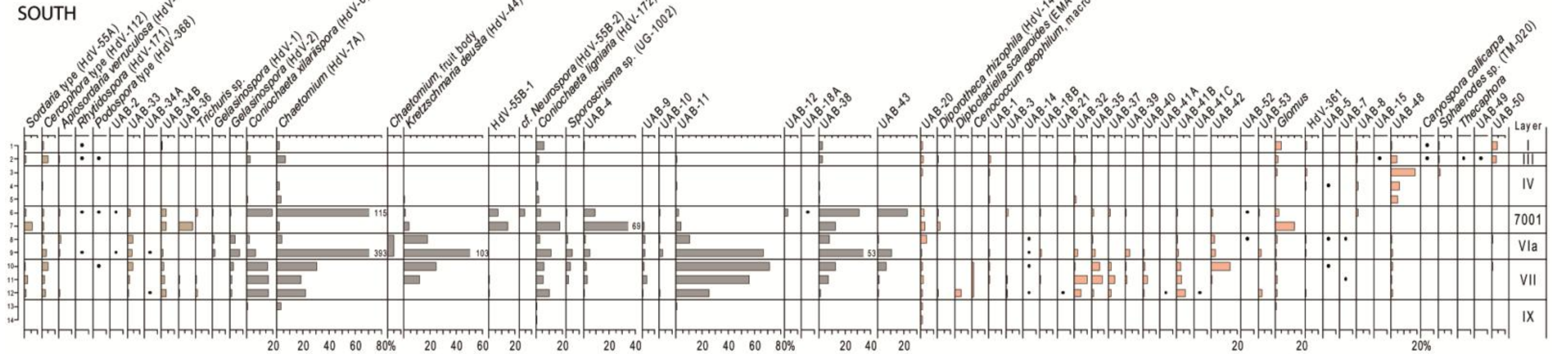
WEST



WEST II



SOUTH



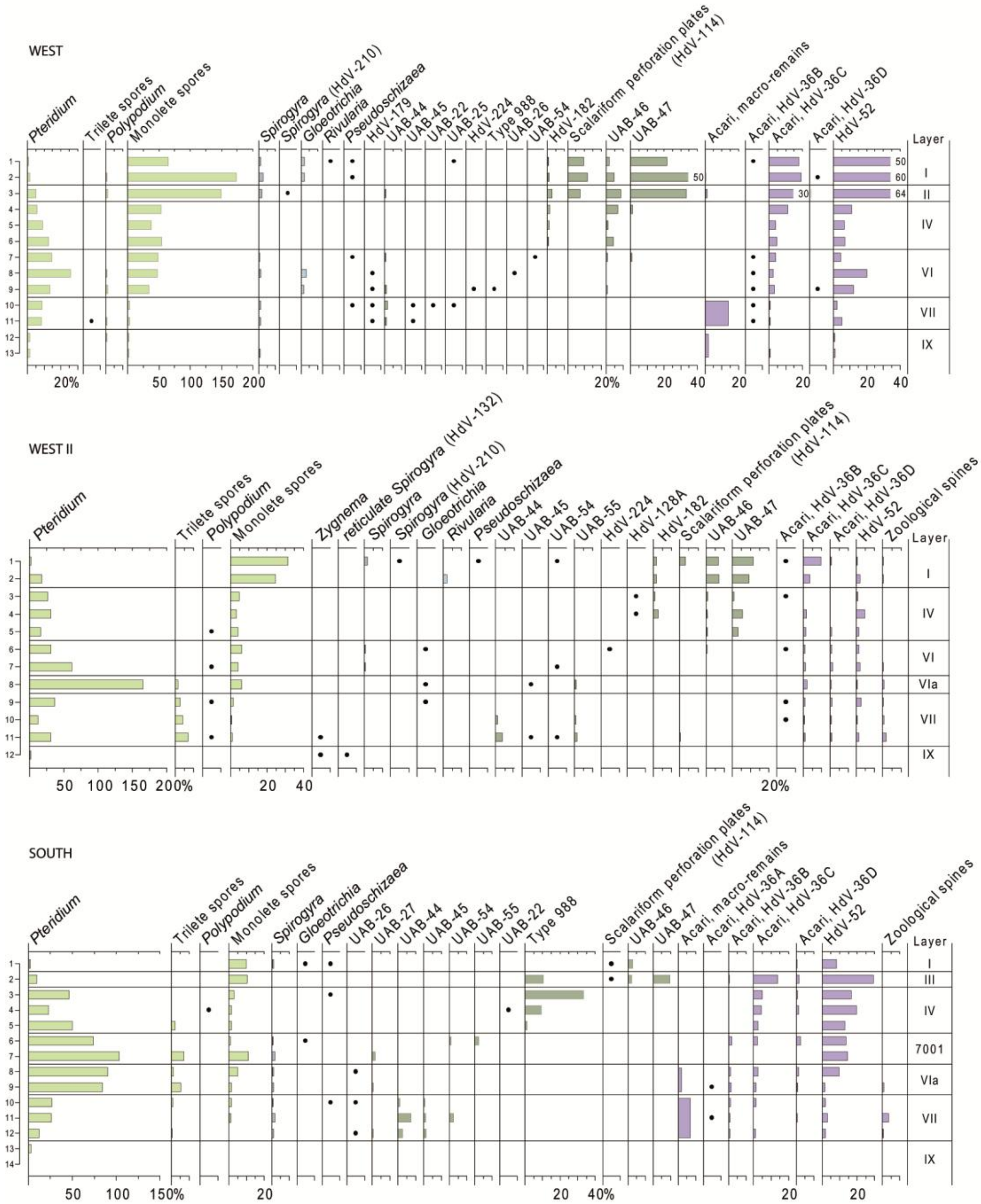


Figure 4. A. Non-pollen palynomorphs diagram. Fungal spores from the West, West II and South profiles are represented. Values below 1% are represented by points. B. Non-pollen palynomorphs diagram. Fern spores, algae, insects and unidentified remains from theWest, West II and South profiles are represented. Values below 1% are represented by points.

Two samples from the charred storage structure (7001) show high values of *Chaetomium* (HdV-7A), *Coniochaeta ligniaria* (HdV-172), *Coniochaeta xilariispora* (HdV-6) and cf. *Neurospora* (HdV-55B-2). Layers IV and VI, from the second phase, record a decrease or disappearance of most of the fungal spores documented in Layers VIa and VII. Instead, high values of *Glomus*, Acari (HdV-36C), HdV-52 and UAB-48 are recorded. In these layers the increase in monolete spores and the presence of HdV-361, HdV-182, Type 988, UAB-5, UAB-7, UAB-9 and UAB-15 is also remarkable.

Layer III, from the second phase shows high values of HdV-52, Acari (HdV-36C), Type 988 and UAB-46, 47, 48, 50, and significant values of *Cercophora* type (HdV-112), *Glomus* and UAB-38. The presence of *Podospora* type (HdV-368), *Rhytidospora* (HdV-171), *Coniochaeta ligniaria* (HdV-172), *Coniochaeta xilariispora* (HdV-6) and *Chaetomium* (HdV-7A) is also noteworthy. Post-occupation layers (I–II) are characterized by a decrease in *Pteridium* and the highest values of monolete spores in the sequence. Similarly, the highest values of *Glomus*, scalariform perforation plates (HdV-114), HdV-361 and the maximum values of UAB-46, UAB-47, UAB-49 and UAB-50 are recorded in this layer.

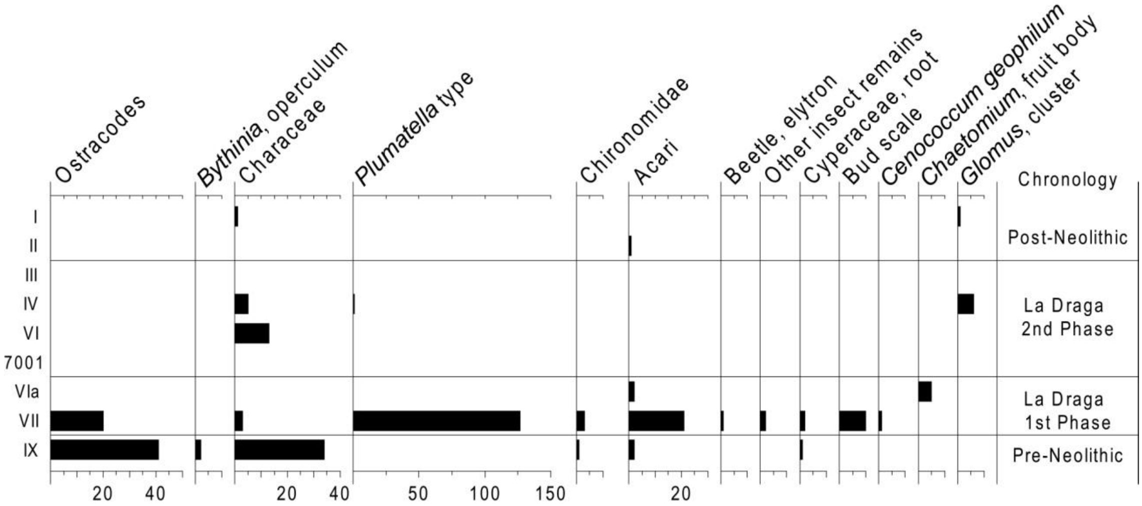


Figure 5. Macrofossil absolute frequency diagram.

Table 2. Results of loss on ignition analysis. Themean and minimum and maximum percentages of organicmatter (OM), carbonates and the residue (otherminerals) are expressed for each layer.

Layer		South			West		West II		Total		
		Min.	Max.		Min.	Max.	Min.	Max.	Mean		
I	OM	11.9	11.9		12.5	20.3	5.4	9.7		12	
	Carbonates	50.2	50.2		38.4	52.2	47.7	51.5		47.9	
	Residue	37.9	37.9		35.3	60.5	42.6	42.8		43.4	
III	OM	2.6	2.6	II	15.7	15.7			2.6		15.7
	Carbonates	83.7	83.7		23.8	23.8			83.7		23.8
	Residue	13.7	13.7		60.5	60.5			13.7		60.5
IV	OM	3.6	4.9		6.1	7.2	3.5	4		5	
	Carbonates	52	64.5		48.4	49.9	34.5	44.7		48.8	
	Residue	31.8	43.4		43	44.1	51.6	61.9		44.6	
7001	OM	5.9	23.4		6	12.7	7.2	7.8	14.7		8

	Carbonates	14.8	59.5		38.1	45.9	26.1	27.2	37		35.4
	Residue	34.6	61.9		47.8	55.6	64.8	66.6	48.25		55.3
VIa	OM	9.9	11.2				8.1	8.1		9.8	
	Carbonates	14.8	17.7				11.6	11.6		6.5	
	Residue	70.9	75.2				80.3	80.3		75.5	
VII	OM	16.2	23.4		18	31.8	8.6	12.6		17.9	
	Carbonates	26.8	55.2		27.9	29.7	19.1	35.9		32	
	Residue	28.4	48.2		38.4	54	51.4	68.2		50.2	
IX	OM	1.9	2.1		2.2	2.8	2.3	2.3		2.2	
	Carbonates	91	92.4		87.4	89	91.9	91.9		90.6	
	Residue	5.7	6.9		8.25	10.3	5.8	5.8		7.4	

4.3. Macrofossil analysis

Macro-remains recovered from the South and West profile show clear diversity variability between layers (Fig. 5). Layer VII is the richest, with Characeae, Ostracoda and Chironomidae, some insects and *Acari*, Cyperaceae roots, macro-remains of fungi (*Cenococcum geophilum*) and high values of bryozoan (*Plumatella* type). This waterlogged layer evidences the importance of lake water in its formation, as shown by coincidences with the macrofossils documented in Layer IX. Albeit in lower values, Acari and Characeae occur in many layers. Fruit bodies of *Chaetomium* in Layer VIa, linked with collapsed wooden structures, and clusters of *Glomus* in Layers I and IV are also of interest.

4.4. Loss on ignition

Organic matter and carbonate content of samples from the three pro_les were quanti_ed with the LOI technique (Table 2). Layers I, II and VII show the highest values of organic matter (means of 12, 15.7 and 17.9%), as do samples fromthe structure 7001 (14.7%). Less organic layers are III and IX, with the highest values of carbonates. Layers IV, VI and VIa also show low values of organic matter (5, 8and 9.8%), in this case influenced by the high content of other minerals (44.6, 55.3 and 75.5%) (Table 2). Carbonate presence in different layers is totally related with the calcite substrate (Layer IX) andwith the presence of travertine particles within the sediment in layers above or within the pavement (III and IV). Organic matter is higher in waterlogged layers (VII), combustion structures (7001) and in post-abandonment peat (I and II). The highest values of residual minerals are recorded in less organic layers (IV, VI, VIa), probably transported by erosive processes (E. Iriarte, personal communication).

Table 3. Results of principal component analysis. The three profiles were individually analysed to explore ordination of samples (objects) considering the NPP percentages (variables).

		West	West II	South
PC1	Eigenvalue	34.82	26.73	25.37
	Variance (%)	49.04	36.61	35.42
PC2	Eigenvalue	13.13	14.83	16.08
	Variance (%)	18.49	20.32	22.45
PC3	Eigenvalue	6.53	11.07	10.12
	Variance (%)	9.20	15.16	14.13
PC4	Eigenvalue	4.94	6.23	9.22
	Variance (%)	6.96	8.54	12.87
PC5	Eigenvalue	4.10	5.56	6.67
	Variance (%)	5.78	7.61	9.31

4.5. Principal component analysis

The PCA results show similar trends for each individualized profile (Table 3). Axis 1 (49.03% in West, 36.61% in West II, 35.42% in South) clearly divide samples from subaerial layers (I, IV, VI), in negative values, and samples fromwaterlogged layers (VIa, VII) in positive values (Fig. 6). The main component is therefore influenced by a taphonomic factor. Ordination by PCA of NPP taxa from the three profiles is shown in Table 4 and Fig. 6. As the variance values of the first and the second PCA axes reach 45.75% and 14.23%, respectively, the ordination biplot explains 59.98% of variance. Axis 1 is strongly correlatedwith taphonomic conditions in the different layers, showing positive values for the most frequent taxa in waterlogged layers, and negative values for the most frequent taxa in layers formed in subaerial conditions. The low value of Axis 2 (14.23%) does not provide a statistically meaningful result. On the one hand, there is a clear division between taxa from Layers I and IV–VI, that is, a separation between a peat layer and terrigenous clays deposited by erosive transportation of sediments. On the other hand, Layers VIa and VII, despite showing differences in composition and representing different formation processes, are not clearly separated, showing amixed group. This can be explained in terms of the high spatial variability shown by these layers (see Fig. 4A and B), probably due to differences between inside/outside spaces or to post-depositional processes. Nevertheless, three main groups of NPP can be defined: 1) NPP from waterlogged sediments associated with a high presence of charcoal and wooden remains; 2) NPP from inorganic clays from the second occupation phase; 3) NPP from subaerial peat deposits formed after the abandonment of the settlement.

Table 4. Results of principal component analysis, considering relationship between samples (variables) and NPP taxa (objects).

PC	Eigenvalue	Variance (%)
1	5.35	45.75
2	1.67	14.23
3	0.85	7.29
4	0.75	6.45
5	0.67	5.72
6	0.64	5.45
7	0.53	4.55
8	0.52	4.42
9	0.33	2.79
10	0.26	2.21
11	0.13	1.14

5. Discussion

5.1. Ecological interpretation of NPP

According to PCA analysis (Fig. 6) and interpretation of the NPP diagram (Fig. 4A and B), NPP types can be classified in 3 main groups.

The first group consists of the taxa showing maximum values or exceptional occurrence in Layers VIa and VII, that is, in samples from the first phase of occupation and the collapse of wooden structures. Both layers are beneath water level, offering exceptional preservation of organic matter (see maximum values of OM in Level VII in Table 2 and Fig. 7). In addition to wooden remains, abundant charcoal remains were recovered in these layers, associated with firewood and burnt constructions, as well as some coprolites recovered in Layer VII. This group includes maximum values of spores of coprophilous fungi (*Sordaria* type (HdV-55A), *Cercophora* type (HdV-112), *Podospora* type (HdV-368), *Apiosordaria verruculosa* (HdV-169)) (van Geel, 1978; van Geel et al., 1981, 1983; van Geel and Aptroot, 2006), parasites (*Trichuris* sp.) and spores of carbonicolous/lignicolous fungi (*Chaetomium* (HdV-7A), *Coniochaeta xylariispora* (HdV-6), *Coniochaeta ligniaria* (HdV-172), *Gelasinospora* (HdV-1 and HdV-2), *Kretzschmaria deusta* (HdV-44), cf. *Neurospora* (HdV-55B-2), *Sporoschisma* sp. (UG-1002)) (van Geel, 1976; van Geel et al., 1981, 1986, 2013; Kuhry, 1985; Garneau, 1993; Goh et al., 1997; Gelorini et al., 2011). Many new types occur within this group and may be associated with a coprophilous or carbonicolous/lignicolous origin, or simply with waterlogged organic sediments. Among these new types, according to their morphology (see Appendix A) or similarity with types described in other works (Cugny, 2011; Gelorini et al., 2011), types UAB-34A and B (similar to *Delitschia*), UAB-2, UAB-33 and UAB-36 (cf. Sordariales) can be considered as coprophilous, and types UAB-9 (similar to TM-257, cf. Coniochaetaceae), UAB-10 (cf. Coniochaetaceae) UAB-11, UAB-12 and UAB-38 (cf. Xylariaceae), as carbonicolous/lignicolous.

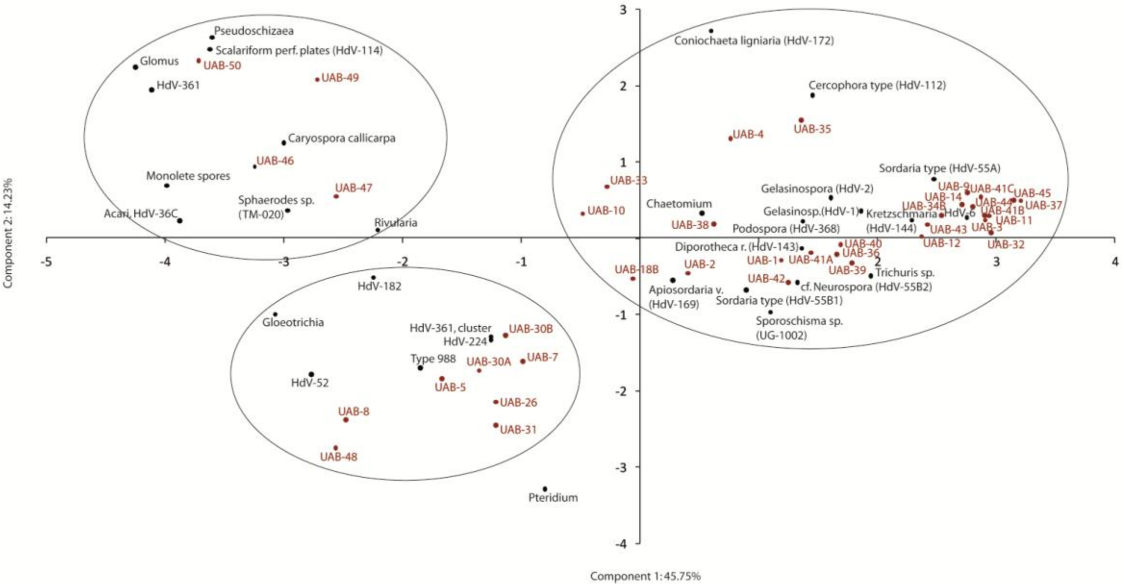


Fig. 6. Principal component analysis showing ordination of taxa. Main groups of taxa were surrounded and new types (UAB) marked in different colour.

The second group consists of the taxa with maximum values or exceptional occurrence in Layers IV and VI, that is, in samples from inorganic clayish layers (Table 2 and Fig. 7) from the second phase of occupation, where organic matter is only preserved in charred state. Furthermore, these sediments, with the highest values of residual minerals, were probably transported by erosive processes. Co-occurrence of *Gloeotrichia*, HdV-182 and Type 988 within this group may point to the existence of stagnant shallow water and progressive eutrophication (van Geel et al., 1983, 1984; Carrión and van Geel, 1999; Hillbrand et al., 2014). The presence of HdV-224, characteristic of sandy layers with plant debris (vanGeel et al., 1989), and clusters of HdV-361, typical of sandy layers deposited by human-induced erosive processes (van Geel et al., 1981), seems to reinforce the hypothesis of soil erosion affecting the formation of Layers IV and VI. Although the highest values of *Glomus*, an indicator of soil erosion (Anderson et al., 1984; López Sáez et al., 2000), are recorded in Layer I, a high concentration of clusters of *Glomus* were documented in Layer IV in the macro-remains analysis, pointing to erosive processes as the cause of the change in sedimentation dynamics in these layers. New types occurring in this group (UAB-5,

UAB-7, UAB-26, UAB-30A, UAB-30B, UAB-31, UAB-48) may be indicators of soil erosion events, stagnant shallow water or simply of inorganic clayish sediments. This is the case of Type UAB-8, similar to TM-382, which reaches high values in clayish sediments and is very rare in peat deposits (Cugny, 2011).

Finally, the third group consists of the taxa with maximum values or exceptional occurrence in Layer I, an organic peat formed after the abandonment of the settlement. The highest values in monolete spores, an indicator of openings in the forest (Dimbleby, 1957, p. 15), are probably related to human perturbation of riverbank forests. The presence of *Rivularia* indicates increased alkalinisation and concentration of oxidizable organics inwater bodies (Van Geel et al., 1983). Indicators of soil erosion are also recorded in this layer, with the highest values of *Glomus*, HdV-361 and *Pseudoschizaea* (Pantaleón Cano et al., 1996). Expansion of riparian forest detected in this layer (Fig. 3), with the highest values of *Alnus*, is reflected in presence of *Caryospora callicarpa*, known from decaying wood of different trees (van Geel and Aptroot, 2006) and with a preference for nitrogen-rich sediments (Hawksworth et al., 2010), and in the highest values of scalariform perforation plates (HdV-114), probably belonging to *Alnus*, due to a great abundance of rungs. New types showing their highest values or exclusive occurrence in this layer (UAB-46, UAB-47, UAB-49, UAB-50) may be indicators of eutrophic water and eroded subaerial peat.

5.2. Environmental conditions during the occupation of La Draga

The first farming societies settled in a humid, densely forested area, with the predominance of deciduous trees (deciduous *Quercus* and *Corylus*) and *Pinus* and *Abies* in the surrounding mountains. This is consistent with data from surrounding peat deposits, where deciduous *Quercus* and *Corylus* are dominant from *ca*. 9000 cal. BP onwards and *Abies* appears in *ca*. 7600 cal. BP (Revelles et al., 2014, 2015). Before La

Draga, there was an aquatic environment at a local level, shown by carbonate-rich sediments forming Layer IX (Table 2 and Fig. 7), high values of Characeae and Ostracoda and the presence of Chironomidae among the macro-remains (Fig. 5). Afterwards, in Layer VII, a transition fromshallowwater in a lacustrine environment to a palustrine wetland is recorded. The presence of Ostracoda, Chironomidae and Characeae points to the presence of shallow water, aswell as the occurrence of *Diporotheca rhizopila*, commonly found in eutrophic moist conditions (van Geel et al., 1986), *Sporoschisma* sp., mainly found on submerged wood in freshwater habitats (Goh et al., 1997), and high concentrations of *Plumatella* type, freshwater bryozoans that can be found in organic and pollutedwater, even in habitats polluted with livestock wastes (Rogick and Brown, 1942; Dendy, 1963; Bushnell, 1974). Bryozoan statoblasts have been used to infer the extent of macrophyte and littoral zone development in lakes (Francis, 2001), consistent in this case with the transition from the aquatic to lakeshore environment, the highest values of aquatic plants in the macro-remains analysis (Antolín, 2013) and the increase in riverbank vegetation (*Fraxinus*, *Salix*, Ulmus, *Pedicularis*, Cyperaceae, *Typha-Sparganium*, Ranunculaceae) (Fig. 3), intensively exploited to gather firewood (Piqué, 2000; Caruso-Fermé and Piqué, 2014).

Once the Neolithic communities had settled on the lakeshore, abrupt changes in vegetation are recorded, as shown by the decrease in deciduous *Quercus* and arboreal pollen in general (Fig. 3). Oak forest deforestation is consistent with previous studies from natural peat deposits, where the intensive exploitation of oak forest to obtain raw materials for the construction of dwellings is shown as the main cause for the changes to the vegetation (Revelles et al., 2014). High values of Poaceae, Asteraceae and other ruderal herbs, as well as the appearance of Cerealia-type, evidence that the clearings opened in the forest were used for crop fields that would have been small and intensively managed (Antolín, 2013; Antolín et al., 2014). Nevertheless, high values of Cerealia-type should be understood in terms of anthropic inputs rather than natural deposition coming from crop fields, due to local swampy conditions unsuitable for cultivation and the well-known short dispersion of Cerealia pollen (Heim, 1970; de Beaulieu, 1977; Diot, 1992). In the same way, the overrepresentation of other herbaceous and shrub taxa (i.e. *Vitis*, Asteraceae, Apiaceae, *Plantago*) should be understood in the context of anthropic inputs to the settlement, a phenomenon previously attested in archaeological deposits (Richard and Gery, 1993; Gauthier and Richard, 2009; Jeraj et al., 2009).

Human impact is consolidated in the second phase, as shown by a decrease in AP, deciduous *Quercus*, *Corylus* and riparian forest, and the maximum values of Cerealia-type, Poaceae, Asteraceae and Apiaceae. The decline in riverbank vegetation and high values of ferns probably point to a local deforested environment. In this context, the presence of shallow water and evidence of soil erosion indicators are related with changes in sedimentation dynamics and probably with the existence of large deforested areas.

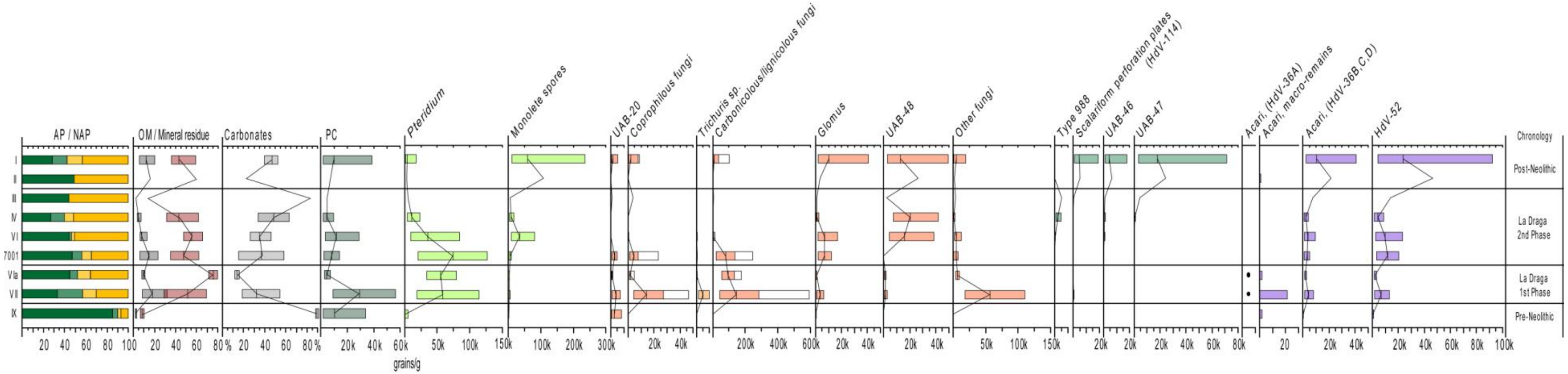


Figure 7. Diagram comparing AP/NAP ratio, LOI results, values of pollen concentration and absolute frequencies (grains, spores or particles/g of sediment) of some NPP taxa and categories. Hollow bars represent values of new types classified as having probable coprophilous or carbonicolous/lignicolous origins.

A slight increase in AP is documented after the abandonment of La Draga, mainly caused by the recovery of a riparian forest environment, with high values of *Alnus* (Fig. 3) and the presence of pollen and macro-remains of *Sambucus* (Antolín, 2013). Nevertheless, low values of Cyperaceae and *Typha-Sparganium* and the lack of waterlogged remains indicate drier local conditions in comparison with the period when the settlement of La Draga was occupied (Fig. 3). The expansion of riparian forests dominated by *Alnus* is a phenomenon also attested by natural deposits on the shore of Lake Banyoles documented from *ca*. 5500 cal. BP, due to a combination of water level regression and infilling of the shore by soil erosion events (Revelles et al., 2015), as well as to the process of migration of *Alnus*, which arrived in this area of NE Iberia in 7000–6000 cal. BP from LGM refugia in the Pyrenees (Douda et al., 2014).

5.3. Formation processes at La Draga and taphonomic evaluation of NPP remains

As mentioned before, NPP distribution is mainly influenced by taphonomic or anthropic processes rather than by natural ecological or climate dynamics. The first taphonomic process to be considered is the scarcity of non-pollen palynomorphs in Layer IX. Despite showing high values of pollen concentration (mean of 10,931 grains/g) (Fig. 7), this lake marl layer prior to the settlement of La Draga has yielded poor NPP results in terms of abundance and diversity (Fig. 4A and B). UAB-20 represents the only significant taxon in this layer, fungal spores probably related with a lacustrine environment poor in nutrients and rich in calcium (Table 2 and Fig. 7). Despite low values of fungi being consistent with this aquatic environment, absence of algae and other aquatic micro-remains may be understood in terms of taphonomy.

Sedimentation dynamics involved in the formation of this archaeological site influenced the composition of the NPP spectra, reflected in the contraposition between waterlogged and subaerial layers, but especially between organic clayish or peaty layers formed at local level and sediments transported by erosive processes. In this lakeshore area, water would have played an important role in sedimentation dynamics, as shown by the presence of aquatic organisms in many layers (Figs. 4B and 5). The exceptions are the occupation soil (Layer III), the charred storage structure (7001) and the collapse of wooden structures (Layer VIa), which formed by anthropic rather than natural processes, as shown by the absence of Characeae (Fig. 5). Regarding the waterlogged/subaerial contraposition, Acari remains are an interesting proxy to carry out a taphonomic evaluation of the different layers. As shown in Figs. 4B, 5 and 7, Acari macro-remains are concentrated in waterlogged layers (VIa, VII and IX), and fragments of Acari (HdV-36B, C and D) are overrepresented in subaerial layers (I, II, III, IV, VI), showing differential conditions of preservation of these micro-remains in these two environments.

The highest abundance and diversity of NPP is recorded in Layer VII, formed by the precipitation of organic matter in a waterlogged area as shown by the highest values of organic matter and pollen concentration (mean of 28,872 grains/g) (Fig. 7). The highest values of coprophilous fungi spores are recorded in Layer VII, corresponding to the first phase of occupation, and consistent with evidence of dung remains recovered during excavation fieldwork in Sector D (Antolín, 2013). Coprophilous fungi spores were also attested in other anthropic layers, such as the collapse of wooden structures (VIa) and the charred storage structure (7001)[3], corresponding to the first phase, and the layer above the travertine stone pavement (III) belonging to the second phase. Bearing in mind archaeozoological data (Saña, 2011; Navarrete and Saña, 2013) and the intensive farming model practiced at La Draga (Antolín et al., 2014), the evidence of coprophilous fungi spores might indicate the presence of flocks within the settlement or in the immediate surroundings.

On the other hand, presence of coprophilous fungi spores could also be due to human faeces, as shown by the presence of *Trichuris trichiura* (human parasite) at La Draga (Maicher, 2013). Some differences can be noted between layers from the first phase (VIa and VII). In terms of absolute frequencies, while carbonicolous/lignicolous fungi display similar values, coprophilous fungi are clearly dominant in Layer VII (Fig. 7). Macro-remains also show differences between these layers, pointing to the existence of a shallow eutrophic water environment in Layer VII with the presence of aquatic organisms (Ostracoda, Characeae) and Bryozoa (*Plumatella* type) (Fig. 5), the highest values of organic matter (Table 2 and Fig. 7), and higher values of riparian vegetation (Fig. 3). In contrast, Layer VIa displays an absence of aquatic organisms and lower values of organic matter. These differences were previously attested at La Draga through macro-remains analysis by Antolín (2013), where the results allowed the separation of Level VII into two sublevels (VIIa and VIIb, here VIa and VII). According to Antolín (2013, p. 275) Level VII could have formed below the dwelling spaces, as a gradual accumulation of residues of human and animal activities and Level VIa may refer to the aerial part of the dwellings. After the collapse of these pile dwellings, these two clearly different environments would have resulted in waterlogged layers differing in their sedimentological composition and macro and microremains assemblages.

The frequencies of the appearance of NPP are associated with natural and anthropic processes involved in the formation of archaeological layers. In that sense, layers belonging to the first phase of occupation (VIa and VII), characterized by the collapse of pile dwellings, concentrate the highest values of carbonicolous/lignicolous fungi spores, with the presence of *Chaetomium* fruit bodies (Fig. 5 and Plate IV). The samples from Layer 7001, a charred storage structure, are of special interest for an in-depth discussion of carbonicolous/lignicolous fungi spores, given the high values of *Chaetomium* (HdV-7A), *Coniochaeta ligniaria* (HdV-172), *Coniochaeta xilariispora* (HdV-6) and cf. *Neurospora* (HdV-55B-2). In this latter case, morphological similarity between HdV-55B-1 and cf. *Neurospora* (HdV-55B-2) should be noted (see Appendix A and Plate III); they both reach their highest values and co-occurrence in Sample 6 from the South profile, corresponding to ashes documented on top of the charred storage structure. Based on their co-occurrence, these two subtypes are thought to be the

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[3] Small modification respect to the original paper. Structure 7001 has to be considered in the 1st phase.

same species and related to a carbonicolous origin rather than coprophilous one. This structure shows high values of UAB-4, UAB-38 and UAB-43, fungal spores which may also be associated with charred substrates. (See Plates I and II.)

As regards the formation of the different layers, in inorganic clayish layers linked to erosion processes, coprophilous fungi spores are almost absent and carbonicolous/lignicolous fungi spores display low values, while many fungi that occur exclusively in Layer VII, the most organic one, disappear: UAB-37, UAB-40, UAB-41A, UAB-41B, UAB-41C, UAB-45. The occurrence of *Glomus* in these clayish layers (single chlamydospores in pollen slides and clusters, connected by mycelium, among the macro-remains) and clusters of HdV-361, as well as lower values of pollen concentration (mean of 4601 grains/g in Layer IV and 11,821 grains/g in Layer VI) and low values of organic matter (Table 2), support the hypothesis of soil erosion affecting the formation of these layers. These soil erosion processes must be understood in relationwith the deforestation started in the first phase and accentuated in the second phase (Fig. 3), a phenomenon previously attested in the analysis of natural peat deposits from the shore of Lake Banyoles (Revelles et al., 2015).

Once the settlement of La Draga was abandoned, the sedimentation changed to local organic layers, causing a recovery of organic matter values (Table 2), the formation of a subaerial peat where *Alnus* expanded, and the presence of more eutrophic water as shown by the presence of *Gloeotrichia* and *Rivularia* (van Geel et al., 1994, 1996; Hillbrand et al., 2014).

6. Conclusions

Pollen and non-pollen palynomorphs fromthe Early Neolithic settlement of La Draga have provided new palaeoenvironmental data about the establishment of the first farming societies in NE Iberian Peninsula. On the one hand, this study has contributed to the understanding of local environmental conditions in the moments prior, during and after the occupation of the settlement of La Draga, aswell as new information about the impact of these Neolithic communities at a local level. The integration of pollen, NPP, macro-remains and Loss On Ignition enabled an understanding of processes that formed this archaeological site. Human exploitation of oak forest produced large deforested areas in the vicinity of the settlement causing soil erosion processes that changed sedimentation dynamics in the second phase of occupation. This study has also accomplished one of the main aims, that is the evaluation of the ecological significance of new NPP types. According to their morphology, similarity to types described by other studies or exceptional occurrence in specific environments, some non-pollen palynomorphs were associated with coprophilous or carbonicolous/lignicolous origins and to soil erosion processes. Furthermore, this paper has demonstrated the utility of the application of NPP analysis in archaeological contexts in order to provide key data to comprehend environmental conditions, human impact and formation processes at archaeological sites.

Finally, this work reveals the need for complementary data to attain a better understanding of the context being studied. On the one hand, sedimentological and geochemical analysis to characterize the composition of sediments, in order to go beyond the data provided by LOI. On the other hand, the analysis of the spatial distribution of NPP in each layer would be of interest to acquire more information about the social management of space and to detect probable activity areas within the settlement.

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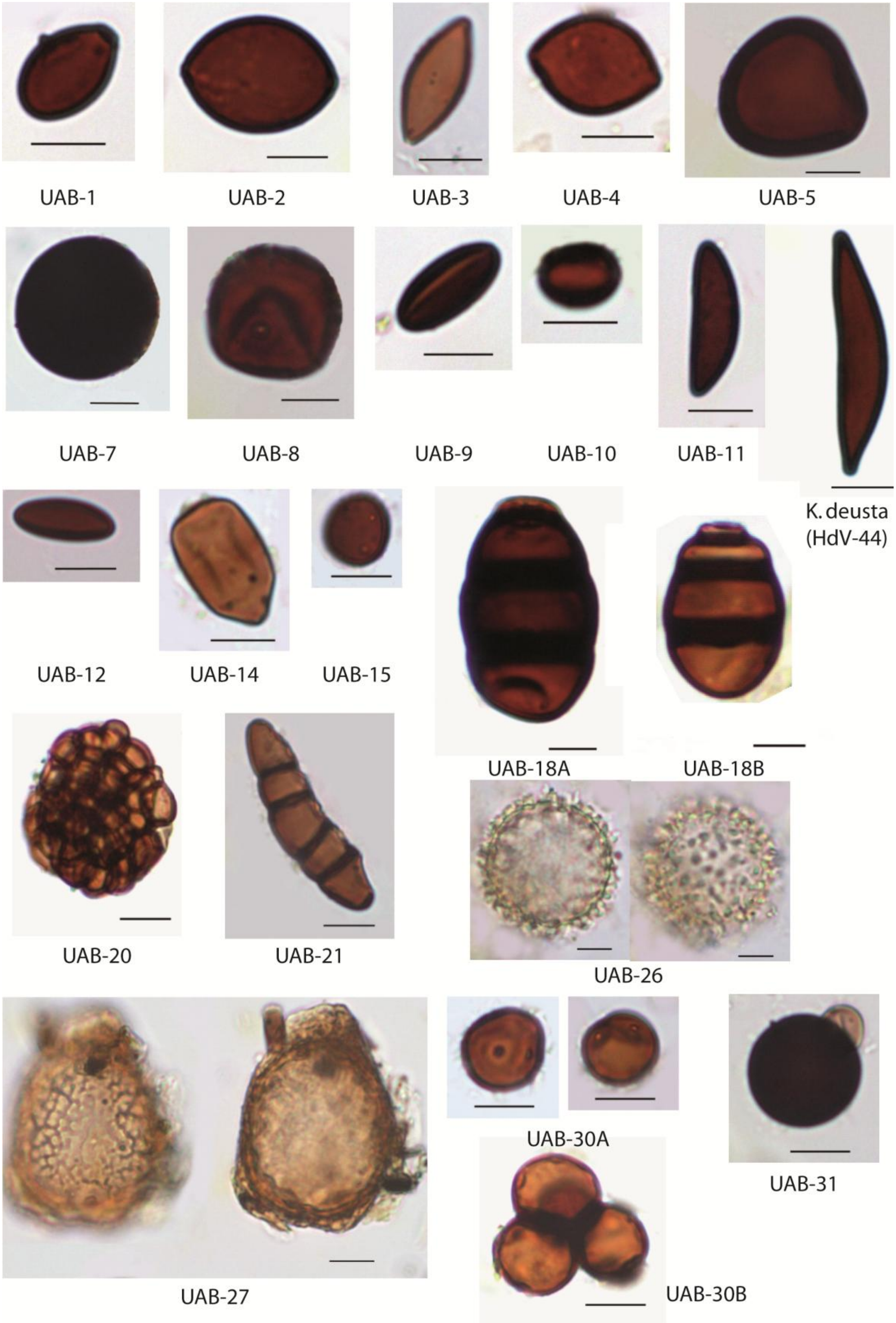


Plate I. Types UAB-1, UAB-2, UAB-3, UAB-4, UAB-5, UAB-7, UAB-8, UAB-9, UAB-10, UAB-11, *Kretzschmaria deusta* (HdV-44), UAB-12, UAB-14, UAB-15, UAB-18A, UAB-18B, UAB-20, UAB-21, UAB-26, UAB-27, UAB-30A, UAB-30B, UAB-31. All scale bars are 10 µm.

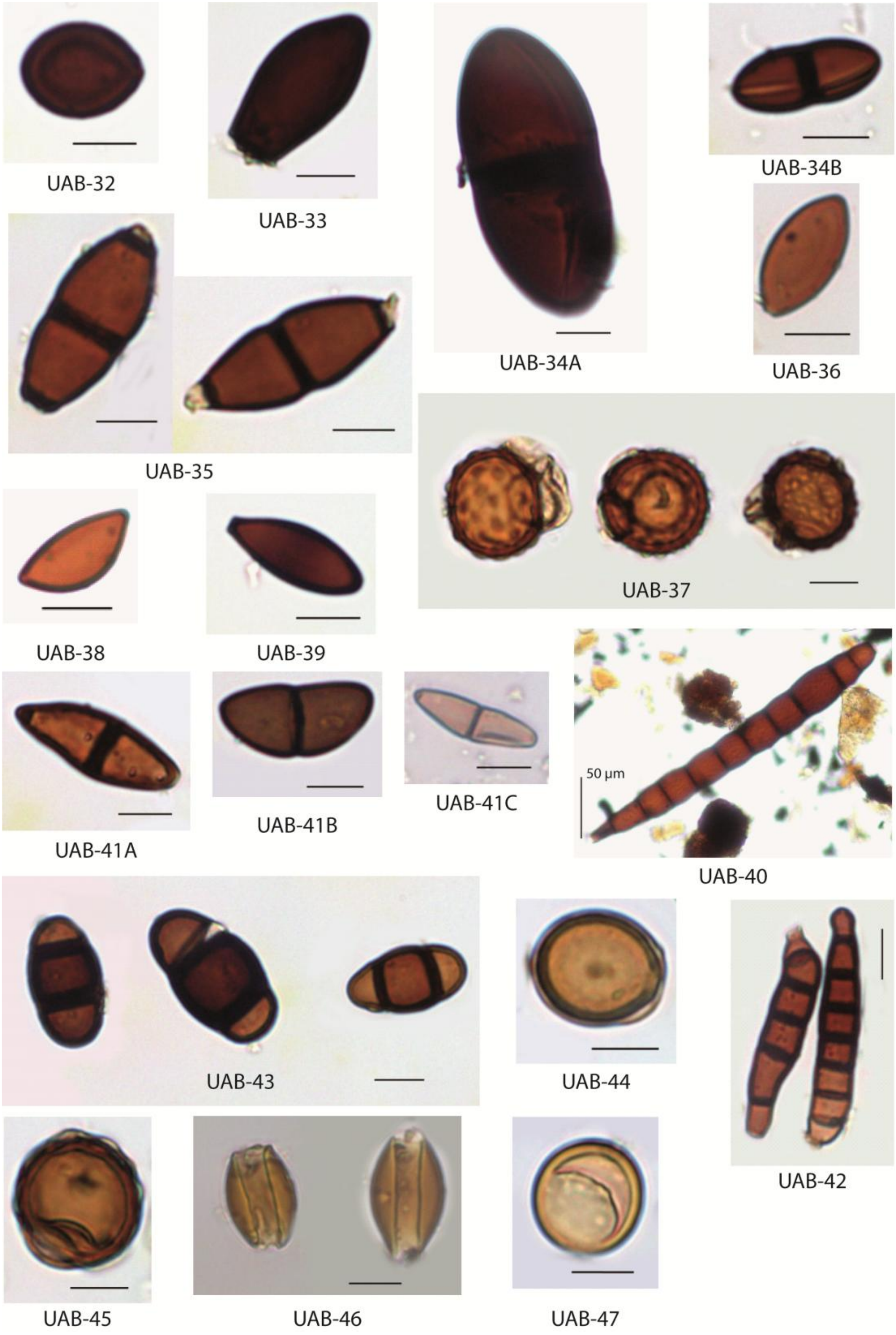
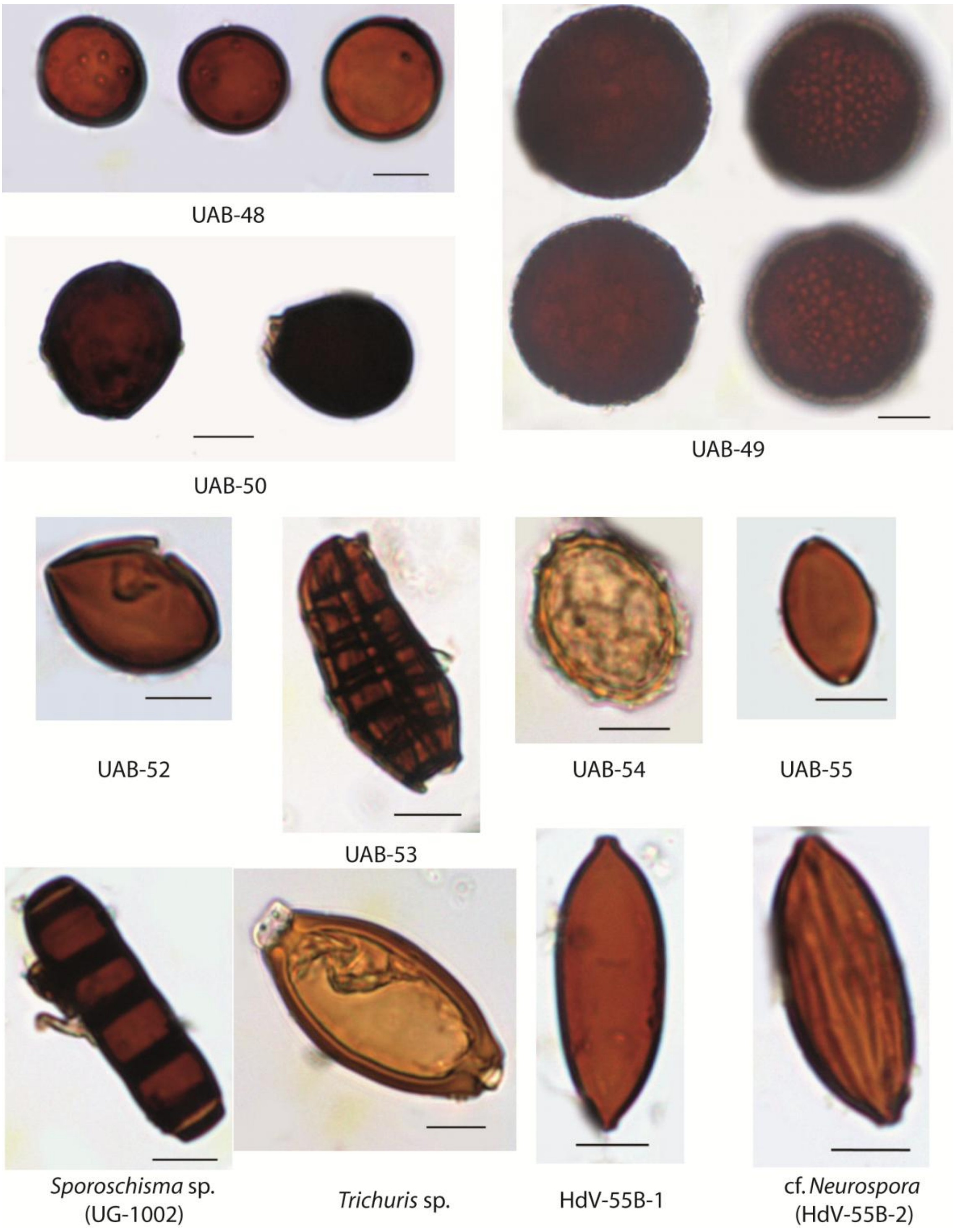


Plate II. Types UAB-32, UAB-33, UAB-34A,UAB-34B, UAB-35, UAB-36, UAB-37, UAB-38,UAB-39, UAB-40, UAB-41A, UAB-41B, UAB-41C, UAB-42, UAB-43, UAB-44, UAB-45, UAB-46, UAB-47. All scale bars are 10 µm, with the exception of 50 µm in UAB-40.


UAB-48

UAB-49

UAB-50

UAB-52

UAB-53

UAB-54

UAB-55

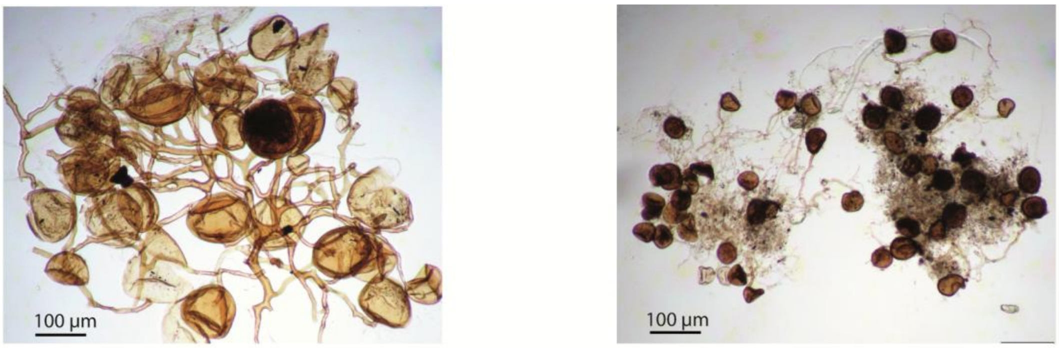
Sporoschisma sp. (UG-1002)

Trichuris sp.

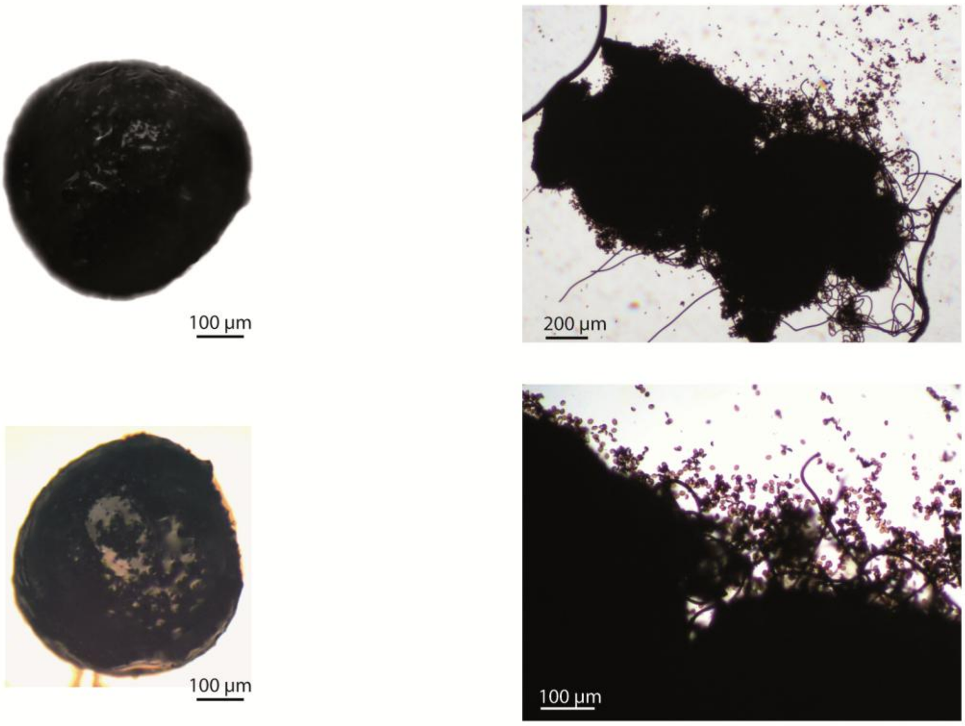
HdV-55B-1

cf. *Neurospora* (HdV-55B-2)

Plate III. Types UAB-48, UAB-49, UAB-50, UAB-52, UAB-53, UAB-54, UAB-55, *Sporoschisma* sp. (UG-1002), *Trichuris* sp., HdV-55B-1, cf. *Neurospora* (HdV-55B-2). All scale bars are 10 µm.



Glomus, cluster



Chaetomium, fruit body

Plate IV. Clusters of *Glomus* and *Chaetomium* fruit bodies.

Appendix A. Descriptions, illustrations and interpretations of new types from La Draga.

UAB-1: Fungal spore, one-celled, ovoidal, dark brown, 12.5–17.5(–20) × 7.5–12.5 µm. Rounded at one end and tappering at the other end, showing a small pore.

Occurring in many layers, highest values in the most organic layer (VII).

UAB-2: Ascospores, one-celled, ellipsoidal, brown, (25–) 27.5–35(–37.5) × (15–)17.5–22.5 µm, showing an apical pore (representative of Sordariales?).

Restricted to layers 7001, VIa and VII. Co-occurrence with highest values of spores of coprophilous fungi.

UAB-3: Ascospores, one-celled, fusiform, light brown to brown, 20–27.5 × 7.5–10 µm, showing a small pore at both ends.

Exclusively found in layers VII and 7001.

UAB-4: Ascospores, one-celled, lemon-shaped, brown to dark brown, 18.75–22.5 (–30) × 12.5 (–15) µm, showing a small pore at both ends.

Highest values in organic layers (I, VII) and in the charred storage structure (7001).

UAB-5: Fungal spores, one-celled, triangular with rounded corners, thick-walled, dark brown to black, 20–30 × 17.5–22.5 µm, showing one apical pore.

Occurring in inorganic clayish sediments (layers IV and VI), formed by soil erosion events.

UAB-7: Globular black spores, 20–30 µm in diameter, without any further visible characteristics.

Irregularly occurring in many layers.

UAB-8: Fungal spores, one-celled, globose to subglobose, dark brown, (17.5–) 20–25 (–27.5) µm in diameter. Somespores showing pores of *ca*. 2.5 µm in diameter. Similar to type TM-382, as described by Cugny (2011), showing high values in clayish sediments and being very rare in peat deposits.

Highest values in inorganic clayish sediments (layers IV and VI), formed by soil erosion events.

UAB-9: Fungal spores one-celled, ellipsoidal, dark brown. 17.5 × 7.5 µm in size, with a longitudinal light brown slit. Similar to TM-257, as described by Cugny (2011). Representative of Coniochaetaceae?

Highest values in waterlogged layers (VIa and VII), where highest values of spores of carbonicolous/lignicolous fungi were recorded.

UAB-10: Fungal spores, one-celled, globose to ellipsoidal, 7.5–10 × 5–7.5 µm, dark brownwith a longitudinal light brown zone. Representative of Coniochaetaceae?

Occurring in waterlogged layers (VIa and VII), where highest values of spores of carbonicolous/lignicolous fungi were recorded.

UAB-11: Ascospores, fusiform, 20–27.5 × 7.5 µm, light to dark brown. One side flattened and bearing a longitudinal germ slit. Similar to *Kretzschmaria deusta* (HdV-44), but shorter and without the characteristic wall thickenings at the ends. Representative of Xylariaceae?

Highest values and occurrence parallel to *Kretzschmaria deusta* (HdV-44). A carbonicolous/lignicolous origin seems probable.

UAB-12: Ascospores, ellipsoidal, 12.5–17.5 × 5–7.5 µm, brown, showing a longitudinal light brown zone (germ slit?). Representative of Xylariacecae?

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001). A carbonicolous/lignicolous origin seems probable.

UAB-14: Ascospores, one-celled, (21.25–) 22.5–25 × 10–15 µm, light brown, flattened at the basal side and rounded at the top, showing an apical pore.

Occurring in waterlogged layers (VIa and VII).

UAB-15: Fungal spores, globose-subglobose, brown to dark brown, 10–12.5 µm in diameter, with some small pores. Similar to type TM-334 (Cugny, 2011).

Irregularly occurring in many layers.

UAB-18A: Fungal spores, ellipsoid, unequally and asymmetrically 4-celled, 37.5–47.5 (–55) × 25–32.5 µm, thick-walled, slightly constricted at the septa, basal cell sub-hyaline and truncated. This Type is similar to UG-1091 (Gelorini et al., 2011), identified as *Bactrodesmium* type, found worldwide on the wood and bark of various deciduous trees (Ellis, 1971).

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001). A carbonicolous/lignicolous origin seems probable.

UAB-18B: Fungal spores, ellipsoid, unequally and asymmetrically 4-celled, brown, (26.25)30–40×(15)17.5–22.5 µm, thick-walled, constricted at the septa, basal cell subhyaline.

Irregularly occurring in many layers.

UAB-20: Globose clusters of fungal cells (each one *ca*. 7.5 µm). Pale brown to dark brown, 25–42.5 µm in diameter.

Consists of the only significant taxon in the lacustrine sediment (layer IX). Probably related to lacustrine environments poor in nutrients and rich in calcium.

UAB-21: Ascospores, inequilateral (one side almost straight), 35–42.5 × 10–12.5 µm, brown, 5-celled, slightly constricted at the septa.

Exclusively found in layer VII.

UAB-26: Globose hyaline microfossils, 25 µm in diameter, including *ca*. 2.5 µm long appendages.

Irregularly occurring in many layers.

UAB-27: Microfossils of irregular shape, 45–65 × 30–50 µm. Walls showing an irregular pattern of thicker and thinner areas, with a characteristic structure between inner and outer layer.

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001).

UAB-30A: Fungal cells, subglobose, 12.5–15 µm in diameter, light brown, showing two flattened areas at relatively short distance, each one with a central pore, and darker walls around the pores. Often occur in clusters of 4 cells (Type UAB-30B).

Occurring in inorganic clayish sediments (layers IV and VI), formedby soil erosion events.

UAB-30B: Spores consisting of 4 subglobose fungal cells, greatest diameter of the spores: 22.5 µm. These spores commonly split up in separate cells (see Type UAB-30A).

Occurring in inorganic clayish sediments (layers IV and VI), formed by soil erosion events.

UAB-31: Fungal spores, consisting of a dark-brown, large cell (17.5–25 µm in diameter) and a hyaline small cell (2.5–5 µm in diameter). Similar to Type UG-1138 (Gelorini et al., 2011).

Irregularly occurring in many layers.

UAB-32: Fungal spores, one-celled, ellipsoidal, dark brown, 17.5–22.5 × 10–17.5 µm, one rounded end; the other end showing an apical pore.

Highest values in the waterlogged organic layer (VII).

UAB-33: Ascospores, one-celled, truncated at the base, pointed at the top, showing an apical pore, 22.5–30 × 12.5–20 µm. Representative of Sordariales?

Occurring in layers 7001, VIa and VII. Co-occurrence with highest values of spores of coprophilous fungi.

UAB-34A: Ascospores, two-celled, ellipsoidal, dark brown, 52.5 × 22.5 µm, slightly constricted at the septum; each cell with a longitudinal germ slit. This type may include some *Delitschia* species (mostly coprophilous, occurring world-wide on dung; Bell, 1983).

Restricted to layers VIa and VII. Co-occurrencewith highest values of spores of coprophilous fungi.

UAB-34B: Ascospores, two-celled, ellipsoidal, brown to dark brown, 22.5–30 × 10–15 µm, slightly constricted at the septum; each cell with a longitudinal germ slit. This type may include some *Delitschia* species (mostly coprophilous, occurring worldwide on dung; Bell, 1983). Similar to Type UG-1066 (Gelorini et al., 2011).

Highest values in layers 7001, VIa and VII. Co-occurrence with highest values of spores of coprophilous fungi.

UAB-35: Ascospores, four-celled, two brown central cells and one hyaline cell at each end, 27.5–35 × 10–12.5 µm. Often, the hyaline cells are not preserved.

Highest values in the most organic layer (VII).

UAB-36: (Asco?)spores, one-celled, ellipsoidal, brown, 22.5 × 15 µm, showing an apical pore, and a slightly flattened base. Similar to type HdV-55A, but without the inside thickening of the wall around the pore.

Highest values and occurrence parallel to *Sordaria* type (HdV-55A). A coprophilous origin seems probable.

UAB-37: Fungal (?) spores, showing one globular yellow cell (22.5 µm in diameter). Two to three hyaline cells (5 × 2.5 µm) attached to the globular cell. Examples with rugulated surface, other spores showing pits. Representative of *Urocystis*? (Compare Type TM-J2 of Cugny, 2011).

Highest values in the waterlogged organic layer (VII).

UAB-38: Ascospores, one-celled, one side almost straight, the other convex, showing one pore at both ends, brown, 15–17.5(–22.5) × 7.5 (–10) µm. Representative of Xylariacecae?

Highest values in waterlogged layers (VIa and VII) and in the charred storage structure. A carbonicolous/lignicolous origin seems probable.

UAB-39: (Asco?)spores, one-celled, ellipsoidal, brown to dark brown, 17.5–22.5 × 5–7.5 µm, one end rounded, the other end flattened.

Occurring in waterlogged layers (VIa and VII).

UAB-40: Fungal spores, 7–10 septate, (147.5–)162.5–275(–345) × (27.5–)32.5–37.5(–42.5) µm (at the broadest part). Often broken off at one or both ends. Brown. Constricted at the septa. Striate pattern on the surface.

Occurring in the most organic layer (VII).

UAB-41A: Ascospores, two-celled, 35–37.5 × 10–12.5 µm, brown, thick-walled. The two cells triangular-shaped.

Occurring in the most organic layer (VII).

UAB-41B: Ascospores, two-celled, inequilateral, 25–30 × 10–12.5 µm. Brown, thin-walled, constricted at the septum.

Occurring in the most organic layer (VII).

UAB-41C: Ascospores, two-celled, 20 × 6.25 µm, brown, thin-walled, constricted at the septum.

Occurring in the most organic layer (VII).

UAB-42: Fungal spores, 6–8 septate, 45–50 × 7.5 µm. Brown cells, the proximal cell, hyaline, showing the attachment to mycelium. Often broken. Several 6–8 septate fungal sporeswith fewdistinctive characters are combined in the aggregate Type UAB-42.

Highest values in waterlogged layers (VIa and VII).

UAB-43: Fungal spores, three-celled, 25–30(–32.5) × 12.5–15 µm. One brown central cell and two pale cells. Some of the pale cells show a former connection with mycelium. The morphological variability of this type may point to several different taxa.

Occurring in waterlogged layers (VIa and VII) and highest values in the charred storage structure. A carbonicolous/lignicolous origin seems probable.

UAB-44: Fungal spore?, one-celled, 17.5–25 × 15–20 µm, ellipsoidal, yellow, surrounded by a hyaline velum. One apical pore.

Occurring in the most organic layer (VII).

UAB-45: Microfossils, globular, yellow, thick-walled, 15–22.5 µm in diameter. Showing a thin, hyaline, undulating outer wall.

Occurring in waterlogged layers (VIa and VII).

UAB-46: Microfossils, "coffee bean-shaped", yellow, 12.5–22.5 × 7.5–15 µm.

Highest values in subaerial peaty layers (I and II).

UAB-47: Microfossils, globular, yellow, 12.5–17.5 µm in diameter. Showing a characteristic "operculum-like" circle, *ca*. 10 µm in diameter.

Highest values in subaerial peaty layers (I and II).

UAB-48: Fungal spores, one-celled, globose to subglobose, orange–brown to dark brown, 17.5–20 _min diameter. Showing one to several pores, *ca*. 1 µm in diameter.

Highest values in inorganic clayish sediments (layers IV and VI), formed by soil erosion events.

UAB-49: Fungal (?) spores, one-celled, globose to subglobose, dark brown, 32.5–42.5 (–50) × 32.5–42.5 µm. Showing a dense pattern of *ca*. 2 µm wide pits all over the surface.

Irregularly occurring in many layers.

UAB-50: Fungal spores, one-celled, ellipsoidal but truncated at one end, dark brown, 17.5–22.5 × 15–20 µm. Often showing hyaline remains at the truncated end.

Highest values in subaerial peaty layers (I and II).

UAB-52: Ascospores, one-celled, brown, 27.5–32.5 × 20 µm. Ellipsoidal butwith one apical pore. Spores often showing an external hyaline wall.

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001).

UAB-53: Muriform fungal spores, 37.5–45 × 12.5–15 µm, (each cell *ca*. 5–7.5 µm), brown.

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001).

UAB-54: Microfossils, ellipsoidal, reticulate, pale orange–brown, 25–32.5 × 20–25 µm. Meshes of the reticulum *ca*. 5 µm.

Irregularly occurring in many layers.

UAB-55: Ascospores, ellipsoidal, one-celled, brown, 20–25 × 10–12.5 µm, showing an apical pore at both ends.

Occurring in waterlogged layers (VIa and VII) and in the charred storage structure (7001).

HdV-55B-1 and HdV-55B-2: Ascospores, one-celled, ellipsoidal, 32.5–37.5 × 12.5–17.5 µm, light brown, with two protruding apical pores, *ca*. 2.5 µm wide. Two subtypes occur: HdV-55B-1, which is smooth, while HdV-55B-2 shows *Neurospora*-like longitudinal grooves. Based on their co-occurrence, we considered these two subtypes to be the same species.

Highest values in sample 6 from South profile, corresponding to ashes documented on the top of the charred storage structure. A carbonicolous/lignicolous origin seems probable, as shown for *Neurospora* (HdV-55C) (van Geel, 1978).

Appendix B. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.revpalbo.2015.11.001. These data include the Google map of the most important areas described in this article.

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4.3.2. Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia).

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Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia)

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Abstract

Several taphonomic factors influence the composition of the palynological record especially in archaeological deposits, where human activities alter the representation of taxa. Spatial analysis by a taphonomic approach to the distribution of pollen and non-pollen palynomorphs (NPP) provides useful information about intra-site spaces and environments in the Early Neolithic lakeside settlement of La Draga (Banyoles, NE Iberia). The spatial correlation of algae, lakeshore and aquatic plants and herbs with an economic value, together with parasites and spores of coprophilous fungi, evidence a humid and organic environment beneath a hut, where consumption waste is concentrated. In contrast, high values of arboreal pollen (AP) and spores of fungi indicators of soil erosion show a sub-aerial environment strongly altered by taphonomic processes in outside areas. Finally, the association of the highest values in Cerealia-type and the spatial distribution of grinding stones within Sector D identifies an area of cereal processing, proving the suitability of spatial analysis in archaeopalynology as a powerful tool for reconstructing activity areas within archaeological settlements.

Keywords: archaeopalynology, geostatistics, taphonomy, lakeside settlement, Neolithic

1. Introduction

Several taphonomic factors influence the composition of the palynological record. Production, transport, sedimentation and post-depositional alteration of pollen grains are taphonomic processes specific to each pollen taxon (Coles et al., 1989; Campbell, 1999), and it is assumed that these processes can result in significant distortion of the fossil pollen spectra with respect to the original pollen rain (Lebreton et al., 2010). Lakes and bogs, where taphonomic processes are less frequent (Faegri and Iversen, 1989), are the most appropriate deposits with which to approach the original pollen rain. In contrast, various taphonomic processes occur in aerial/subaerial mineral deposits such as archaeological sites where they can deform the original deposition of pollen and non-pollen palynomoprhs (NPP). In other words, while pollen deposition in natural deposits is presumably homogenous, significant differences can be attested in pollen abundance within small areas, and this is more likely in records affected by taphonomic agents, especially in archaeological contexts.

Anthropogenic sediments from lakeside settlements cannot be regarded as an ideal archive for palaeo-environmental reconstruction given the overrepresentation of taxa introduced by humans, but they represent an essential tool to focus on socio-historical research questions (Doppler et al., 2010). The application of palynological analyses in archaeological deposits is able to obtain evidence of socioeconomic practices, in terms of documenting crops, gathered plants, stabling of flocks, exploitation of forests etc. In addition, the integration of archaeopalynological and spatial analyses allows the reconstruction of the dynamics of formation of the archaeological record and provides crucial information to assess the use of space within the settlement. The comparison with spatial distribution of archaeological remains and parasites helminth eggs can provide relevant information to comprehend the use of space in terms of management of waste and residues.

The application of geostatistic methods in archaeology has recently been evidenced as an essential tool for reconstructing social activities in the past (Rondelli et al., 2014; Achino, 2016; Negre et al., 2016).This type of integrated analysis is extremely valuable and necessary in open-air pile dwelling sites, where the reconstruction of domestic structures and spaces is hard. In this study, an intra-site spatial analysis of pollen and NPP has been carried out in order to obtain a better understanding of the use of space at the site of La Draga (Banyoles, NE Iberia).

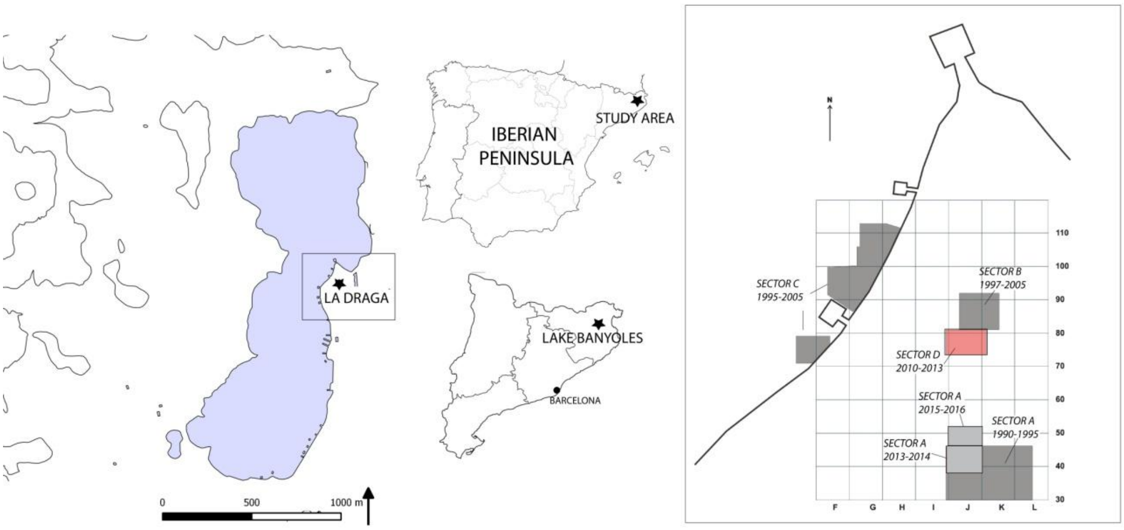

Figure 1. Location of the site (left) and location of Sector D within the site of La Draga (right)

La Draga is located in the eastern shore of Lake Banyoles (173 m asl) (Girona, NE Spain) (Fig. 1). The site has yielded evidence of one of the earliest farming societies in open-air settlements in NE Iberia, dated to 7270-6750 cal BP (Palomo *et al.* 2014). Two different construction phases during the early Neolithic occupation have been documented: Phase I (7270–6930 cal BP) is characterized by the collapse of wooden structures, which have been preserved in an anoxic environment; Phase II (7160–6750 cal BP) displays several pavements of travertine stone. Phase I at La Draga is characterised by a palimpsest of wooden remains, where it is difficult to define the shape and location of huts and structures. The huts would have been built on stilts and platforms above the water, but their coexistence together with land constructions in the areas presenting a higher topography, as attested in other European regions (Leuzinger, 2000; Menotti, 2001), is a possibility. Seven different assemblages of architectonical wooden elements were defined in the westernmost part of Sector D according to the differential distribution and morphology of wooden remains (vertical posts and horizontal boards) (López-Bultó, 2015). In this article we will focus on describe four of them (Fig. 3), as the other do not have a special relevance respecting with the sampled area for palynological analysis. From West to East, Assemblage A consists of a 3 m board fitted in a vertical post in the north-west area of Sector D, remarkable for the scarcity of archaeological remains recovered in it. Assemblage B consists of three large horizontal boards fitted together to make a rectangle, getting in the northern profile in the north-east of the sampled sector. Assemblage C consists of a concentration of horizontal boards with distinct morphological and anatomical characteristics in the eastern part of the sampled area. Finally, Assemblage D is formed by an alignment of vertical posts also bearing different morphological and anatomical features, related to the horizontally fitted boards in Assemblage B. In Assemblages B and D, previous spatial analysis showed a significant concentration of archaeological remains (Morera, 2016).

In this context, the oldest phase (I) sediments (Level VII) would have formed in exterior areas, between constructions and beneath the huts, in a wetland environment at least seasonally puddled. The extent of permanent waterlogged areas in the settlement would have conditioned the differential preservation of pollen and NPP and, for that reason, a taphonomic approach can provide useful information about intra-site spaces and environments. A diachronic palaeo-environmental reconstruction of this Neolithic settlement has been published (Revelles et al., 2016); therefore, the present study mainly focuses on the spatial distribution and taphonomic aspects.

Thus, the main objectives of this paper are:

- to develop a taphonomic evaluation of the formation of an archaeopalynological record.
- to assess if the varying taphonomic conditions observed in the archaeopalynological record are related to the human use of space.
- to prove the suitability and interest of spatial analysis in archaeopalynology.
- and lastly, to provide new data for a more precise knowledge of the use of the space at La Draga settlement.

2. Material and Methods

2.1. Sampling

The sampling strategy consisted of retrieving sediment samples from Level VII in Sector D (see Fig. 2), 1 cm^3 for Loss on Ignition (LOI), 3 cm^3 for pollen and NPP and 5 cm^3 for macrofossil identification. For paleoparasitological analysis, samples of 10 to 50 g of sediment were collected and sent to the Chrono-environment laboratory (Besançon, France). Sector D, consisting of a surface area of 58 m^2, 20 m from the lake shore, was excavated from 2010 until 2013, although samples for pollen and NPP analyses were collected in the 2012 and 2013 seasons. For that reason, only the western part of Sector D (32 m^2) has been analysed. Level VII consists of dark organic clay preserved in anoxic conditions and formed during the oldest phase of occupation in La Draga (7270–6930 cal BP). Coordinates were attributed to each sample according to the centroid in a one square-metre grid.

2.2. *Pollen and NPP analysis*

The preparation of the samples followed standard methods (Burjachs et al., 2003) and 400–500 pollen grains of terrestrial taxa were counted using an Olympus BX43 microscope fitted with ×10 oculars and ×40/60 objectives. Cyperaceae, *Typha latifolia* and *Typha/Sparganium* have been excluded from the pollen sum to avoid overrepresentation by local lakeshore taxa. All pollen types are defined according to Reille (1992) and Cerealia-type was defined according to the morphometric criteria of Faegri and Iversen (1989). Non-pollen palynomorph (NPP) identification followed van Geel (1978, 2001), van Geel et al. (2003), and Revelles et al. (2016). Pollen concentration (PC) is expressed in pollen grains/cm^3 of sediment following the volumetric method (Loublier, 1978).

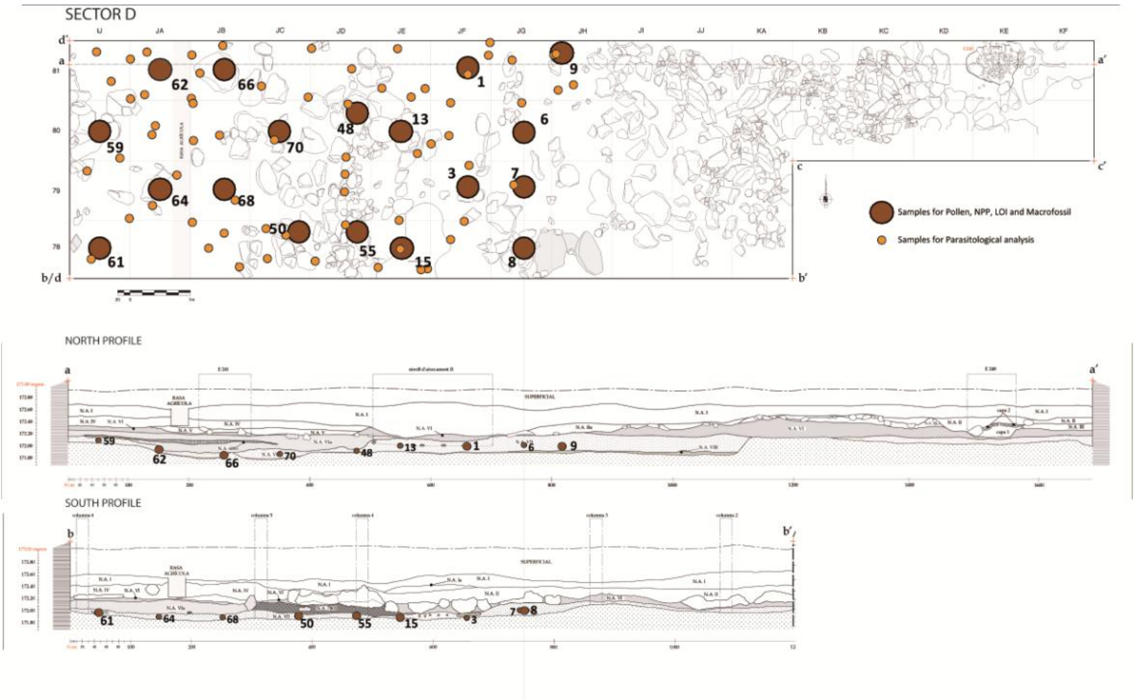

Figure 2. Plan view, cross section and location of samples (pollen, NPP, Macrofossils and LOI in brown; parasitological analysis in orange).

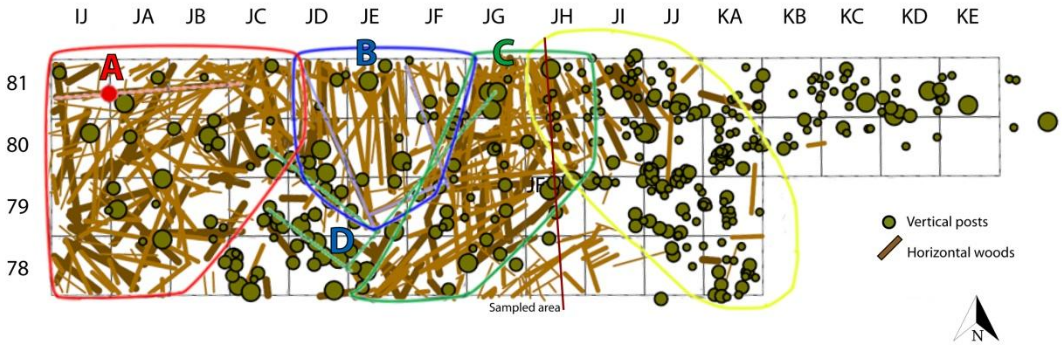

Figure 3. Architectural wooden assemblages in the 1st phase at La Draga based on the distribution of horizontal boards and vertical posts.

2.3. Macrofossil identification

5 cm^3 samples were boiled in 5% KOH solution for peat digestion andsieved with a 150 µm mesh size. Then, macrofossils were transferred to a petridish and scanned using a stereoscopic microscope (10–50×). Seeds and fruits, vegetal tissues, fungal macro-remains, bryozoans and insects have been identified, according to literature and reference collections (Cappers et al., 2006; Mauquoy and van Geel, 2007). Charcoal and wooden remains were not identified because they have already been widely analysed and published (Piqué, 2000; Caruso-Fermé and Piqué, 2014; López-Bultó, 2015).

2.4. Loss on Ignition

Samples of 1cm^3 were retrieved for the application of the loss on ignition (LOI) method (Heiri et al., 2001). Firstly, samples are dried for 48 h at 60 °C. Afterwards, organic matter is oxidized for 4 h at 550 °C to carbon dioxide and ash. In a second reaction, carbon dioxide is evolved from carbonate for 4 h at 950 °C, leaving oxide. The weight loss during there actions is measured by weighing the samples before and after heating and this weight loss is closely linked to the organic matter and carbonate content of the sediment (Bengtsson and Enell, 1986). A molecular conversion factor (weight loss at 950 °C × 2.27) was used to assess the proportion of carbonates (CaCO^3) in the sediment (Dean,1974), where 2.27 is the result of molecular weight of CaCO^3 (100.088 g/mol)/molecular weight of CO^3 (44.009 g/mol).

2.5. Parasitological analysis

A total of 72 samples were extracted for the paleoparasitological analysis (Fig. 2). The extraction of helminth eggs was performed using the standardized RHM (Rehydration-Homogenization-Microsieving) method (Dufour and Le Bailly, 2013). All the samples were firstly placed in a solution of glycerol (5%) and trisodic-phosphate (0.5%) for one week corresponding to the rehydration step. During the homogenization step, the samples were crushed in a mortar and submitted to ultrasounds (50-60Hz) for one minute. Finally, samples were filtered through a column of four sieves with decreasing mesh size (315 µm, 160 µm, 50 µm and 25 µm). Solely the remains retrieved from the 50 µm and 25 µm sieves were transferred to PVC tubes and stored. For the analysis ten slides of each fraction were examined under a light microscope (Leica DM-2000 LED) associated with a digital camera (Leica ICC50-HD). All parasitological residues were counted.

2.6. ***Numerical analysis***

2.6.1. Univariant statistics

A selection of 94 variables was chosen for the analysis. The criteria used to make the selection was based on the consideration of how much information the different taxa might provide; in that sense, the most informative were chosen while the rare and scarce taxa were omitted. All taxa selected were submitted, first of all, to a set of tests in order to characterise each spatial pattern of the microfossils' distribution. In this regard, the variables under study were submitted to Poisson, Geometric, Negative Binomial and Exponential theoretical models of distribution in order to visualize their corresponding adjustment. The significance of the first theoretical model has to be related to a random distribution while the others are indicators of the existence of intentionality in their distribution. The software used for all these tests was Systat v.13.

Moran's I was applied – to 5 nearest neighbours – to quantify the magnitude, extent and intensity of spatial autocorrelation. Varying from -1 to 1 and expressing, in the former case, negative autocorrelation and in the latter, positive correlation; an expected value close to zero indicates the absence of spatial autocorrelation. Local indicator of spatial association (LISA) was also applied to identify similar or dissimilar values of autocorrelation in the spatial pattern. The software used in both cases was SpaceStat4.

Mapping techniques were also applied in order to visualize the most probable distribution of the different taxa analysed in the space. The procedure used was the performance of an interpolation for each variable by the application of the Kriging algorithm. All spatial interpolations elaborated were automatically adjusted to the theoretical models of a Gaussian or an Exponential, considering the optimal models to fit the variogram to the data analysed. The software used was RockWorks17.

2.6.2. Multivariant statistics

The purpose of the analysis comes out of the need to interrelate the different variables to characterise the uses given to the space. With this aim, a two-step procedure is involved: running a Correspondence Analysis using the algorithm "Detrended" (DCA) in order to avoid distortion in ordination and overemphasis of rare taxa (Achino, 2016); and the creation of interpolations of the row scores obtained in the DCA for Axis 1 and 2 on the *x*, *y* coordinates so as to localise the particular cells with statistically significant discriminant values (Achino, 2016). For these interpolations the algorithm used was Inverse Distance Weighting (IDW) and the software was Past v. 3.12.

It should be mentioned that a selection of variables (N24) was carried out before applying DCA. The criteria used to choose the variables focused on those variables that showed a significant spatial autocorrelation at Ii Local Moran, as well as those taxa that might have had anthropogenic significance (monolete spores).

Finally, correlation analysis was performed for the whole database (18 rows-samples/216 columns-variables) to determine the strength and significance of the relationships between variables. A p value <0.05 in Spearman's rs is indicative of strong evidence of correlation while its positive or negative nature is indicative of the type of correlation.

3. Results

3.1. Pollen and NPP analysis

Pollen analysis from Level VII in Sector D at La Draga shows the dominance of oak forests and the importance of *Pinus*, as well as the presence of *Abies* and *Quercus ilex-coccifera* on a regional scale, and the existence of a nearby riparian forest with *Salix* and *Fraxinus* as the predominant trees (Fig.4). The settlement would have been surrounded by a quite open landscape (values of 51-76% in AP). In general, most of the taxa shows heterogeneity in their frequencies in different samples (i.e. *Pinus*: 10.9-39.4%; Cerealia-t: 0.3-8.6%; *Pteridium*: 2.8-160.5%). The analysed samples provided a high pollen concentration (between 15585 and 76000 pollen grains/cm^3), diverse richness (23 taxa in the poorest sample and 48 in the richest) and low values of undeterminable (corroded, deteriorated, broken) pollen (between 3 and 29%).

Fungal spores dominate the NPP record, both in quantitative and qualitative terms (67 taxa), and display differential representation between samples (i.e. *Chaetomium* (HdV-7A): 0-568%; *Cercophora*-t (HdV-112): 0-41.15%; *Coniochaeta* cf. *ligniaria* (HdV-172): 0.4-79.7%) (Fig.5). Fern spores (Monolete spores, *Pteridium*, *Polypodium*, *Ophioglossum*), Cyanobacteria (*Gloeotrichia*), Freshwater algae (*Spirogyra*, *Mougeotia*, *Zygnema*-t), vegetal tissues (Cyperaceae root cells, Poaceae epidermis, charred monocot epidermis) and parasites (*Trichuris* sp.) were also identified.

3.2. Macrofossil analysis

The macrofossil analysis provided different kinds of remains: fungi and fruit bodies, insect remains, bryozoa, molluscs, algae oogonia and plant seeds and fruits (Fig.6). Although the sampling resolution (samples of 5cm^3) is not optimal for statistically reliable carpological analysis, according to Antolín (2013), it provided interesting accumulations of some macrofossils. For this reason only *Cenococcum geophilum*, *Acari* and *Plumatella*-t were included in the numerical analysis to evaluate their spatial distribution.

3.3. Loss on Ignition (LOI)

The LOI analysis was able to characterise the sedimentological composition of Level VII. This level is formed by an important component of organic matter (mean of 12.14%), above all in the north-eastern part of the sampled area (19-23%), while the south-western area of the sector is quite inorganic (4.9-6.9%). $CaCO_3$ content is quite homogeneous in the sector (between 11.7-27.9%; mean of 24%), with extreme values in Samples 8 and 68 (59.2 and 45.4%, respectively). The content of other minerals is the main component of Level VII sediments in most part of the samples (58.2-81.4% mean of 63.9%) (Table 1).

Sample	OM	CaCO3	Other mineral
01	22,03	16,44	61,53
03	16,21	23,54	60,25
06	19,36	17,17	63,47
07	8,37	27,92	63,71
08	8,89	59,25	31,86
09	14,8	24,99	60,21
13	23,05	16,62	60,33
15	14,92	26,87	58,21
48	10,08	27,00	62,92
50	6,9	11,71	81,39
55	13,58	18,24	68,18
59	7,44	21,01	71,55
61	12,10	13,74	74,16
62	11,57	26,45	61,98
64	4,91	16,33	78,76
66	11,94	11,9	76,16
68	5,53	45,44	49,03
70	6,8	27,3	65,9

Table 1. Results of Loss on Ignition analysis

3.4. Parasitological analysis

Nine taxa were retrieved during paleoparasitological analysis of the Level VII samples. 93% of the samples tested positive for at least one parasite taxa (Maicher et al., submitted) (Table 2). The major taxa, i.e. the human whipworm (*Trichuris trichiura*), represents 75.43% of the residues. Then comes the roundworm (genus *Ascaris*), representing 16.69%. Both are geohelminths and indicate an oral/faecal way of contamination. They are related to bad management of faecal waste and poor hygiene conditions. The other seven taxa of parasites, representing less than 10% of the residues

(Table 2) are related to diet habits, way of life and also hygiene. Most of the parasite residues, especially those of *Trichuris trichiura* and *Ascaris* sp., are concentrated in the eastern part of the sector D, in squares JE/JF-78/79/80/81.

Taxa	Nb Eggs (total)	%
Taenia saginata	47	2.29
Diphyllobothrium sp.	14	0.68
Trichuris trichiura	1550	75.43
Ascaris sp.	343	16.69
Capillaria sp.	21	1.02
Paramphistomum sp.	24	1.17
Macracanthorhynchus sp.	56	2.73

Table 2. Results of parasitological analysis

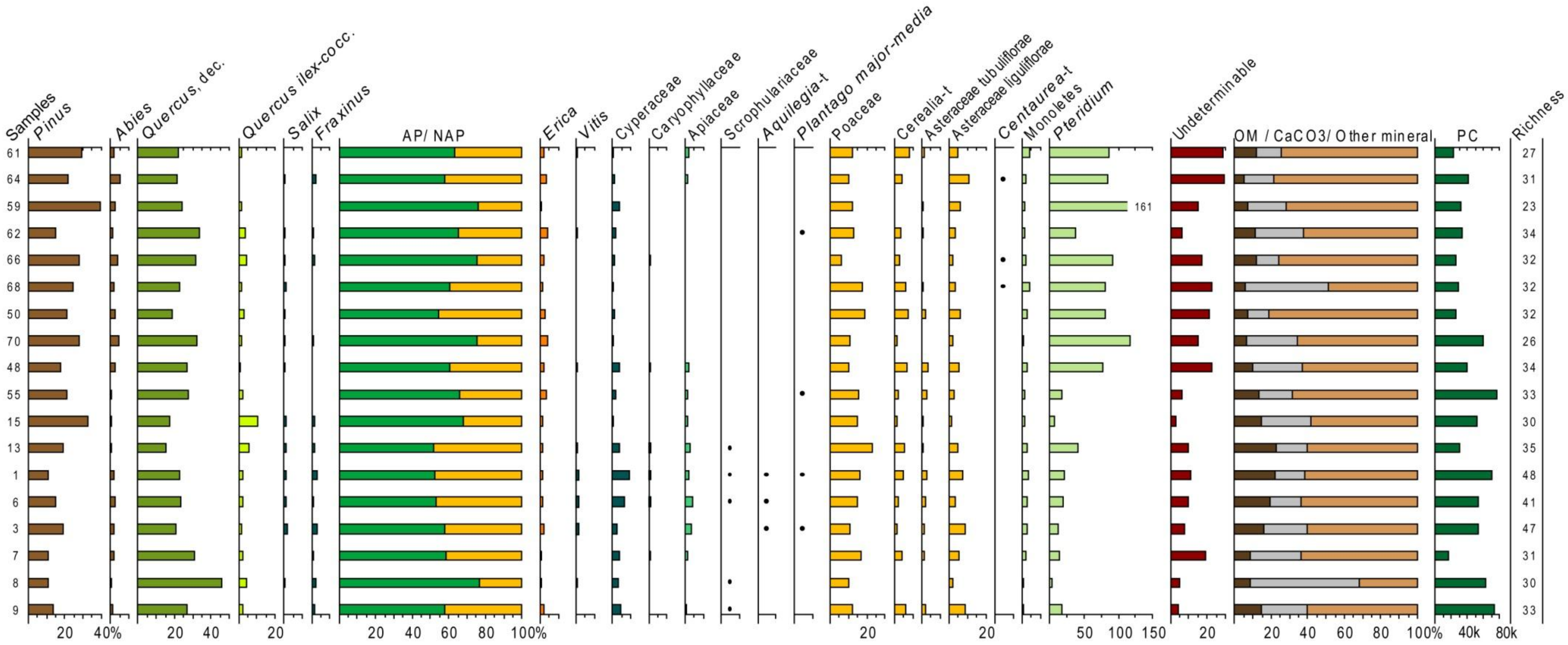

Figure 4. Percentage pollen diagram of samples from Level VII in Sector D. Values <1% are represented by dots. Pollen concentration is expressed in pollen grains/cm^3.

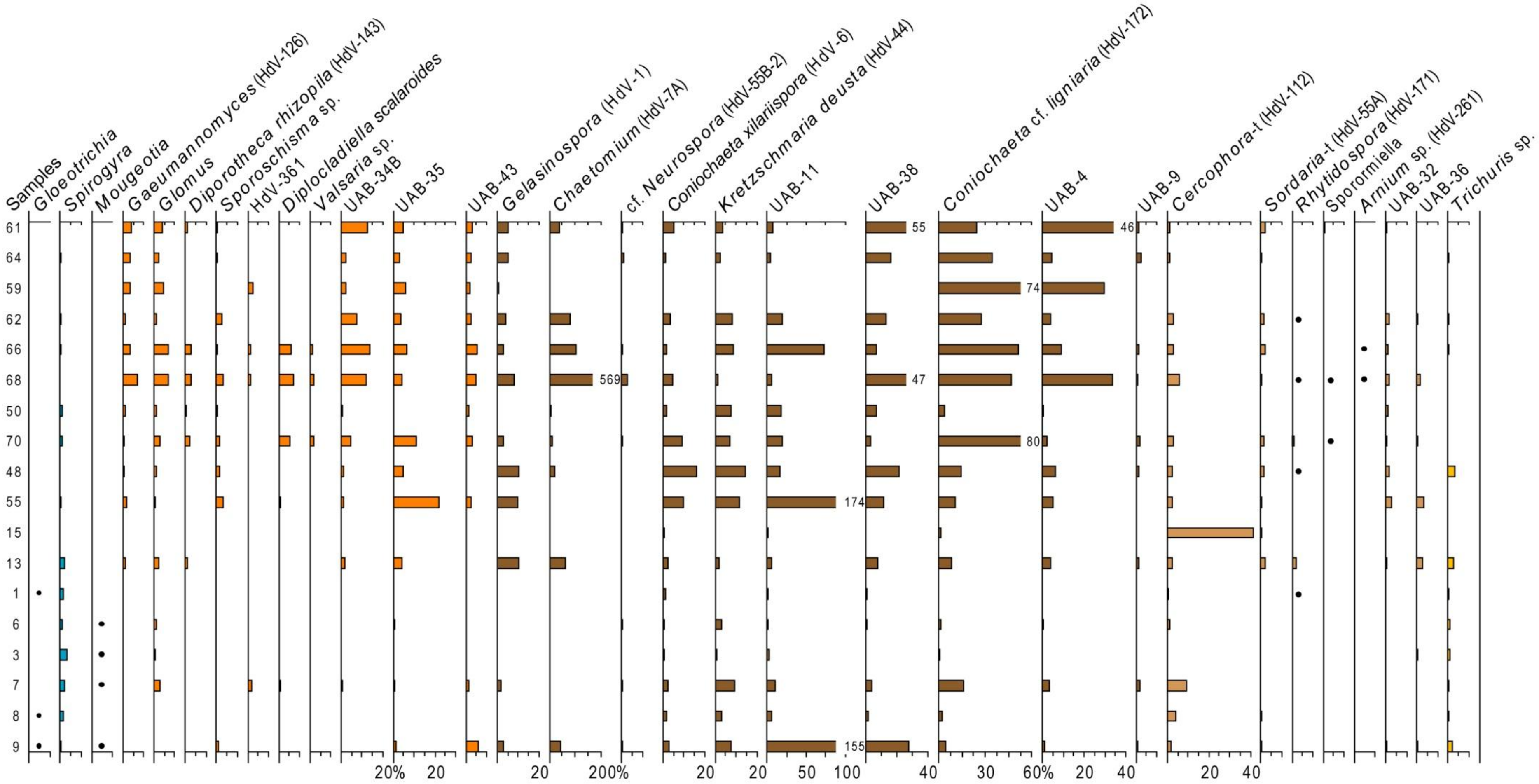

Figure 5. Percentage NPP diagram of samples from Level VII in Sector D. Values <1% are represented by dots. Algae in blue, fungi soil-erosion indicators in orange, carbonicolous-lignicolous fungi in dark brown, coprophilous fungi in light brown.

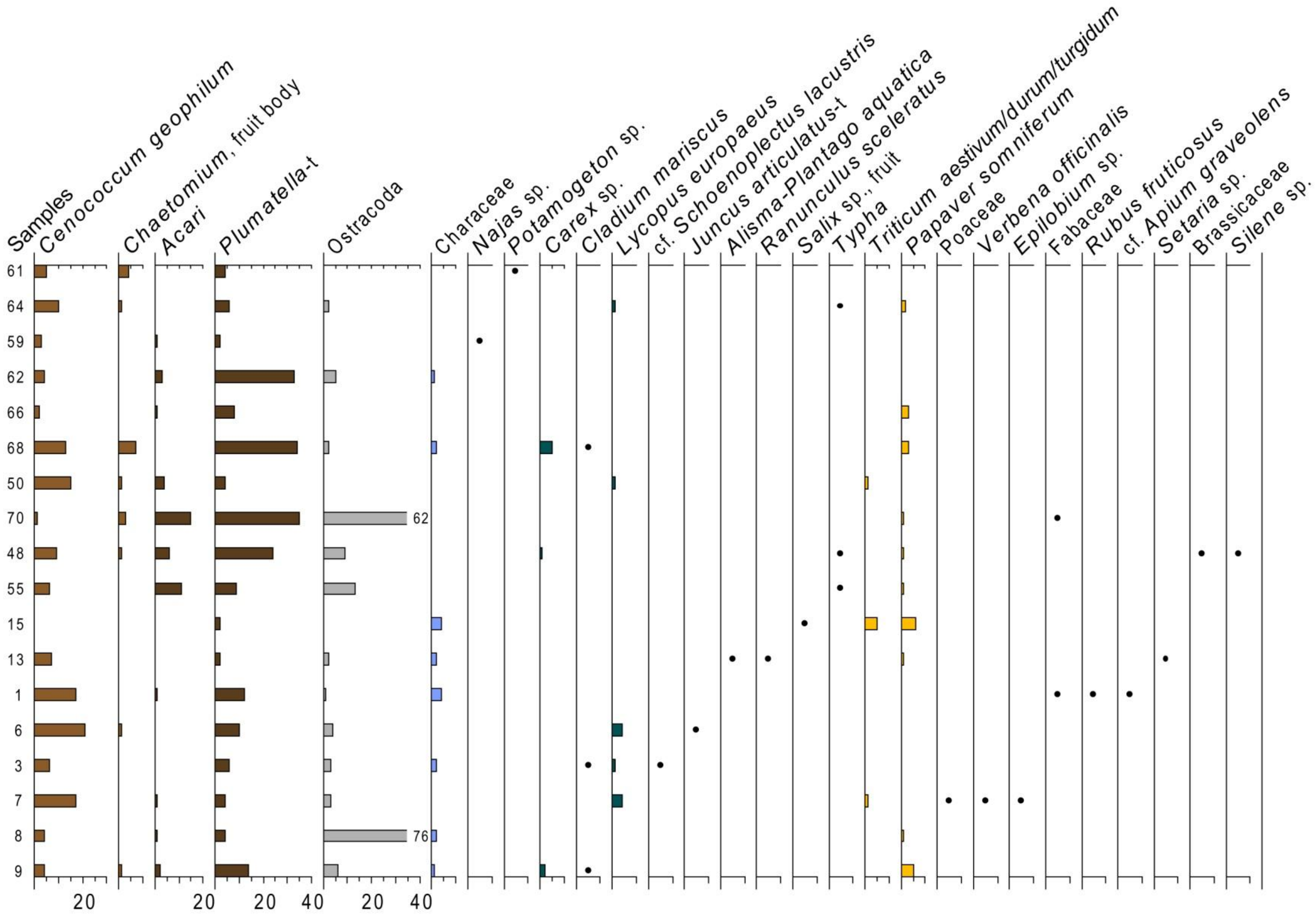

Figure 6. Macrofossil diagram of samples from Level VII in Sector D. Values plotted consist of absolute frequencies/5 cm^3 of sediment and single occurrences are represented by dots.

3.5. Numerical Analysis

3.5.1. Univariate statistics

The rejection of the null hypothesis of a Poisson distribution in all variables attested the existence of spatial accumulations and that the different variables are not randomly distributed in the space. The rejection of Geometric and Negative Binomial distribution evidenced a non-intentional distribution of taxa in a unique deposition event; which can be expected when working with ecological or environmental parameters.

Positive correlation is attested by Moran's I, showing areas of spatial autocorrelation (Table 3; Figs. 7A, 7B and 8D). Some variables show a significant concentration (high values surrounded by high values) in the north-eastern part of Sector D (Organic Matter (OM), Richness of pollen taxa, *Vitis*, Caryophyllaceae, Cyperaceae, Apiaceae, *Mougeotia*, *Rhytidospora* (HdV-171), *Trichuris* sp. in pollen slides and *Trichuris trichiura* and *Ascaris* sp. in parasitological analysis) and in the southwestern/western area (*Pteridium*, *Coniochaeta* cf. *ligniaria*, Undeterminable pollen, *Glomus*, *Gaeumannomyces*). Other variables show areas of positive autocorrelation (absence/underrepresentation) (low values surrounded by low values) in the north-east/east (Arboreal Pollen –AP–, *Pinus*), in the south-east (*Gaeumannomyces*, *Coniochaeta* cf. *ligniaria*, Cerealia-type, *Abies*, *Erica*, *Pteridium*) and in the north-west/west (Apiaceae, Asteraceae tubuliflorae, Pollen Concentration (PC) and Richness) (Figs.7A and 7B).

Kriging interpolation provided a two-dimensional representation of variables distribution in space and an estimation of predicted values between measured points (Figs. 8A, 8B, 8C and 8D). Exponential and Gaussian models were the best fitting models, with 0.88-0.99 values in r^2. Based on these results, three different areas were identified within Sector D at La Draga:

- North-eastern area: concentration of OM, lakeshore plants both in pollen and macrofossils records (*Salix*, *Fraxinus*, *Vitis*, Cyperaceae, Caryophyllaceae and Apiaceae), algae (*Spirogyra* and *Mougeotia*) and ruderals and cultivars (Cerealia-type, Poaceae, Asteraceae tubuliflorae, Caryophyllaceae and Apiaceae [4]). Highest values of PC and Richness and significant underrepresentation of AP. Concentration of parasites (*Trichuris trichiura* and *Ascaris* sp.).
- North-western/western area: concentration of AP (north-west), *Pinus*, *Abies*, *Pteridium*, *Glomus*, *Coniochaeta* cf. *ligniaria*, *Valsaria* sp., *Diplocladiella scalaroides*, *Diporotheca rhizopila*. Lowest values of PC. Overrepresentation of taxa positively correlated with Undeterminable pollen distribution (i.e. *Abies:* r=0.74; p=0.0005 and *Pteridium:* r=0.68; p=0.002) and negatively correlated with OM (i.e. *Abies:* r=-0.53; p=0,023 and *Pteridium:* r=-0.48; p=0.045).

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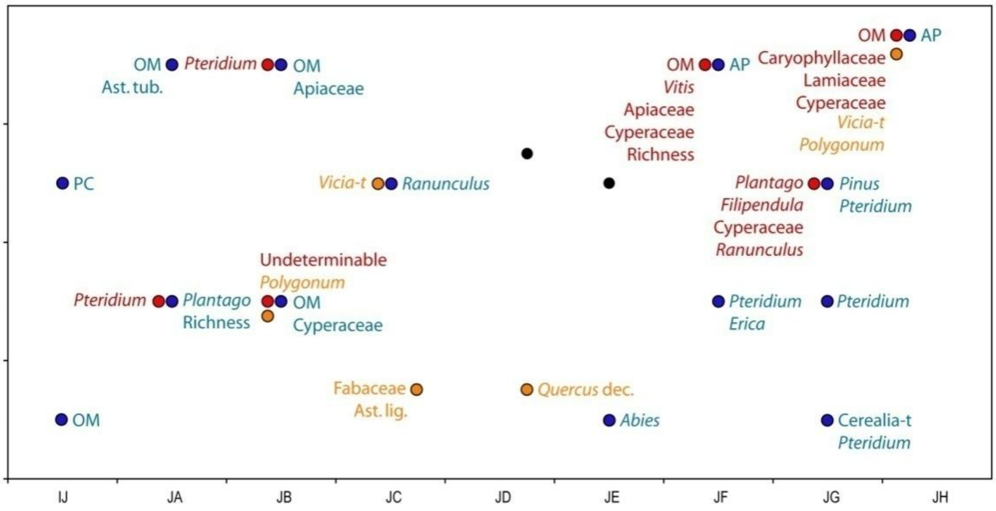
[4] Caryophyllaceae and Apiaceae families include genera and species of both ecological groups, lakeshore plants and ruderal herbs.

South-western area: concentration of Undeterminable pollen, Cerealia-type, Asteraceae liguliflorae, *Centaurea*-type, Monolete spores.

Table 3. Moran's I results of selected pollen, NPP, parasites and macrofossil taxa.

Taxa	Moran's I	*p* value	Taxa	Moran's I	*p* value
OM	0.36	0.001	*Spirogyra*	0.25	0.007
PC	0.04	0.232	*Mougeotia*	0.28	0.003
Richness	0.22	0.005	*Zygnema*	-0.07	0.459
AP	0.13	0.044	*Gloeotrichia*	0.004	0.226
Pinus	0.24	0.027	*Glomus*	0.4	0.004
Abies	0.18	0.028	HdV-361	0.02	0.19
Quercus, deciduous	-0.04	0.438	*Gaeumannomyces*	0.45	0.002
Erica	0.07	0.12	*Diplocladiella*	0.21	0.001
Vitis	0.12	0.023	*Diporotheca rhizopila*	0.2	0.011
Cerealia-t	-0.005	0.24	*Sporoschisma* sp.	-0.001	0.29
Caryophyllaceae	0.08	0.113	*Coniochaeta cf. ligniaria*	0.47	0.001
Lamiaceae	0.12	0.04	*Chaetomium* (HdV-7A)	-0.02	0.228
Vicia-t	-0.1	0.319	cf. *Neurospora*	0.03	0.058
Polygonum	-0.14	0.089	*Coniochaeta x.* (HdV-6)	0.09	0.021
Filipendula	0.12	0.032	*Sordaria*-t (HdV-55A)	0.05	0.184
Asteraceae tubuliflorae	0.18	0.013	*Rhytidospora* (HdV-171)	0.008	0.124
Asteraceae liguliflorae	-0.04	0.433	*Podospora* (HdV-368)	-0.18	0.058
Plantago	0.36	0.008	*Cercophora*-t (HdV-112)	-0.07	0.312
Fabaceae	-0.1	0.297	UAB-4	0.26	0.013
Apiaceae	0.25	0.003	UAB-11	-0.13	0.059
Cyperaceae	0.4	0.001	UAB-32	0.07	0.1
Ranunculus	0.32	0.006	UAB-34B	0.36	0.007
Undeterminable	0.24	0.012	UAB-35	-0.03	0.35
Pteridium	0.51	0.001	UAB-38	0.04	0.127
Trichuris trichiura	0.24	0.001	UAB-43	0.28	0.006
Ascaris sp.	0.1	0.038	*Plumatella*-t	0.07	0.08
			Monocots charred ep.	0.48	0.004



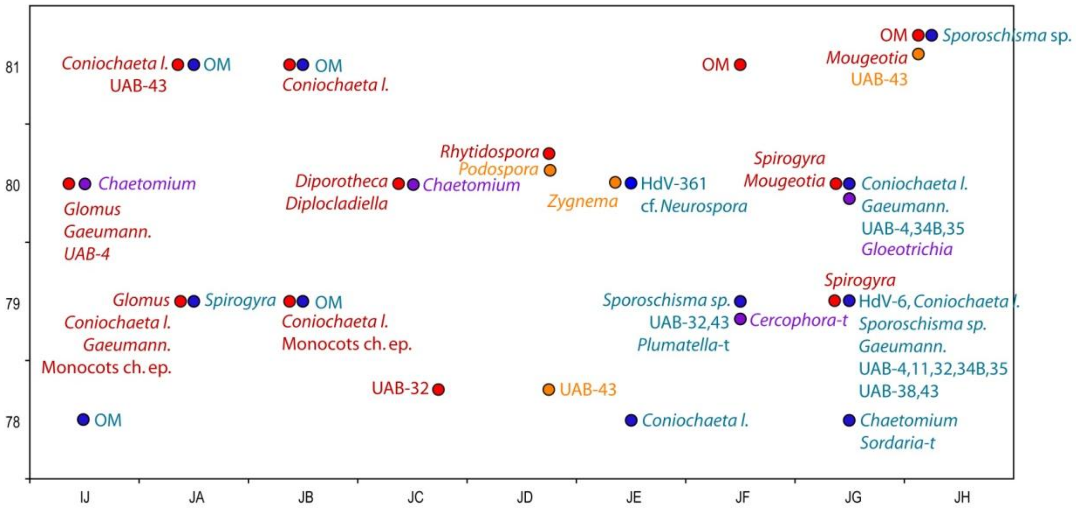


Figure 7A. Distribution of pollen taxa with higher measures of positive and negative autocorrelation using Local Moran analysis (by SpaceStat4 software). Red and blue dots represent positive autocorrelation (high values surrounded by high values and low values surrounded by low values, respectively). Orange dots represent negative autocorrelation (high values surrounded by low values) (also in Fig. 7B).

Figure 7B. Distribution of NPP taxa with higher measures of positive and negative autocorrelation using Local Moran analysis (by SpaceStat4 software). Purple dots represent negative autocorrelation (low values surrounded by high values).

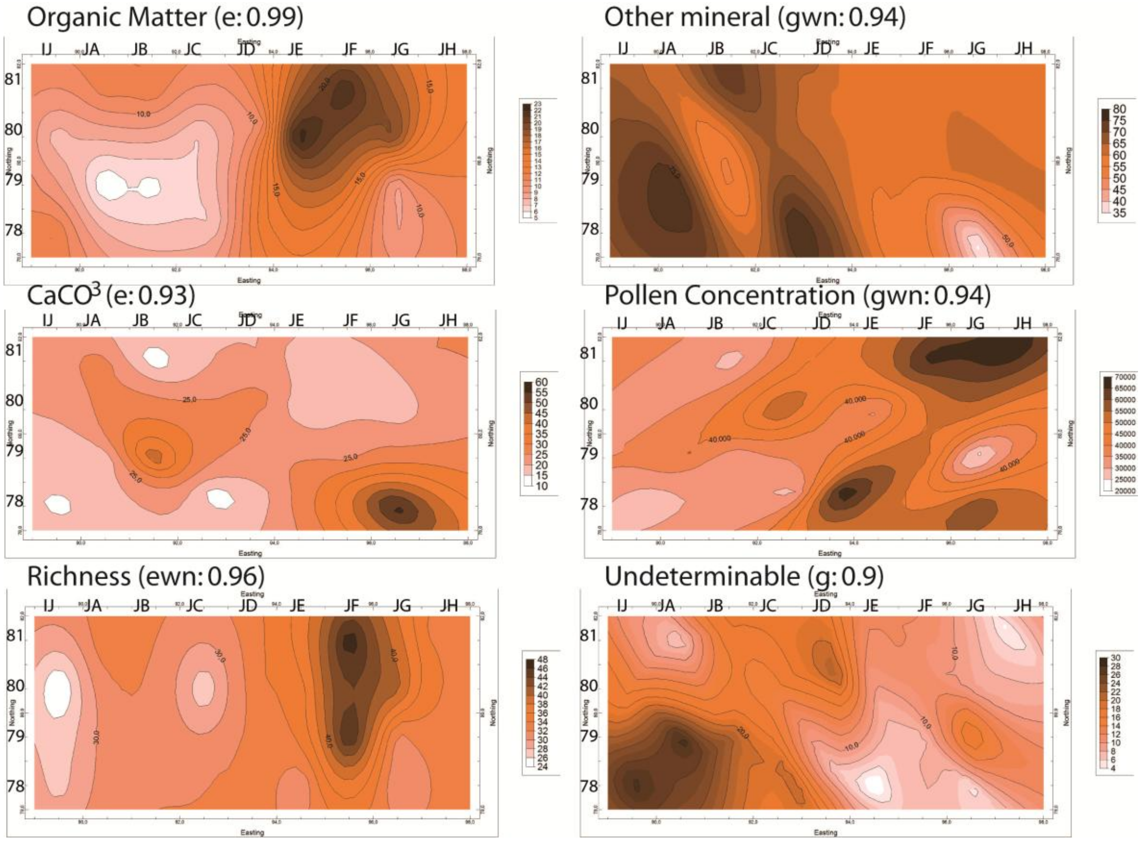
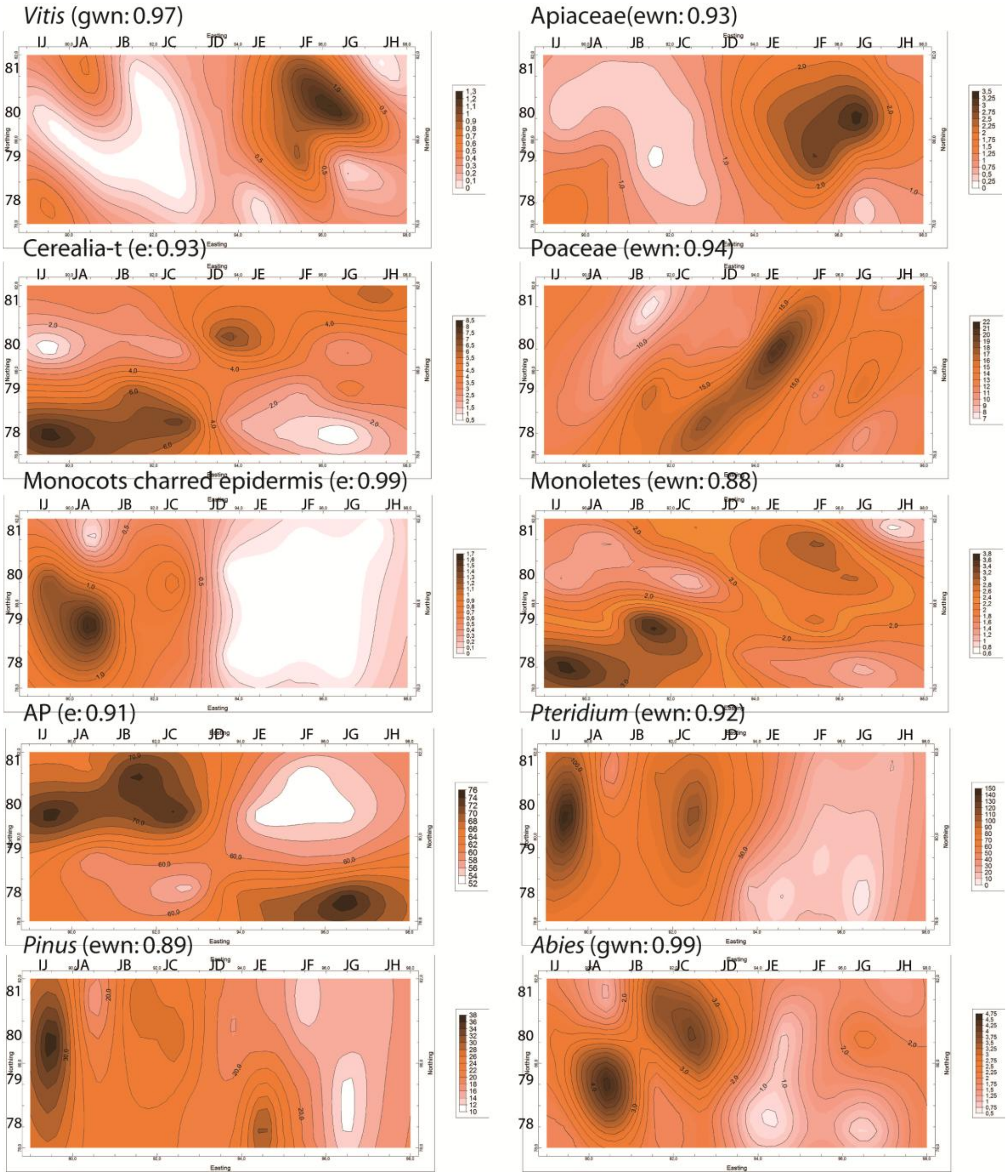


Figure 8A. Kriging interpolation maps of LOI results (OM, CaCO^3 and other mineral) and pollen record features (Undeterminable, PC, Richness). Best fitting model and correlation are plotted for each taxa (e: exponential; ewn: exponential with nugget; g: Gaussian; gwn: Gaussian with nugget) (also in Figs. 8B,8C and 8D).



Vitis (gwn: 0.97)

Apiaceae(ewn: 0.93)

Cerealia-t (e: 0.93)

Poaceae (ewn: 0.94)

Monocots charred epidermis (e: 0.99)

Monoletes (ewn: 0.88)

AP (e: 0.91)

Pteridium (ewn: 0.92)

Pinus (ewn: 0.89)

Abies (gwn: 0.99)

Figure 8B. Kriging interpolation maps of selected pollen taxa.

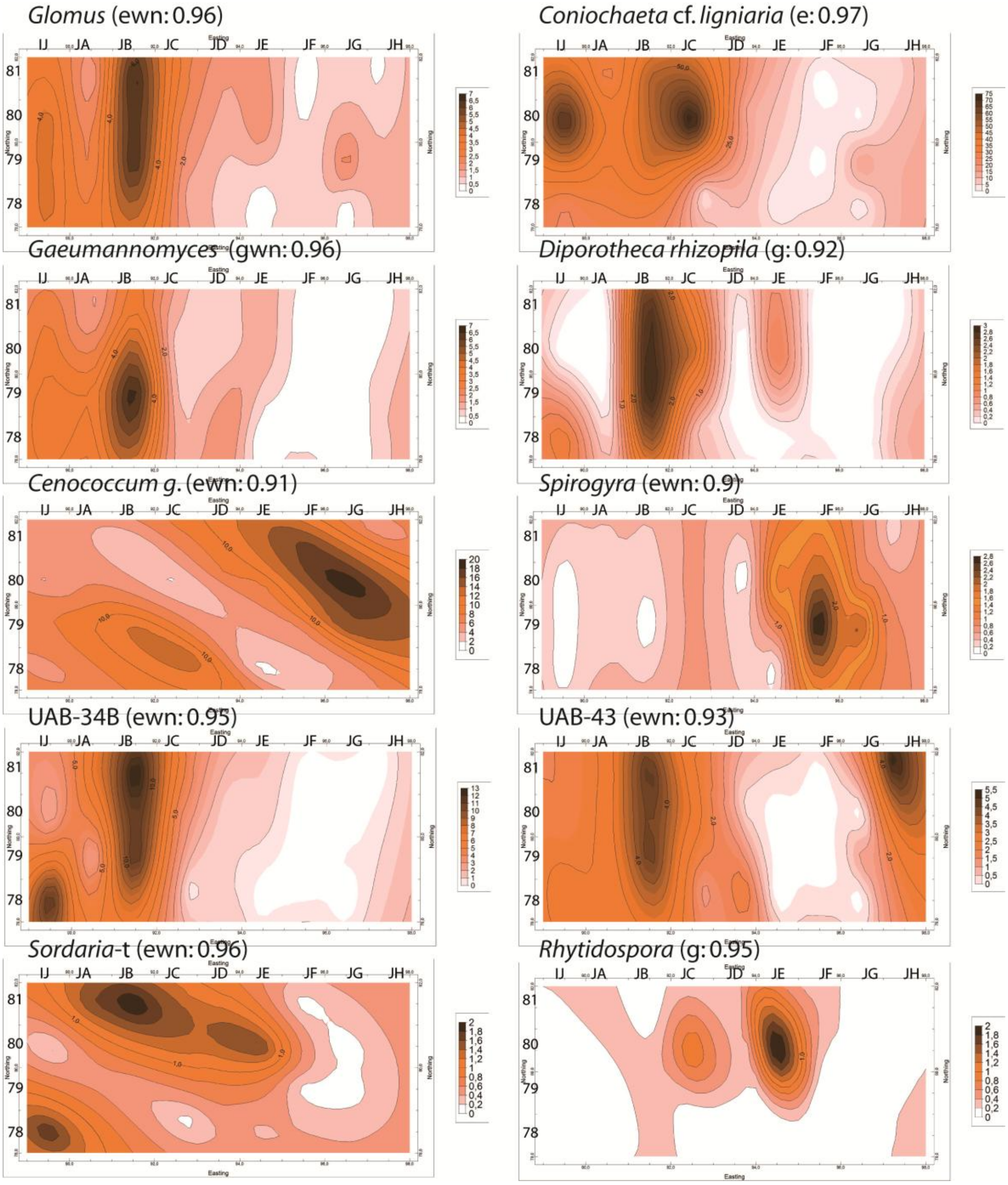
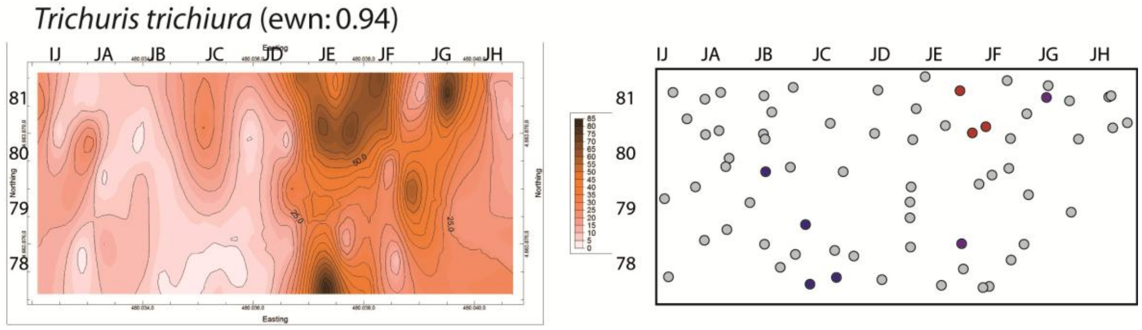
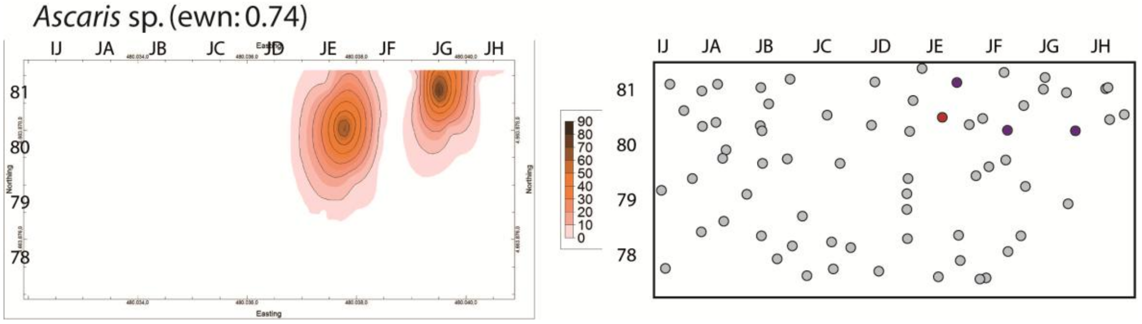


Figure 8C. Kriging interpolation maps of selected NPP.



Trichuris trichiura (ewn: 0.94)



Ascaris sp. (ewn: 0.74)

Figure 8D. Kriging interpolation and Local Moran analysis maps for parasites *Trichuris trichiura* and *Ascaris* sp. Red and blue dots represent positive autocorrelation (high values surrounded by high values and low values surrounded by low values, respectively).

Table 4. Eigenvalues and percentages of Correspondence Analysis and Detrended Correspondence Analysis

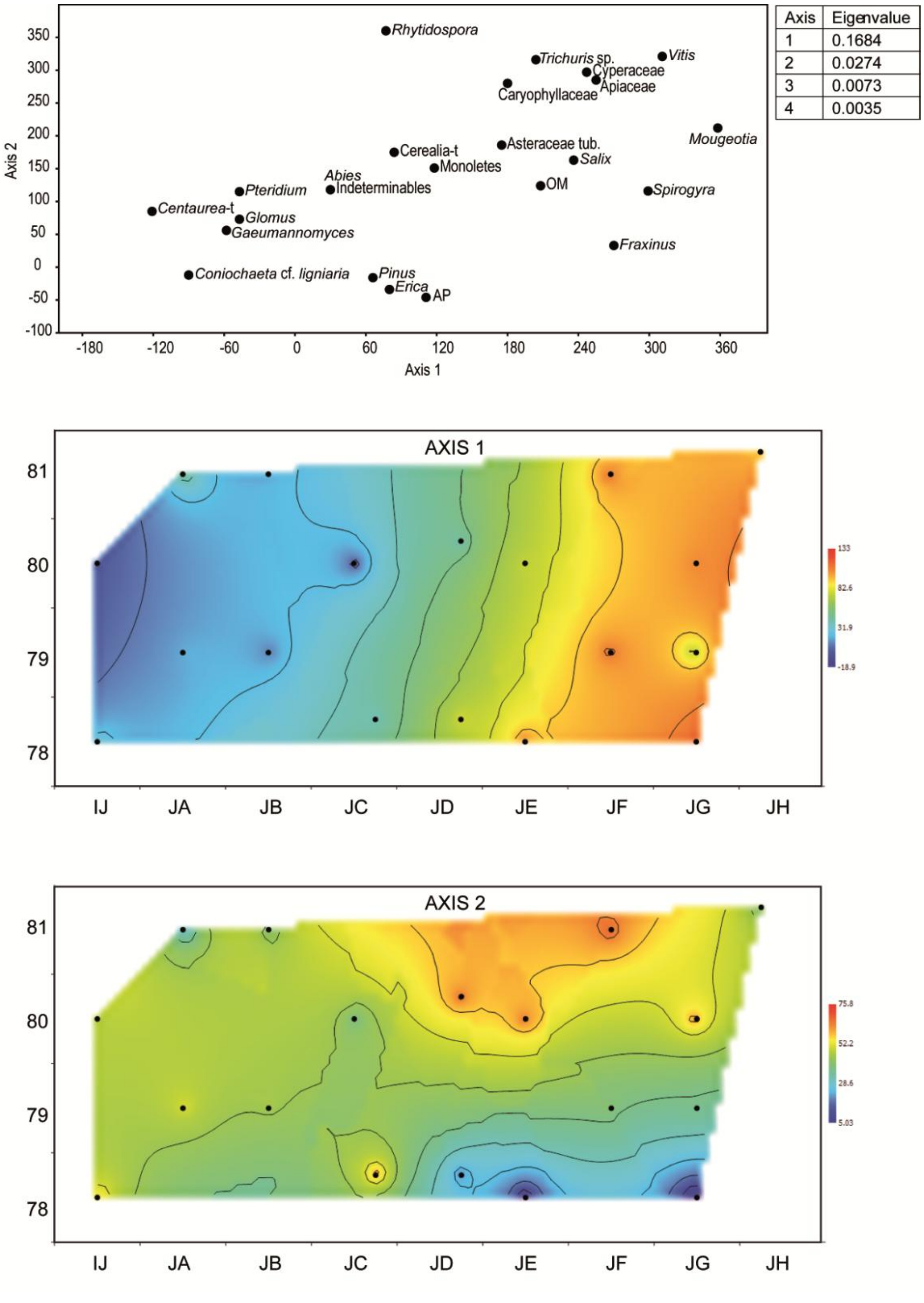
	Correspondence Analysis			Detrended Correspondence Analysis		
Axis	Eigenvalue	% of total	Cumulative	Eigenvalue	% of total	Cumulative
1	0.168366	57.88	57.877	0.1684	81.52	81.52
2	0.037894	13.03	70.903	0.0274	13.26	94.78
3	0.020546	7.06	77.965	0.007281	3.52	98.30
4	0.015871	5.46	83.421	0.003499	1.7	100
5	0.011639	4.00	87.422			
6	0.008967	3.08	90.505			
7	0.007274	2.50	93.005			
8	0.005011	1.72	94.727			
9	0.003792	1.30	96.031			
10	0.003525	1.21	97.243			
11	0.002425	0.83	98.077			
12	0.002141	0.74	98.813			
13	0.001242	0.43	99.239			
14	0.000906	0.31	99.551			
15	0.000693	0.24	99.789			
16	0.000455	0.16	99.946			
17	0.000158	0.05	100			

3.5.2. Multivariant statistics

The CA results show that Axis 1 and 2 explain 70.9% of the variance (57.87 the first, 13.03 the second). The DCA shows an Eigenvalue of 0.1684 (81.51%) for Axis 1 and 0.0274 (13.26%) for Axis 2 (Table 4). The IDW represents the spatial distribution of Axis 1 and 2 (Fig. 9), showing an east-west gradient for Axis 1. Thus, in the East higher richness (diversity) was recorded and many taxa bore maximum values, while in the west few taxa dominate the record with high values. In the case of Axis 2, a concentration of some taxa was identified in the north-eastern area.

Spearman’s correlation analysis was performed for the entire database and some negative and positive significant correlations were identified (Table 5). The most remarkable correlations were:

- Organic matter (OM), positive with *Quercus ilex-coccifera*, *Vitis*, Apiaceae, Scrophulariaceae, Papaveraceae, *Hedysarum*-t, *Aquilegia*-t and UAB-7; negative with *Abies*, *Centaurea*-t, Undeterminable pollen, *Pteridium*, charred monocot epidermis, *Glomus*, *Coniochaeta* cf. *ligniaria*, *Gaeumannomyces* and UAB-9, 21, 26, 34A, 42, 43, 50.
- Richness, positive with *Salix*, Cistaceae, *Vitis*, Asteraceae tubuliflorae, *Plantago major-media*, Apiaceae, Scrophulariaceae, Lamiaceae, Cyperaceae, *Aquilegia*-t, OM, *Cenococcum geophilum* and *Trichuris* sp.; negative with AP, *Pinus*, *Nymphaea*, *Coniochaeta* cf. *ligniaria*, UAB-9 and charred monocot epidermis.
- Undeterminable pollen, positive with Other mineral (LOI), *Abies*, Cerealia-t, *Centaurea*-t, *Asphodelus*, Monoletespores, *Pteridium*, charred monocot epidermis, *Glomus*, *Coniochaeta* cf. *ligniaria*, *Sporormiella*, *Neurospora*, *Gaeumannomyces*, and UAB-4, 9, 10, 15, 34B, 44; negative with OM, *Quercus ilex-cocc*. and *Alnus*.
- Arboreal Pollen (AP), positive with *Coniochaeta* cf. *ligniaria*, *Quercus ilex-cocc.* and *Nymphaea*; negative with Poaceae, Cerealia-t, Ast. liguliflorae, Apiaceae, *Symphytum*-t, Scrophulariaceae, *Rumex tingitanus*, *Aquilegia*-t, Monolete spores, UAB-7, *Trichuris* sp., *Cenococcum*, *Lycopus europaeus* seed and Richness.



Axis	Eigenvalue
1	0.1684
2	0.0274
3	0.0073
4	0.0035

Figure 9. Graph showing the results of Detrended Correspondence Analysis and interpolation by Inverse distance weighting analysis (IDWA) (Past software), plotting the row scores of the first and second axis on the *x*,*y* coordinates.

Table 5. Correlation by Spearman’s rs between OM, Richness, Undeterminable pollen, AP and selected taxa.

	AP		***Pinus***		***Abies***		***Quercus* d.**		***Q. ilex-cocc.***		***Salix***		***Vitis***		**Poaceae**		**Cerealia-t**		**Ast. tub.**		**Ast. lig.**	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
OM					-0,53	0,024			0,47	0,046			0,69	0,001								
Richness	-0,7	<0.001	-0,55	0,018							0,55	0,018	0,7	0,001					0,47	0,049		
Undets.					0,73	<0.001			-0,69	0,001							0,56	0,016				
AP							0,6	0,008							-0,49	0,037	-0,57	0,013			-0,59	0,009
	Undets.		**Richness**		***Centaurea***		***P. maj-med***		**Scroph.**		***Aquilegia***		**Cyperaceae**		**Apiaceae**		**Monoletes**		***Pteridium***		***Cenococcum***	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
OM	-0,6	0,014	0,64	0,004	-0,47	0,048			0,59	0,009	0,56	0,015			0,65	0,003			-0,48	0,045		
Richness							0,54	0,021	0,47	0,048	0,65	0,003	0,5	0,032	0,58	0,011					0,52	0,026
Undets.					0,52	0,027											0,57	0,013	0,68	0,002		
AP									-0,47	0,049	-0,54	0,02			-0,7	0,001	-0,54	0,02			-0,75	<0.001
	OM		**Other min.**		**Mon. ch. ep.**		***Glomus***		***Coniochaeta***		***Gaeumann.***		**UAB-4**		**UAB-7**		**UAB-9**		**UAB-43**		***Trichuris* sp.**	
	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p	r	p
OM					-0,7	0,001	-0,52	0,027	-0,69	0,001	-0,47	0,049			0,51	0,029	-0,5	0,033	-0,5	0,032		
Richness	0,64	0,004			-0,64	0,003			-0,59	0,009							-0,48	0,04			0,61	0,007
Undets.	-0,6	0,014	0,6	0,008	0,68	0,002	0,69	0,001	0,49	0,038	0,64	0,004	0,6	0,008			0,53	0,023				
AP																	0,54	0,02			-0,51	0,03

4. Discussion

4.1. The spatial distribution of pollen and NPP at La Draga: a taphonomic evaluation

Differences in productivity and dispersion cause differential representation of taxa in pollen records. These divergences in representation are even wider when the pollen record is affected by taphonomic agents or processes, more common in mineral soils (Havinga, 1974; Hall, 1981; Faegri and Iversen, 1989). Differential preservation of pollen grains, influenced by the sporopollenin form and content (Kwiatkowski and Lubliner-Mianowska, 1957; Brooks and Shaw, 1972), is the cause of common over and/or underrepresented taxa and is recognizable when the pollen record shows the dominance of the most resistant pollen grains. Several processes can produce deterioration of pollen grains, but weathering-oxidation and changes in humidity are evidenced as the most influential. In that sense, Holloway (1989), Campbell (1991) and Campbell and Campbell (1994) have shown experimentally that wet–dry cycles can cause mechanical damage to pollen grains. In addition, sub-aerial exposure causes oxidation and enables further degradation by bacteria or fungi (Elsik, 1971).

Differential preservation is attested at La Draga, evidenced in the spatial distribution of Pollen Concentration (PC), Richness and in Undeterminable pollen values (Fig. 8A). PC and Richness display their highest values in the north-eastern part of the sampled area, coinciding with the highest values of Organic Matter (OM). In contrast, Undeterminable pollen is concentrated in the south-western area, coinciding with the highest values of Other Mineral content in the sediment. Strong evidence of differential preservation of pollen grains in Level VII is the contraposition of distributions of some well-known vulnerable taxa versus highly resistant taxa. While the highest values of Caryophyllaceae, Apiaceae, *Vitis*, Cyperaceae, *Salix, Fraxinus, Ulmus, Plantago* and *Plantago major-media* are concentrated in the north-eastern/eastern area, the highest values of *Pinus*, *Abies*, *Pteridium* and Asteraceae liguliflorae are concentrated in the western area. This explains the positive (*Vitis*, Scrophulariaceae, *Aquilegia*-t and Apiaceae) and negative (*Abies*, *Centaurea*-t, *Pteridium*, Undeterminable) correlations with OM and the positive correlation of *Abies*, Cerealia-t, *Centaurea*-t, Monoletes, *Pteridium* with Undeterminable pollen values (Table 5). In that sense, 81.5% of the variance in DCA (70.9% of the variance in CA) (Table 4) is influenced by this differential preservation of pollen grains in Level VII, reflected in the graphic result of the inverse distance weighting analysis for Axis 1 (Fig. 9). In this figure an east-west gradient can be observed, explaining the negative correlation between taxa showing their highest values in an area (north-east/east) where pollen grains are better preserved (undeterminable pollen values of 4.5-11.3%) and an area where oxidation-resistant taxa are overrepresented (west). This is consistent with previous analysis, where ordination of pollen and NPP taxa on a diachronic scale was also influenced by taphonomic conditions in the different layers at La Draga, with positive values for the most frequent taxa in waterlogged layers, and negative values for the most frequent taxa in layers formed in sub-aerial conditions (Revelles et al., 2016).

Parasite remains do not display marked alteration traces of mechanical or chemical origin on the eggshells. The analysis appears consistent with homogenous preservation conditions in the whole of Sector D. In these conditions, the higher concentration of the parasite residues (*Trichuris trichiura* and *Ascaris* sp.) observed in the north-eastern part of Sector D would therefore be the result of either an anthropogenic waste accumulation or an accumulation effect caused by a slope or a trough in the sediment (Maicher et al., submitted).

Experimental studies on pollen grain preservation showed that Caryophyllaceae was very sensitive to oxidation, leading to an unidentifiable periporate pollen grain or periporate fragment (Lebreton et al., 2010). This could be the case for such other pollen grains as *Ulmus*, *Plantago* or *Plantago major-media*, as their identification is difficult after degradation. On the other hand, taxa like *Pinus*, *Abies* or Asteraceae liguliflorae are easily recognisable even after being altered by oxidation, and they cannot be confused with other taxa. In the case of fern spores, they are highly resistant to corrosion (Havinga, 1964, 1984) and high frequencies within a pollen sample have been used to infer that an assemblage has been modified as a result of differential pollen loss (Dimbleby, 1957; Bunting and Tipping, 2000; Tomescu, 2000).

The differential preservation of pollen grains at La Draga can be explained in terms of the existence of different environments within the site, a hypothesis reinforced by the NPP record. While in the north-eastern area there is a concentration of freshwater algae (*Spirogyra*, *Mougeotia*) and Cyanobacteria (*Gloeotrichia*) (Figs. 7B and 8C), showing a humid and at least seasonally flooded area; in the western area there is a concentration of fungi spores, some of them indicating soil erosion and disturbance (*Glomus*, HdV-361, *Diporotheca rhizopila*; Anderson et al., 1984; van Geel et al., 1989; Hillbrand et al., 2012) and decomposition of wood in wet environments (*Coniochaeta* cf. *ligniaria* (HdV-172), *Diplocladiella scalaroides*; van Geel et al., 1983; Gönczöl and Révay, 2004). Other fungi spores spatially correlated with the above are *Valsaria* sp. (HdV-263), *Gaeumannomyces* (HdV-126), UAB-34B and UAB-43, which could indicate similar conditions. Despite being a lignicolous fungi, *Coniochaeta* cf. *ligniaria* (HdV-172) often reaches its highest values in soil erosion phases (López-Merino et al., 2012; Revelles and van Geel, 2016), so the occurrence in the western part of Sector D would indicate not only decomposition of wood but also eroded soils in a sub-aerial humid environment. Thus, although anaerobic bacterial and fungal activity also occurs under reducing conditions in waterlogged areas (Lillie and Smith, 2009), the significant spatial difference and concentration of fungi evidences different deposition and preservation conditions between the east and west areas, probably indicating a waterlogged (or at least humid) environment in the north-east and a sub-aerial environment in the west, leading to the alteration of pollen grains by weathering-oxidation. These differences can be partially influenced by a slight east-west slope in the northern part of the sector (see north cross-section in Fig. 2).

As different deposition environments have been identified, we will discuss in the next section if the significant spatial concentrations of pollen and NPP and the taphonomic processes affecting the formation and preservation of the palynological record would have been related to the human use of space.

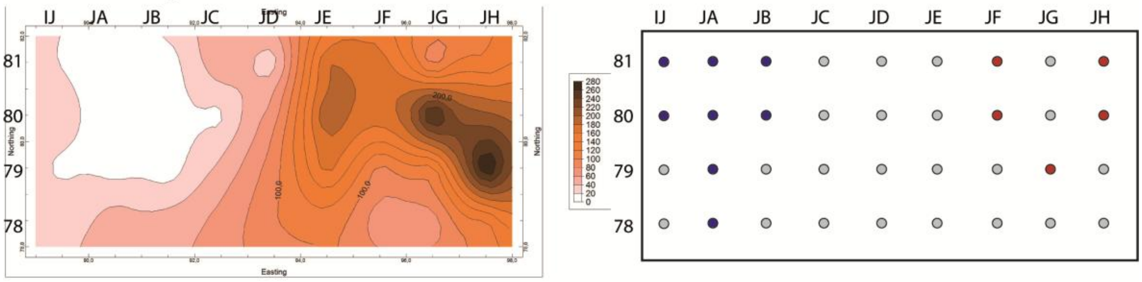
4.2. Use of space in the oldest phase at La Draga: an archaeopalynological approach

Palynological analysis in archaeological sediments (archaeopalynology) is a valuable tool to approach archaeological questions from a different perspective, given the influence of human activities in the pollen record composition. In that sense, significant accumulations of pollen grains and spores could respond to gathered plants, stored cultivars and presence of dung (animal and/or human) within the settlement. Although the spatial distribution of pollen and NPP at La Draga mainly obeys to taphonomic issues, two questions arise when dealing with the interpretation of this spatial distribution: "are these different deposition environments influenced by human use of space?" and "are there taxa accumulations produced by anthropogenic activities or events?"

The integration of palynological data with the spatial distribution of archaeological remains and with wooden structures is essential for a better understanding of the use of space in the settlement of La Draga. The study of the spatial distribution of archaeological remains (fauna, pottery, grinding stones, lithic remains, etc.) evidenced a clear accumulation of consumption waste in the northeastern area (squares JE/JF-79/80/81) (Morera, 2016) (Fig.10) coinciding with the structuring of space evidenced in the study of horizontal boards and posts (assemblages B and D in Fig.2) (López-Bultó, 2015). In that context, the association of the highest values of OM, freshwater algae, cyanobacteria and lakeshore plants (in pollen and macrofossils) points to a humid environment, at least seasonally flooded, that may have corresponded to the space beneath a pile dwelling. The differential preservation and deposition environments would have been caused by insolation in outside spaces contrasting with moisture beneath the structures. In that sense, Axis 2 of DCA indicates that 13.26% of the Variance is explained by this accumulation of taxa in the north-eastern part of the sector (Fig. 9). In other words, Axis 2 is associated with the pollen and NPP record formed beneath the hut/structure, especially influenced by anthropogenic activities.

When assessing inside/outside spaces, the AP spatial distribution can provide an interesting view of the areas representing a more reliable image of the original pollen rain (outside spaces). On the contrary, inside spaces strongly altered by human input of plants, gives a distorted image of pollen rain, with herbs overrepresented (Van Campo and Leroi-Gourhan, 1956). In that sense, the spatial distribution of AP at La Draga shows a significant positive spatial autocorrelation in the north-eastern area, that is, displaying lowest values surrounded by lowest values (Table 3; Fig. 7A). In contrast, the highest values in the north-west and south-east may indicate exterior areas where AP deposited directly on the ground without barriers (i.e. huts), whereas negatively correlated taxa (Poaceae, Cerealia-t, Asteraceae liguliflorae, Scrophulariaceae, *Aquilegia*-t, Apiaceae, Monolete spores, *Cenococcum geophilum* and *Trichuris* sp.) would indicate interior spaces.

Archaeological remains (e: 0.9)



Grinding stones (e: 0.94)

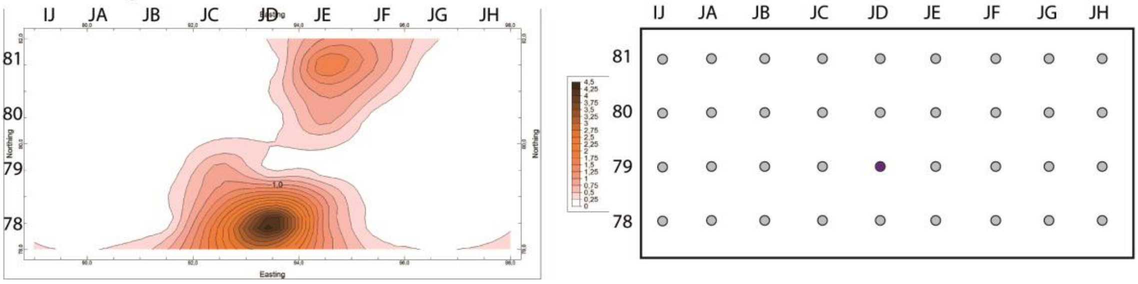


Figure 10. Kriging interpolation and Local Moran analysis maps for all archaeological remains and grinding stones. Purple dots represent negative autocorrelation (low values surrounded by high values).

In the north-east, a concentration of cultivars (Cerealia-type) and some taxa (Apiaceae, Asteraceae tub., Caryophyllaceae, Cyperaceae, Poaceae, *Polygonum*, Scrophulariaceae, *Vicia*-t, *Vitis*) is attested and these may have been brought to the settlement for their subsistence value (Figs. 7A and 8A), as recorded in other archaeological sites (Richard and Gery, 1993; Gauthier and Richard, 2009; Jeraj et al., 2009). Although most of these taxa were identified at family level, and it is thus not possible to specify their potential uses, several species within these families have been documented in the carpological record (*Apium graveolens*, *Apium* sp., *Bromus* cf. *arvensis*, *Carex* sp., *Cladium mariscus*, *Cyperus* sp., *Eupatorium cannabinum*, *Phragmites* sp.; Antolín, 2013) evidencing the local occurrence of these plants within the settlement. In the case of *Vitis*, its gathering is evidencedin both carpological and anthracological records (*Vitis vinifera* subsp. *sylvestris*, Antolín, 2013; Caruso-Fermé and Pique, 2014).

In this context, high frequencies of Poaceae (Van Zinderen Bakker, 1982) and ferns (Van Campo and Leroi-Gourhan, 1956; Bui Thi and Girard, 2010) have been postulated as resulting from the practice of using ferns/grasses as bedding; both species show accumulations in the north-east area. Thus, the integration of spatial distribution of archaeological remains, wooden structures and palynological data is able to identify the location of a hut in the north-east part of the sampled area in Sector D. The sediments from this area would have formed in a humid environment beneath the structure, with abundant organic matter and archaeological remains in the waste from the production or consumption activities carried out within the hut.

Spores of coprophilous fungi and parasites provided interesting data for the discussion about the use of space within the settlement. Although the occurrence of coprophilous fungi spores in pollen records from natural deposits is usually interpreted in terms of grazing pressure of domestic flocks (Ralska-Jasiewiczowa and van Geel, 1992; Cugny et al., 2010; Gauthier et al., 2010) or even attesting the presence of dung of wild herbivores (Raper and Bush, 2009; Ekblom and Gilson, 2010), their occurrence in archaeological sediments might also be related to human dung. In this way, the identification of *Trichuris trichiura* during the parasitological analysis (Maicher, 2013; Maicher et al., submitted) points to the existence of human faeces at La Draga. Nevertheless, the occurrence of other parasites related to animals, like swine (*Macracanthorhynchus* and *Ascaris* sp.) or ruminants such as cattle (*Dicrocoelium dendriticum* and *Paramphistomum* sp.) combined with the highest values of *T. trichiura* in the squares JE/JF-78/79/80/81 (Fig. 8D) shows that humans and animals shared the space, thus confirming, the stabling of livestock within the settlement. In that sense, cattle dung was recovered in the square JD80 during the excavation in 2012. The above-mentioned parasites are concentrated in the north central part of the sampled area, coinciding with the distribution of some spores of coprophilous fungi (*Sordaria*-t (HdV-55A), *Podospora* (HdV-368) and *Rhytidospora* (HdV-171)) and *Plumatella*-t, freshwater bryozoans that can be found in organic and polluted water, even in habitats polluted with livestock waste (Rogick and Brown, 1942; Dendy, 1963; Bushnell,1974). Another particular case is Sample 15 (square JE78), where a concentration of parasites (especially *T. trichiura*) coincides with an exceptional concentration of *Cercophora*-t (HdV-112). The composition of this sample follows a different pattern from the rest of the samples, as shown in the special concentration of *Quercus ilex-coccifera* pollen and in the macrofossils record (Figs.4 and 6), with the remarkable accumulation of plants with economic value (*Triticum aestivum/durum/turgidum* and *Papaver somniferum*). This evidence could indicate another point of accumulation of dung and it seems that both accumulations of parasites coincide in space with the limits of the architectural assemblage B-D and with the accumulations of herbs and archaeological remains indicating the location of a hut. Two separate depositional areas are highlighted; one in the north-eastern part of the sector with a significant amount of archaeological material, cultivars and parasite eggs, another in the south-eastern part, with an accumulation of cereal remains and the human parasite *T. trichiura*. This distribution of domestic waste points to a differential management of it.

Finally, the correlation of the highest values of Cerealia-type, Asteraceae liguliflorae, *Centaurea*-t, Monolete spores and Undeterminable pollen in the south-western part of Sector D should be noted. The dominance of such highly resistant taxa to oxidation and the high values of undeterminable pollen evidence a taphonomic alteration of the pollen record in this area. Apart from oxidation by weathering, fire should also be considered in this area, as shown by remarkable accumulations of spores of carbonicolous (cf. *Neurospora* (HdV-55B-2) and carbonicolous/lignicolous fungi (*Chaetomium* (HdV-7A), *Gelasinospora* (HdV-1), UAB-4 and UAB-38) and the accumulation of charred monocot epidermis. Thus, highest values of Cerealia-type are spatially correlated with

Monocots charred epidermis (Fig. 8B) and a significant concentration of charred *Triticum aestivum/durum/turgidum* seeds (7001 in Fig. 2), interpreted as a probable storage structure (Berrocal, 2013), as well as with a concentration of grinding tools in the area nearby (Fig. 10) indicating, consequently, a probable area of wheat processing (Morera, 2016).

5. Conclusions

The spatial analysis of the distribution of pollen and NPP within the settlement evidenced the usefulness of this kind of approach in archaeopalynology. The consideration of the taphonomic processes involved in the formation of the palynological record and the integration of pollen and NPP distribution with the spatial analysis of archaeological remains and architectural assemblages enabled the reconstruction of different environments/spaces within the settlement of La Draga.

Despite taphonomic issues explaining most of the distribution of taxa within Sector D at La Draga, human use of space is included within the processes involved in the differential preservation of pollen and spores. Cereal grinding and the occurrence of fire in the south-western/south-central area of Sector D caused considerable alteration of pollen (highest values of Undeterminable, lowest of PC) and proliferation of fungi in an eroded subaerial mineral soil. In the opposite corner (north-east), a humid organic environment was identified beneath a hut built on stilts and platforms above the water, where an accumulation of archaeological remains from consumption waste was documented, as well as a concentration of herbs, plants with subsistence value and associated parasites (human and animal) and spores of coprophilous fungi.

In conclusion, this work evidenced the need to carry out spatial analysis in palynological studies of archaeological sites, owing to the spatial heterogeneity of results caused by human impact in terms of input of plants to the settlement (gathering, cultivation, storage), in arrangement of structures and in soil erosion. Additionally, spatial analysis in archaeopalynology has proved to be an appropriate method to comprehend site formation processes and obtain new data to understand the use of space within a lakeside settlement.

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5. DISCUSSION

The archaeoecological evidence obtained by the analyses performed in the framework of this thesis contributed relevant data about 1) Vegetation history, climate change and human impact during the Middle Holocene in the Lake Banyoles area; 2) Socio-ecological consequences of Neolithisation in the NE Iberian Peninsula and 3) Potential and contributions of archaeopalynology in lakeside settlement research.

5. 1. VEGETATION HISTORY, CLIMATE CHANGE AND HUMAN IMPACT DURING THE MIDDLE HOLOCENE IN THE LAKE BANYOLES AREA

The application of multi-proxy analysis and the interdisciplinary collaboration carried out in the framework of this PhD enabled information to be obtained at two different scales. Firstly, pollen analysis supplied data about vegetation history at a regional scale (Lake Banyoles area) during the Middle Holocene, allowing the evaluation of causes of environmental changes, discriminating in some cases between climate and human impact on the landscape. On the other hand, the integration of sedimentological studies and macrofossil and non-pollen palynomorph analyses provided relevant data to reconstruct the palaeo-environmental evolution of the Lake Banyoles shore, to comprehend the formation of natural deposits, the limnological evolution and the history of local vegetation in the edges of the lake. Additionally, a major effort has been made to characterise palaeo-environmental evolution and landscape transformation during the occupation of the site of La Draga, during the Early Neolithic (7.27-6.75 cal ka BP).

Lake water level regression and vegetated lakeshore formation during the last centuries of the Early Holocene (8.9-8.2 cal ka BP)

The chronological framework of this PhD thesis starts in the last centuries of the Early Holocene, *ca*. 8.9 cal ka BP, when a significant ecological change is attested in Lake Banyoles. The start of the SB2 sequence coincides with peat formation along the lakeshore about 8.9 cal ka BP, expressed by the sedimentological change from shallow water lacustrine carbonate facies to palustrine peaty wetland. This trend represents a lowering of the lake level and a transition from a shallow lacustrine charophyte-rich platform sub-environment to a vegetated lakeshore margin. This change led to the colonization of the lakeshore by vegetation, constituting a sub-aerial swamp with *Cladium mariscus*, as shown in the macrofossils record in Revelles et al. (2015), pointing to the existence of an alkaline substrate, poor in nitrogen. In that context, NPP indicators of alkaline lacustrine environments were resilient until 8.1/8.0 cal ka BP, as shown in the NPP record (Revelles and van Geel, 2016).

Peat formation was probably due to water-level regression caused by a cooling/drying event, as previously attested in other lacustrine records in Siles Lake (south-eastern Iberian Peninsula, 9.3 cal ka BP) (Carrión, 2002), in Fuentillejo Maar (central Iberian Peninsula, 9.2‑8.6 cal ka BP) (Vegas et al., 2009), in Basa de la Mora (Pyrenees, 9.3 and 8.8 cal ka BP) (Pérez-Sanz et al., 2013), in Lake Cerin (Jura Mountains, France, 9.0

cal ka BP) (Magny et al., 2011) and Lake Accesa (central Italy, 9.0 cal ka BP) (Magny et al., 2007).

In fact, this lowering in lake water level corresponds to one of the main rapid Holocene climate changes (Mayewski et al., 2004) that is globally detected as a phase of decreasing fluvial activity in Mediterranean areas (Magny et al., 2002), dry episodes detected in the Mediterranean Sea (Fletcher et al., 2010, 2013), episodes of reduced rainfall measured in $\delta^{18}O$ values in Katerloch Cave (southeastern Alps) (Boch et al., 2009) and Hoti Cave (Oman; Neff et al., 2001). Nevertheless, this cooling/drying episode is not strongly reflected in vegetation, which was dominated by dense broadleaf deciduous forests, and is only noticed in the decline of *Corylus* after its maximum values in 8.9-8.8 cal ka BP (in SB2 core), a process that is also attested in the core Lake Banyoles (LB) by Pérez-Obiol and Julià (1994), but some centuries later, *ca*. 8.5 cal ka BP (Fig. 13).

This process is not exclusive to this moment. In fact, Neolithic communities that settled at La Draga in *ca*. 7.3 cal ka BP, found a newly exposed carbonate-sand beach on their arrival to the lakeshore, probably formed by a similar process of lake water regression to the one in *ca*. 8.9 cal ka BP. On the other hand, it could be due to the infill caused by the rate of carbonate deposition exceeding the rate of underground water influx. In both cases, a climate aridification or cooling process would have been the cause of these changes in sedimentation and in hydrology. A similar phenomenon occurred during the Early Neolithic in the Circum-Alpine region, where some lakeside dwellings were established on empty platforms when the lake levels were low (Magny, 1978, 1993; Ismail-Meyer et al. 2013).

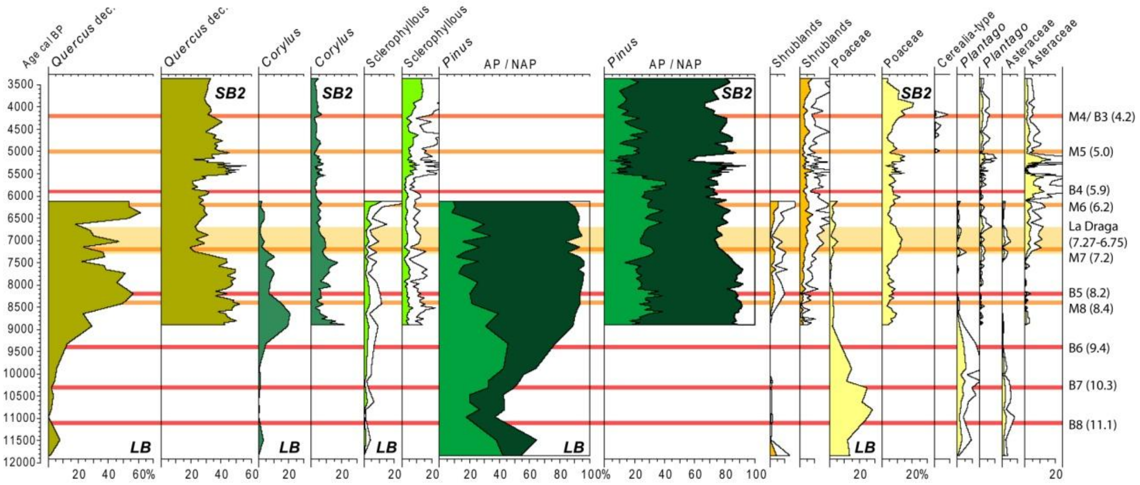

Figure 13. Percentage pollen diagrams from Lake Banyoles (LB redrawn based on data in Pérez-Obiol and Julià, 1994). Cooling and drying episodes are indicated (B: Bond events in Bond et al., 1997, 2001; M: Minorca cold events in Frigola et al., 2007).

The Holocene Climate Optimum and the 8.2 cal ka BP event in the Lake Banyoles area

Broadleaf deciduous forests in Lake Banyoles had their maximum expansion in the phase 9.0-7.5 cal ka BP, due to the establishment of a warmer and humid climate during the Early Holocene and consistent with the maximum expansion of broadleaf deciduous forests after 9.5-9.0 cal ka BP in other records in the Iberian Peninsula (Carrión et al., 2010; Pérez-Obiol et al., 2011; González-Sampériz et al. 2017). Nevertheless, the relatively stable climate established during the Early Holocene was firstly punctuated by the cooling episode in *ca*. 9.0 cal ka BP, as mentioned in previous sections, and then in 8.2 cal ka BP, considered the boundary between the Early and the Middle Holocene (Walker et al., 2012). This last global cooling episode did not have a strong impact on the Lake Banyoles area vegetation. The SB2 record shows in 8.2-8.1 cal ka BP a slight decrease in deciduous *Quercus* values, the presence of sedimentary charcoal, the onset of increasing input of allochthonous terrigenous fine sediment to the lake, as well as a slight increase in mountain taxa like *Pinus* and *Betula* and sclerophyllous trees like *Olea* and *Phillyrea*. The study by Pérez-Obiol and Julià (1994) has already shown this slight incidence of the 8.2 cal ka BP cooling event, reflected in a decline in deciduous *Quercus*, an increase in *Pinus* and a slight expansion in Ericaceae, but no regression is recorded in arboreal pollen (Fig. 13). Nevertheless, despite this slight evidence of drier conditions and the subsequent susceptibility to burning, the AP decline after the fire episode is smaller than expected during such an arid event, as recorded in other areas of the Iberian Peninsula in these chronologies (Riera, 1993; Davis and Stevenson, 2007; Carrión and van Geel, 1999; Carrión, 2002; Carrión et al., 2001a, 2001b; Pantaleón et al., 1996, 2003; López Sáez et al., 2007).

However, this minor impact of the 8.2 cal ka BP cooling event in the Lake Banyoles area contrasts with other pollen records in the north-eastern Iberian Peninsula, where this dry event was detected in Mediterranean coastal areas (Barcelona) (Riera, 1993), in regions with continental climates (Davis and Stevenson, 2007; González-Sampériz et al., 2008) and in high mountain areas (Pyrenees) (González-Sampériz et al., 2006; Pérez-Sanz et al., 2013). On the other hand, in lowlands regions influenced by a wetter sub-Mediterranean climate, where deciduous broadleaf formations prevail, the 8.2 cal ka BP event impact would have been low. This situation is consistent with the fact that this cooling phenomenon would correspond to a wetter climate in European middle latitudes, locating the southern limit about 38–40° N (central Iberian Peninsula) (Magny et al., 2003, 2013).

Climate conditions and landscape transformation by first Neolithic communities (7.4-6.0 cal ka BP)

On their arrival to the Lake Banyoles area, the first farming societies settled in a humid and dense forested area, with the predominance of broadleaf deciduous forests (deciduous *Quercus* and *Corylus*) and conifers (*Pinus* and *Abies*) in the surrounding mountains and the presence of evergreen sclerophyllous taxa (*Quercus ilex-coccifera, Olea* and *Phillyrea*) at a regional scale. At a local level, riparian forests (*Ulmus, Fraxinus* and *Salix*) developed along the lakeshore, where hygrophyte (Cyperaceae, *Typha latifolia, Typha-Sparganium, Juncus articulatus* type, *Juncus effusus* type, *Cladium mariscus* and *Mentha* cf. *aquatica*) and aquatic plants (*Potamogeton coloratus*) were also present and dominant in areas with higher water availability.

The pollen record from the SB2 core indicates that an abrupt decline in deciduous *Quercus* values started *ca.* 7.6–7.4 cal ka BP and consolidated at much lower percentages by 7.3–7.2 cal ka BP, a phenomenon also attested previously by Pérez-Obiol and Julià (1994) (Fig. 13). This regression of broadleaf deciduous forests could have been caused by a cooler climate, as indicated by Frigola et al. (2007) in a marine core from the western Mediterranean where an abrupt cold event was identified in the period 7.4-6.9 cal ka BP, with the central age in 7.2 cal ka BP. Short cold and arid phases are detected in other Iberian lacustrine records during this period (Jalut et al., 2000; Vegas et al., 2009; Pérez-Sanz et al., 2013), which constitutes one of the drying/cooling phases in the global compilation by Mayewski et al. (2004). Additionally, stalagmite records in Soreq Cave (Israel) and Antro del Corchia (Northern Italy) show a decrease in rainfall from *ca*. 7.4 cal ka BP onwards (Bar-Matthews et al., 1999; Zanchetta et al., 2007). This period of dryness in the Iberian Peninsula could have affected the woodland cover around Lake Banyoles and indeed coincides with the onset of a decrease in the values of broadleaf deciduous trees in SB2 and LB (Fig. 13). This regression of oak forests is also recorded in other areas in the Eastern Pre-Pyrenees, as in the Vall d'en Bas-Olot basin (Pérez-Obiol, 1988) in 7.7-7.2 cal ka BP and in the Empordà basin (Parra et al., 2005) in 7.3-6.4 cal ka BP. Therefore, although human impact associated with the adoption of farming and the establishment of permanent settlements should also be considered to comprehend these changes in vegetation, it seems that the Neolithisation process in the Iberian Peninsula would have occurred in the context of a cooling and drying climate.

A compelling argument suporting this cooling/drying phase is the aforementioned lake water level regression occurring just before the establishment of Neolithic communities at La Draga. In fact, on their arrival these communities found a newly exposed beach that would have been formed by an abrupt regression of the lake water level. This major hydrological change would make sense in the context of a cooling phase and in a drier climate and would demonstrate the near-synchrony of this climate oscillation and the settlement of Neolithic communities in the area.

Nevertheless, it seems unlikely that climate cooling would have caused such an abrupt decline in oak and broadleaf deciduous forests given the limited impact of previous cooling episodes (9.0 and 8.2 cal ka BP) and the available archaeological data in the area, so climate change would not have been the exclusive cause of the described environmental changes. In fact, once Neolithic communities settled at La Draga in *ca*. 7.27 cal. ka BP, a fall in deciduous *Quercus* values is recorded at the site (Burjachs, 2000; Pérez-Obiol, 1994; Revelles et al., 2016) and in lakeshore peat deposits (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015).

The importance of deforestation activities is attested by the analysis of charcoal and wood from La Draga. Deforestation in oak forests would have been linked with the need for firewood and raw material for construction, as shown in the archaeobotanical record at La Draga (Piqué, 2000; Caruso-Fermé and Piqué, 2014; López-Bultó, 2015). The low values of sedimentary charcoal recorded in the SB2 sequence suggest that burning was not involved in the deforestation process, thus confirming that the slash-and-burn farming model was not practiced in the Lake Banyoles area during the Early Neolithic. The disturbance to forests caused by Neolithic communities stimulated fungal infections of trees as shown in the NPP record in SB2 core. The cutting of oak trees may have provided the proper conditions for infection and rapid wood decomposition by lignicolous fungi and the ascospores would have reached the lakeshore due to the input of allochthonous muds from disturbed upland areas.

The settlement of Neolithic communities in the immediate surroundings of the lake also implied strong sedimentation changes. The adoption of farming activities and the intensive deforestation carried out since the Neolithic induced significant acceleration in soil erosion processes. Lack of plant cover implied higher propensity to soil erosion in lakeshore environments, a phenomenon attested both at La Draga (2nd phase, *ca.* 7.16-6.75 cal ka BP) and in the SB2 record (progressively increasing from 7.25 cal ka BP but clearly attested in the period 6.0-5.55 cal ka BP). Nevertheless, the climatic factor should be considered as a possible amplifier of these erosion phases during the first half of the Holocene (Simonneau et al., 2013), when torrential episodes led to high hydrological activity causing erosion (Berger et al., 2016).

Soil erosion linked with deforestation had an important effect on the limnological evolution of the lakeshore. The input of streams carrying terrigenous sediments caused higher turbidity in the water and higher levels of phosphorous were induced by farming in upland areas. These new ecological conditions conferred an adaptive advantage to green algae against cyanobacteria, given that under high turbidity, light becomes the limiting factor for nitrogen fixation (Zevenboom and Mur, 1980). In the same way, Characeae decreased, as water transparency (Langangen, 1974) and phosphorous levels are decisive for their distribution (Haas, 1994).

Resilience of broadleaf deciduous forests in the transition to the Late Holocene

Oak forests experienced a recovery after the end of Early Neolithic occupations around the lake and, consequently, of human pressure in *ca*. 5.5 cal ka BP. Nevertheless, the sedimentation in the lakeshore by allochthonous terrigenous mud continued after 5.5 cal ka BP with maximum peaks at *ca*. 5.5, 5.3 and 4.3 cal ka BP. Changes in seasonality after Bond event 4 (5.9 cal ka BP) led to the establishment of drier conditions in Mediterranean areas (Jalut et al., 2009; Magny et al., 2012), as attested in Iberian lacustrine (Morellón et al., 2009) and marine records (Frigola et al., 2007). These changes in climate would lead to concentration of rainfall in torrential episodes, as recorded in soil erosion during the 6th and 5th millennia cal BP in the SB2 record. The combination of this drier climate context and the infill of the lakeshore by the high sedimentation rate related to the allochthonous mud proceeding from soil erosion episodes, would have caused the creation of widely exposed swampy plains close to the lakeshore. The transition to subaerial drier vadose substrates explains the colonization by *Alnus*, resulting in the establishment of a larger riparian forest in the newly emerged lands, a process consolidated from *ca*. 5.25 cal ka BP with the expansion of other riparian trees (*Salix*, *Ulmus* and *Fraxinus*). In that newly established alder carr environment, short deforestation episodes, fire activity in riparian vegetation and the presence of Cerealia-type coincide with records of coprophilous fungi (*Cercophora*-type and *Sordaria*-type), fungi indicating soil disturbance and an increase in monolete spores, revealing clear evidence of local human impact and cultivation near the lakeshore in the period *ca*. 5.0–4.2 cal ka BP, that is, in the Late Neolithic period.

Despite the occurrence of some sedimentation and local vegetation changes caused by a change in the hydrological regime due to changes in seasonality (greater drought in summer) after 5.9-5.5 cal ka BP, no major changes in vegetation at a regional scale are documented in the transition to the Late Holocene. As suggested by climate conditions and as attested in other Iberian regions, after 4.2 cal ka BP significant changes might be expected, such as the succession of evergreen sclerophyllous forests against broadleaf deciduous forests and the expansion of xerophytic taxa (Jalut et al., 2009; Carrión et al., 2010; Pérez-Obiol et al., 2011). Nevertheless, only minor changes are recorded in Lake Banyoles in that period. At a local scale, the highest values in Cyanobacteria indicate excessive eutrophication resulting from the combination of human impact and lake level lowering, while the highest values in Monolete spores evidence oxidation in peat environments (Dimbleby, 1957), probably seasonally dried. This local evidence of relative drier conditions would be consistent with palaeoclimatic evidence in the western Mediterranean from the 4.2 cal ka BP event onwards (Bond et al., 1997; Denèfle et al., 2000; Jalut et al., 2000, 2009; Roberts et al., 2001; Sadori and Narcisi, 2001; Carrión et al., 2010; Sadori, 2013), although no remarkable changes to drier conditions are recorded in upland vegetation.

From *ca*. 4.2 cal ka BP onwards, an increase in *Quercus ilex-coccifera*, *Olea* and *Phillyrea* is recorded, consistent with the succession process from deciduous broadleaf tree forests to sclerophyllous evergreen forests across the northern Iberian Peninsula (Carrión et al., 2010; de Beaulieu et al., 2005; Jalut et al., 2009; Pérez-Obiol et al., 2011). The start of this succession is registered in the SB2 sequence, so a trend of a decline in deciduous trees and an expansion in evergreen trees is documented. However, the end-result of this succession is not recorded, as the sequence ends at *ca*. 3.35 cal ka BP, and it would probably have occurred several centuries later. The reason for this later succession could be the south–north orientation of the process, starting in the south-eastern Iberian Peninsula in the early Holocene and reaching the north (41° N) around 2.87 cal ka BP (Jalut et al., 2000). As shown in this study, in sub-Mediterranean areas of the north-eastern Iberian Peninsula, the resilience of broadleaf deciduous forests prevailed during the Early and Middle Holocene. From the data presented here, the origin of the current vegetation in the Lake Banyoles area should be seen in the context of the transition from the Sub-boreal to Sub-Atlantic periods (drier conditions in the Late Holocene) and in the multiplication of anthropogenic impact since Roman times.

5. 2. SOCIO-ECOLOGICAL CONSEQUENCES OF NEOLITHISATION IN THE NE IBERIAN PENINSULA

The spread of the farming mode of production had significant long-term social and ecological impacts. The transformation of subsistence strategies from hunting and gathering to farming involved significant changes in the economy, ideology and social organization, as well as in the relationship between humans and the environment. The Neolithic consists of the appearance of organizational strategies based on the inclusion of the appropriation of reproductive cycles of some plants and animals within mechanisms of social production and reproduction.

Thus, the most relevant innovation in that period was the adoption of agriculture and husbandry as the basis of subsistence and the character of early farming has been widely discussed. As mentioned in the introduction, bioarchaeological research carried out in recent decades has shown that intensive mixed farming (small-scale, labour-intensive cultivation integrated with small-scale herding) emerges as the most plausible model across Europe. In fact, the available archaeozoological (Saña, 2011; Navarrete and Saña, 2013) and archaeobotanical (Antolín, 2013) data recovered at La Draga suggest that small-scale, labour-intensive cultivation and small-scale herding in an intensive mixed farming strategy were practiced (Antolín et al., 2014). An intensive cultivation system implies high yields due to high inputs of labour, through careful tillage, weeding and manuring (Bogaard, 2004b, 2005).

The oak forest regression attested both at La Draga (Burjachs, 2000; Pérez-Obiol, 1994; Revelles et al., 2016) and in lakeshore peat deposits (Pérez-Obiol and Julià, 1994; Revelles et al., 2014, 2015) led to the expansion of herbs (Poaceae, Asteraceae and *Plantago*), shrubs (*Erica*, in the pollen record, and *Buxus* cf. *sempervirens*, in the anthracological record) and secondary trees (*Pinus*, *Tilia* and *Corylus*). Part of the clearances would have been used for cultivation and grazing, but a large part of them remained unused and were colonised by secondary trees, resulting in only a slight decrease in AP. Thus, Neolithic forest disturbance involved the expansion of light-demanding trees and shrubs in a more open landscape. Besides, burning was not involved in the deforestation process as evidenced in the sedimentary charcoal record.

The practice of intensive farming practices in small crop fields would have resulted in an almost imperceptible impact of agriculture in pollen records from off-site deposits, and deforestation would be linked with the need for firewood and raw material for construction (Revelles et al., 2014). Nevertheless, despite the low impact of agriculture at extra-local level, small-scale, labour-intensive cultivation was documented at La Draga, with six crops identified: *Hordeum distichum* (two-rowed hulled barley), *Triticum durum/turgidum* (tetraploid naked wheat), some scarce finds of *Triticum aestivum* s.l. (hexaploid naked wheat), *Triticum dicoccum* (emmer), *Triticum monococcum* (einkorn) and *Papaver somniferum* (opium poppy) (Antolín, 2013; Antolín et al., 2014).

Therefore, a high concentration of Cerealia-type pollen is documented in the archaeological profiles coinciding with both occupation phases at La Draga. Crop fields could not be in the immediate surroundings of the settlement, because it was established in a swampy area unsuitable for cultivation. The plots would have been far enough away to prevent Cerealia-type pollen from reaching the off-site peat deposits (Revelles et al., 2014) and high concentrations within the settlement have to be understood in terms of anthropic input of spikelets, either for storage of crops or by-products. This is consistent with the presence of mixed cereal grains and chaff within archaeological contexts, suggesting domestic storage (Antolín et al., 2014) and the identification of probable storage structures, as is the case of structure 7001 (Berrocal, 2013).

Although the first farming societies in the Lake Banyoles area transformed the landscape noticeably, in terms of oak woodland deforestation, from 7.3 cal ka BP, no impact of grazing has been detected contemporary with this phenomenon. The lack of spores of coprophilous fungi during the onset of the Early Neolithic could be understood in the context of the intensive farming system documented at La Draga (Antolín et al., 2014), where the flocks would have grazed in the immediate surroundings of the settlement (along the opposite shore from the SB2 core) or in the upland crop fields. Nevertheless, the geomorphologic conditions of the lakeshore must be considered in order to comprehend this lack of spores of coprophilous fungi. Considering the swampy lakeshore, the animals could not approach the area and there is no evidence of grazing pressure until the occurrence of soil erosion episodes bringing allochthonous material from uplands in the period from 6.0 to 5.5 cal ka BP (Revelles and van Geel, 2016).

Thus, the integration of interdisciplinary analyses in both archaeological and natural deposits succeeded in recording human impact during the Early Neolithic on both local and extra-local scales in the Lake Banyoles area. The signal of farming activities was only identified at intra-site level, indicating the limited impact of the intensive economic model practised by the first farmers. The precise location of the crop fields has still not been located, but the immediate surroundings of La Draga and, in general, of the lakeshore, can be excluded because of the geomorphologic conditions (swampy substrate and seasonal flooding). The crop fields would have been on higher land in oak forest clearings, to the east of the settlement, in an area close enough to make an intensive management strategy possible (Antolín et al., 2014).

Landscape transformation at local and extra-local scale occurring from the time Neolithic communities settled in the area was mainly due to deforestation to obtain firewood and raw materials for construction. Nevertheless, the human transformation of landscape attested in the Lake Banyoles area during the Early Neolithic was not definitive, as broadleaf deciduous forests regenerated after the end of human pressure.

In conclusion, social organization around farming societies implied significant landscape transformation in the Lake Banyoles area. The high labour and resource investment involved in the adoption of farming became the backbone of the settlement of human communities in the territory from the Neolithic onwards. This model of human transformation of landscape is consistent with data from NE Iberia and, in general, from the whole Iberian Peninsula, where a sustainable small-scale and intensive farming system would have left scarce evidence of the impact of agriculture during the Early Neolithic. In any case, social changes linked with the adoption of farming can be considered the main cause of landscape transformation from the 8th–7th millennia cal. BP onwards. Thus, the establishment of permanent settlements and an intensive and reiterative exploitation of natural resources caused a noticeable modification of previous ecosystems.

5.3. POTENTIAL AND CONTRIBUTIONS OF ARCHAEOPALYNOLOGY IN LAKESIDE SETTLEMENTS RESEARCH

Coeval pollen records from natural and archaeological deposits were able to assess the representativeness of archaeopalynological analysis to obtain reliable data about the vegetal landscape. Apart from the overrepresentation of crops and grasslands due to higher local impact and anthropic input of some taxa to the settlement, the pollen record at La Draga has shown the reliability of archaeological deposits in order to determine vegetal landscape evolution at a local scale during several occupation phases. Nevertheless, the development of archaeoecological projects involving the integration of palaeo-environmental data from natural and archaeological deposits becomes essential to comprehend the intensity of human activities on the landscape at local and extra-local levels. But archaeopalynology has other potential contributions than assessing palaeo-environmental evolution, such as reconstructing site formation processes and the evaluation of different environments and activity areas within a settlement, and non-pollen palynomorph analysis and the consideration of taphonomic processes are essential to assess such goals.

The role of non-pollen palynomorphs (NPP) in site formation-process reconstruction

The integration of NPP analysis within archaeopalynological studies provides relevant information about local environmental conditions, such as changes in hydrology and trophic conditions, soil erosion episodes, fire occurrence and the presence of dung. Nevertheless, the ecological requirements of many NPP are still under debate, while many new types are defined in every new published work. In that sense, one of the main challenges of NPP research is to obtain information about the ecological significance of these microremains. As mentioned in the introduction, the scarcity of palaeorecords providing descriptions and illustrations of palynomorphs in the Iberian Peninsula is further accentuated in NE Iberia and only focused on such topics as high mountain area palaeorecords or surface samples. This PhD thesis therefore attempts to address the lack of knowledge about the ecological significance of NPP in lowland areas in NE Iberia, and to provide descriptions and illustrations of newly recorded NPP types, which is an essential step in order to make progress in NPP research.

In total, this study attempted to shed new light on NPP documented in the archaeological site of La Draga and in the SB2 record, with special attention to 51 new types (*UAB* types). Some of them were attributed to probable carbonicolous/lignicolous (UAB-4, 9, 10, 11, 12, 18A, 38) or coprophilous (UAB-2, 33, 34A, 34B, 36) origins, other were associated with soil erosion episodes or to subaerial soils exposed to weathering (UAB-1, 3, 5, 8, 13, 17, 18B, 34B, 43, 48). The ecological significance of some NPP is still uncertain (UAB-7, 15, 16, 21, 22, 26, 27, 31, 32, 35, 37, 39, 40, 41A, 41B, 41C, 42, 44, 45, 46, 47, 49, 50, 52, 53, 54, 55) and others indicate very specific conditions, like the indicators of alkaline environments poor in nutrients (UAB-20, 23, 24), waterlogged wet environments (UAB-14), disturbed soils in an alder carr environment (UAB-29, 30A, 30B) or eutrophic waters (UAB-25).

The studied records showed that NPP distribution is mainly influenced by taphonomic or anthropic processes rather than by natural ecological or climate dynamics. Sedimentation dynamics involved in the formation of La Draga influenced the composition of the NPP spectra, reflected in the contraposition between waterlogged and subaerial layers, but especially between organic clayish or peaty layers formed at local level and sediments transported by erosive processes. In the SB2 record, major NPP fluctuations corresponded to vegetation changes, and soil erosion induced by deforestation during the Early Neolithic (7.3–5.5 cal ka BP) caused major changes to the lakeshore, influencing the aquatic ecosystem and the fungal spectra.

One factor showing the representativeness of the analysis carried out in the archaeological profiles at La Draga concerns NPP diversity. In this respect, the analysis of three profiles was able to identify 44 new types (UAB types), and the posterior analysis focused on Level VII (spatial analysis) did not identify any new palynomorphs. Therefore, the classical diachronic studies in archaeological profiles are reliable enough to represent the diversity of palynomorphs within an archaeological site.

In conclusion, the NPP analyses carried out at La Draga and on the SB2 record were a key factor to comprehend the formation of natural and archaeological deposits given the strictly local information that this kind of approach obtains and provided significant data to comprehend and interpret the pollen record from both sites.

The importance of palynological taphonomy for comprehension of pollen record formation

Various taphonomic processes occur in aerial/subaerial mineral deposits such as archaeological sites where they can deform the original deposition of pollen and NPP. In other words, while pollen deposition in natural deposits is presumably homogenous, significant differences can be attested in pollen abundance within small areas, and this is more likely in records affected by taphonomic agents, especially in archaeological contexts. Consequently, anthropogenic sediments from lakeside settlements cannot be regarded as the best archive for palaeo-environmental reconstruction given the overrepresentation of taxa introduced by humans and the deterioration of palynomorphs by soil erosion, weathering, oxidation of sediments..., but they represent a relevant tool to focus on archaeological questions. The application of palynological analyses in archaeological deposits is useful to obtain evidence of socioeconomic practices, in terms of documenting crops, gathered plants, stabling of flocks, exploitation of forests etc., but taphonomic processes involved in the formation of the palynological record must be considered.

The differential representation of taxa in pollen records caused by natural differences in productivity and dispersion is even wider when the pollen record is affected by taphonomic agents or processes, more common in mineral soils (Havinga, 1974; Hall, 1981; Faegri and Iversen, 1989). Differential preservation of pollen grains, influenced by the sporopollenin form and content (Kwiatkowski and Lubliner-Mianowska, 1957; Brooks and Shaw, 1972), is the cause of common over and/or underrepresented taxa and is recognizable when the pollen record shows the dominance of the most resistant pollen grains. In fact, differential preservation is attested at La Draga, evidenced in the spatial distribution of Pollen Concentration (PC), Richness and in Undeterminable pollen values. PC and Richness display their highest values in the north-eastern part of the sampled area, coinciding with the highest values of Organic Matter (OM). In contrast, Undeterminable pollen is concentrated in the south-western area, coinciding with the highest values of Other Mineral content in the sediment. Strong evidence of differential preservation of pollen grains in Level VII is the contraposition of distributions of some well-known vulnerable taxa versus highly resistant taxa. While the highest values of the vulnerable Caryophyllaceae, Apiaceae, *Vitis*, Cyperaceae, *Salix*, *Fraxinus*, *Ulmus*, *Plantago* and *Plantago major-media* are concentrated in the north-eastern/eastern area, the highest values of the resistant *Pinus*, *Abies*, *Pteridium* and Asteraceae liguliflorae are concentrated in the western area.

Several processes can produce deterioration of pollen grains, but weathering-oxidation and changes in humidity are evidenced as the most influential. In addition, sub-aerial exposure causes oxidation and enables further degradation by bacteria or fungi (Elsik, 1971). In this context, the extent of permanent waterlogged areas in the settlement conditioned the differential preservation of pollen and NPP, showing that higher diversity, pollen concentration and organic matter coincide with concentrations of freshwater algae (*Spirogyra*, *Mougeotia*) and Cyanobacteria (*Gloeotrichia*), revealing a humid and at least seasonally flooded area in the NE of Sector D. In contrast, in the western area there is a concentration of fungi spores, some of them indicating soil erosion and disturbance (*Glomus*, HdV-361, *Diporotheca rhizopila*) and decomposition of wood in wet environments (*Coniochaeta* cf. *ligniaria* (HdV-172), *Diplocladiella scalaroides*).

In conclusion, the significant spatial difference and concentration of fungi evidences different deposition and preservation conditions between the east and west areas, indicating a waterlogged (or at least humid) environment in the north-east and a sub-aerial environment in the west, leading to the alteration of pollen grains by weathering-oxidation. Therefore, the differential preservation of pollen grains at La Draga can be explained in terms of the existence of different environments within the site, thus demonstrating, that a taphonomic approach to archaeopalynological studies can furnish useful information about intra-site spaces and environments.

Contributions of archaeopalynology to the research at La Draga

The archaeopalynological study carried out in the framework of the present PhD thesis has contributed relevant data to the research project of La Draga, important to achieve a better understanding of past social activities and palaeo-environmental evolution. Firstly, it has determined the evolution of the environment at local scale within and surrounding the settlement. An aquatic environment existed on the current eastern lakeshore previously to the occupation. The lake water regression just before the arrival of Neolithic communities to the Lake Banyoles area created the exposure of a carbonated sand beach. This newly created beach devoid of vegetation constituted the perfect place to establish the Neolithic settlement given the densely forested landscape at the time of their arrival. In that sense, only some aquatic plants (*Potamogeton* sp., *Najas* sp. Characeae), and hygrophyte herbs (Cyperaceae –*Cladium mariscus*, *Carex* sp.–, *Juncus articulatus*, *J. effusus*, *Typha latifolia*, *Typha-Sparganium*, *Mentha* cf. *aquatica*) existed in a poor-in-nutrients environment, preventing trees from growing in such a setting. Thus, even bearing in mind the short dispersal of *Fraxinus*, *Salix* and *Ulmus*, the riparian forest would have been relatively distant from the settlement as shown in the pollen record at La Draga and surely not within the settlement.

The first occupation phase would have taken place in a wet environment, at least seasonally flooded. According to data from archaeological profiles (Revelles et al., 2016) it seems that 1st phase sediments (Level VII) were absolutely formed in a waterlogged environment. However, the spatial analysis of this level (Revelles et al., submitted) has shown that spatial differences existed, between wetter and probably permanent waterlogged spaces below huts, and drier areas more exposed to weathering in outside spaces. In addition, the palynological analysis was useful to determine the differences between two layers belonging to the first phase (VIa and VII), previously indicated by macrofossil analysis in Antolín (2013), showing that while Level VII would have been formed during the 1st phase of occupation as a gradual accumulation of residues and waste of human and animal activities within the settlement, Level VIa was formed after the collapse of wooden structures. Afterwards, during the construction of the travertine pavement belonging to the 2nd phase, soil erosion episodes brought to the settlement allochthonous terrigenous muds (Levels IV and VI), causing the infill and cover of the remains of 1st phase constructions. In fact, the construction of this pavement could have arisen as a solution to the flooding of the area by these mud inputs. These soil erosion processes must be understood in relation with the deforestation started in the first phase and accentuated during the occupation of the site, a phenomenon previously attested in the SB2 record (Revelles et al., 2015).

However the application of archaeopalynology did not have only a significant contribution in diachronic terms, as the application of geostatistic methods enabled the reconstruction of the dynamics of formation of the archaeological record and provided crucial information to assess the use of space within the settlement. The integration of spatial distribution of pollen and NPP with the spatial distribution of archaeological remains, wooden structures and parasitic helminth eggs at La Draga provided relevant information to comprehend the use of space in terms of management of waste and residues, and the identification of a hut in the north-eastern part of the sampled area in Sector D (northern central part considering the whole sector). The achievement of this kind of goal is extremely valuable in open-air pile dwelling sites, where the reconstruction of domestic structures and spaces is hard. The association of the highest values of OM, freshwater algae, cyanobacteria and lakeshore plants (in pollen and macrofossils) points to a humid environment, at least seasonally flooded, that may have corresponded to the space beneath a pile dwelling. The sediments from this area would have formed in a humid environment beneath the structure, with abundant organic matter and archaeological remains in the waste from the production or consumption activities carried out within the hut. The differential preservation and deposition environments would have been caused by insolation in outside spaces contrasting with moisture beneath the structures.

The archaeopalynological study also provided detailed data about farming practices. The high values of Cerealia-type pollen documented in different layers at La Draga should be understood in terms of anthropic inputs rather than natural deposition coming from crop fields, given the local swampy conditions unsuitable for cultivation and the well-known short dispersion of Cerealia pollen (Heim, 1970; de Beaulieu, 1977; Diot, 1992). Additionally, the integration of carpological analysis (Berrocal, 2013) and palynological data (Revelles et al., submitted) identified a spatial correlation between Cerealia-type pollen grains, Monocots charred epidermis and a significant concentration of charred *Triticum aestivum/durum/turgidum* seeds (level 7001), interpreted as a probable storage structure (Berrocal, 2013), as well as with a concentration of grinding tools in the area nearby indicating, consequently, a probable wheat processing area (Morera, 2016).

As mentioned in a previous section, the precise location of the crop fields has still not been determined, but the lakeshores were presumably not used for cultivation because of the swampy substrate. The crop fields would have been on higher land, probably to the east of the settlement, in an area close enough to make an intensive management strategy possible (Antolín et al., 2014). In the same way, the overrepresentation of other herbaceous and shrub taxa (i.e. *Vitis*, Asteraceae, Apiaceae, *Plantago*) should be understood in the context of anthropic inputs to the settlement, a phenomenon previously attested in archaeological deposits (Richard and Gery, 1993; Gauthier and Richard, 2009; Jeraj et al., 2009). This argumentation becomes stronger after the spatial analysis, because accumulations of these taxa (*Vitis*, Apiaceae and *Plantago* in NE of sector D) have been identified in specific areas, specifically associated with the location of a hut (sediments formed below the hut).

Spores of coprophilous fungi and parasites provided interesting data for the discussion about the husbandry practices and farming strategy at La Draga. Thus, the evidence of many types of spores of coprophilous fungi points to local presence of animals within the settlement, consistent with an intensive farming model, which would imply a close integration of crops and husbandry, through livestock kept within settlements, the use of crops as fodder and the introduction of manuring (Bogaard *et al*., 2013). Nevertheless, the occurrence of coprophilous fungi in archaeological sediments might also be related to human dung, as evidenced by the identification of *Trichuris trichiura* (human parasite) during the parasitological analysis (Maicher, 2013; Maicher et al., submitted). However, the occurrence of other parasites related to animals, like swine (*Macracanthorhynchus* and *Ascaris* sp.) or ruminants such as cattle (*Dicrocoelium dendriticum* and *Paramphistomum* sp.) combined with the highest values of *T. trichiura* shows that humans and animals shared the space, thus confirming, the stabling of livestock within the settlement.

The archaeoecological project carried out at La Draga, integrating palynology and geoarchaeology also provided information about the interaction of the Neolithic communities with climate change. The cooling phase affecting the Neolithisation in the Lake Banyoles area started before the occupation and lasted until almost the end of the occupation. Afterwards, despite drier conditions being attested in the second phase, these would have been caused by the infill of the deposit and not by a climate cooling episode. In fact, the amelioration of climate after the cooling phase in 7.4-6.9 cal BP could have been the cause of the site abandonment, because the end of a cooling phase might imply an increase in rainfall and an increase in lake water level making the lakeshore uninhabitable and forcing the population to move towards higher land or to other areas. In fact, climate change has been mentioned as an important factor conditioning life in lakeside settlements. Neolithic communities would have been sensitive to lake level fluctuations and the occupation at La Draga occurred between two higher lake-level phases (7.55-7.25 cal ka BP/6.35-5.9 cal ka BP) documented in the Jura Mountains, French Alps and Swiss Plateau (Magny, 2004). In this case, however, a cooler climate would have not been the limiting factor for the Neolithic communities but quite the opposite.

Once the settlement of La Draga was abandoned, the sedimentation changed to local organic layers, causing a recovery of organic matter values, the formation of sub-aerial peat where *Alnus* expanded, and the presence of more eutrophic water as shown by the presence of Cyanobacteria (Revelles et al., 2016). This new environment could have been formed in a wetter environment (the 2nd phase shows the occupation of a dry space in part thanks to the constructed travertine pavement) probably due to an increase in lake water level, configuring a peat land similar to the alder carr environment after 5.5 cal ka BP on the opposite lakeshore (Revelles et al., 2015).

6. CONCLUSIONS

Vegetation history and climate change during the Middle Holocene

Broadleaf deciduous forests in Lake Banyoles had their maximum expansion in the phase 9.0-7.5 cal ka BP, a decline in 7.5-6.5/5.5 cal ka BP, but a recovery afterwards, indicating persistence of oak forests as the dominant vegetation until the onset of the Late Holocene, at the end of the SB2 sequence (3.35 cal ka BP). Despite showing a decreasing trend from 7.5 cal ka BP onwards, broadleaf deciduous forests were resilient against cooling oscillations during the Middle Holocene; slight mesophilous taxa regressions in the 8.2 cal ka BP event only consisted of minimal declines in the total AP and no significant peaks of shrubs or grasslands (Poaceae, Asteraceae) were recorded. More important would have been the cooling phase in 7.2 cal ka BP, but the regression of deciduous forests should also be understood in the context of the arrival of the first farming societies in the area in 7.27 cal ka BP. Atlhough cooling events detected in the Minorca Sea in 5.0 and 4.1 cal ka BP coincide with phases of slight regressions of oak forests in the SB2 sequence, these cooling episodes did not cause irreversible changes and forests rapidly recovered.

It was the change in seasonality, with a longer dry season and lower precipitation and water availability in summer in the transition to the Late Holocene (5.0-4.0 cal ka BP), that was the decisive factor for the onset of progressive changes in vegetation history explaining the current landscape in the Mediterranean area, in general, and in the NE Iberian Peninsula in particular. Broadleaf deciduous woodland was replaced by evergreen sclerophyllous forests and shrublands in a progressively more open landscape. Nevertheless, although a slight expansion of sclerophyllous trees is documented from 5.5 cal ka BP onwards, resilience of broadleaf deciduous forests against climate change is attested in the Lake Banyoles area and the onset of this succession from broadleaf deciduous to evergreen sclerophyllous forests only began in the transition to the Late Holocene, and the process was culminated more recently, in historical times. In fact, this new evidence indicating that the process of replacement of broadleaf deciduous by sclerophyllous forests was not always homogeneous, and sub-Mediterranean climate areas showed the resilience of broadleaf deciduous woodland until the Late Holocene, as on the northern shores of the central Mediterranean.

Socio-ecological consequences of Neolithisation

The settlement of the first farming societies in the Lake Banyoles area was the cause of major palaeo-environmental changes. This process has been documented in diverse records, from the Neolithic site of La Draga and from peat deposits on the western lakeshore. Thus, the comparison between intra-site and off-site records allowed us to assess vegetation, palaeo-environment and human impact both in the settlement surroundings and at an extra-local scale, in the area of Lake Banyoles. Furthermore, the comparison of the anthropic impact evidenced in these two different types of deposit enabled an evaluation of the social use of space and the impact on the landscape of the different economic practices carried out in the settlement of La Draga during the Early Neolithic (7.27–6.75 cal. ka BP).

Neolithisation implied the spread of a new lifestyle based on the inclusion of farming activities within organizational strategies, causing profound change in the relationship between humans and environment. Nevertheless, social practices involved in agriculture and animal husbandry should be understood in a global productive process. This economic change lead to social changes, including permanent settlement patterns, a growing population and more intensive productive activities increasingly reiterated in the territory. These socioeconomic changes started a progressive process of landscape transformation, involving deforestation to open clearings for agriculture, grazing or permanent open-air settlements. In that context, archaeobotanical data becomes an essential key to assess the process of social change associated with the origin of farming societies, enabling vegetation history reconstruction and the characterisation of the impact of the exploitation of vegetal resources by Neolithic communities.

The practice of intensive farming models during the Early Neolithic, implying small-scale and labour-intensive cultivation, left little evidence of the impact of agriculture, in terms of absence or low values of crops and weeds in off-site pollen records. Nevertheless, deforestation linked to intensive exploitation of oak forests to obtain firewood and building materials has been documented in the Lake Banyoles area. While a sustainable small-scale and intensive farming system would have left scarce evidence of the impact of agriculture during the Early Neolithic, the intensive and reiterative exploitation of natural resources associated with permanent settlements led to significant landscape transformation. In any case, the adoption of agriculture should be considered the cause of these changes because the high labour and resource investment involved in the adoption of farming determined a permanent settlement in the territory since the Neolithic, and therefore, a reiterated impact on the landscape.

Changes in food production, in natural resource management and in settlement patterns involved in Neolithisation originated the onset of progressive human impact on the landscape that, together with climatic oscillations during the Holocene, caused considerable changes in the original geosystem. In that sense, the described human impact was enlarged and amplified in the context of a cooling phase in 7.4-6.9 cal ka BP, as attested in some global and regional palaeoclimatic records. Thus, this study evidenced the important role of climate change in amplifying Neolithic human impact, which in another climate context would have been less detectable in palaeo-environmental records. Therefore, it was the combination of climate cooling and human impact that produced such a landscape transformation as recorded in Lake Banyoles from 7.4-7.2 cal ka BP during the Early Neolithic period.

Potential and contributions of archaeopalynology in lakeside settlements research

The location of the site of La Draga on the shore of Lake Banyoles offered an exceptional opportunity in the context of the Iberian Peninsula to carry out an archaeoecological project comparing intra-site and off-site pollen records. The integration of bioarchaeological data from La Draga and from off-site pollen records provided significant data for the comprehension of human-environment interactions and the scale of human impact in the NE Iberian Peninsula during the Early Neolithic. Specifically, the application of integrated pollen, NPP, macrofossil and sedimentological analyses enabled an understanding of site formation processes, the reconstruction of palaeo-environmental evolution and human impact at a local scale and provided new data about socioeconomic practices during the Early Neolithic as well as about use of space within a pile dwelling site.

The multiproxy analysis applied at La Draga evidenced that local environmental conditions and ecological changes were mainly influenced by taphonomic or anthropic processes rather than by natural or climate dynamics. In that context, the application of NPP analysis has proved to be a valid tool for obtaining essential data from archaeological contexts to comprehend local environmental conditions, human impact and formation processes at archaeological sites. Referring to anthropic processes involved in the formation of the palynological record, the archaeopalynological study provided new data about farming practices at La Draga. On the one hand, accumulations of Cerealia-type pollen grains were linked to the storage of crops and/or by-products within the settlement; on the other, association of spores of coprophilous fungi and parasites indicated the keeping of flocks within the settlement, consistent with an intensive farming model.

The palaeo-environmental data obtained through the different analyses provided information to comprehend settlement dynamics on the eastern shore of Lake Banyoles over time. The newly-formed beach devoid of vegetation created by a lake water regression constituted the perfect place to establish the Neolithic settlement, given the densely forested landscape existing in the Lake Banyoles area on their arrival. In that sense, only some aquatic plants and hygrophyte herbs existed in an environment impoverished in nutrients, preventing riparian trees from growing in the immediate surroundings. During the 1st phase of occupation, different environments existed within the settlement: wetter and probably permanent waterlogged spaces below huts, and drier and more exposed to weathering in outside spaces. After the collapse of wooden structures, the area was infilled by allochthonous terrigenous mud arriving in the context of soil erosion episodes in deforested areas. The construction of a travertine stone pavement would have been the solution against the flooding of the area by mud.

Apart from amplifying the impact of deforestation by Neolithic communities, climate change could have influenced settlement dynamics on the shore of Lake Banyoles. Actually, the occupation at La Draga (7.27-6.75 cal ka BP) occurred during a cooling phase (7.4-6.9 cal ka BP), and the consequent drier conditions enabled the establishment in a newly exposed beach on the eastern lakeshore. The end of this cooling phase could have led to an increase in lake level, making uninhabitable the beach where Neolithic communities had settled for *ca.* 300 years.

The spatial analysis of the distribution of pollen and NPP within the settlement evidenced the usefulness of this kind of approach in archaeopalynology. The consideration of the taphonomic processes involved in the formation of the palynological record and the integration of pollen and NPP distribution with the spatial analysis of archaeological remains and architectural assemblages enabled the reconstruction of different environments/spaces within the settlement of La Draga.

Despite taphonomic issues explaining most of the distribution of taxa within Sector D at La Draga, human use of space is included within the processes involved in the differential preservation of pollen and spores. Cereal grinding and the occurrence of fire in the south-western/south-central area of Sector D caused considerable alteration to pollen (highest values of Undeterminable, lowest of PC) and proliferation of fungi in an eroded subaerial mineral soil. In the opposite corner (north-east), a humid organic environment was identified beneath a hut built on stilts and platforms above the water, where an accumulation of archaeological remains from consumption waste was documented, as well as a concentration of herbs, plants with subsistence value and associated parasites (human and animal) and spores of coprophilous fungi.

This work evidenced the need to carry out spatial analysis in palynological studies in archaeological sites, owing to the spatial heterogeneity of results caused by human impact in terms of input of plants to the settlement (gathering, cultivation, storage, foddering), in arrangement of structures and in soil erosion. Additionally, spatial analysis in archaeopalynology has proved to be an appropriate method to comprehend site formation processes and to obtain new data to understand the use of space within a lakeside settlement.

Final remarks and future perspectives

The present doctoral thesis has provided interesting data about vegetation history and human-environment interactions during the Neolithic in the NE Iberian Peninsula. The interdisciplinary archaeoecological research carried out in the Lake Banyoles area enabled an assessment of human impact on local and regional scales as well as reconstructing use of space and site formation processes in a Neolithic pile-dwelling settlement, La Draga. The application of non-pollen palynomorph (NPP) analysis contributed significant data to understand palaeo-environmental evolution at a local scale. Nevertheless, future work should focus studying ecological requirements of the different palynomorphs in greater depth, especially the new types described in this thesis (UAB types). In that sense, collaboration with mycologists would shed new light on the ecology of unknown fungal spores and on the potential of NPP analysis for addressing archaeological and palaeoecological questions.

The pollen record at Lake Banyoles provided outstanding data for reconstructing vegetation history during the Middle Holocene, both at local and regional scales. However, quantitative reconstruction of vegetation calibrating the relationship between plant abundance and pollen record by correcting production and dispersal biases would achieve a more reliable image of past landscapes. This is a pending issue that will be interesting to address in the future, involving detailed modern pollen-vegetation data sets in the area. In fact, the lack of the required data for carrying out this kind of calibration implies a hard work that would justify an entire PhD thesis.

This research has evidenced the relevance of climate change in Neolithic settlement dynamics. Although palynology and other palaeoecological disciplines (palaeobotany, sedimentology…) contributed significant information about environmental responses to climate change, it would be interesting to count on the reconstruction of the local palaeo-climatic evolution in Lake Banyoles through isotopic analysis, Chironomidae, etc. In general, although this PhD integrated different proxies (pollen, NPP, macrofossils, sedimentary charcoal, sedimentology), more interdisciplinary collaboration (i.e. diatoms) is needed to complete the knowledge about past landscape evolution in the Lake Banyoles area. Obviously, more proxies and more records would provide a better understanding of past climate and environmental change. Concerning the option of obtaining new cores, for the future it would be interesting to seek Holocene lacustrine sequences offering high-resolution records. The lacustrine carbonated sediments would offer a more regional signal than the peat deposits on the shores, and it would be especially interesting to carry out sedimentary charcoal analysis, given the fact that the analysed core did not provide enough resolution for fire history modelling. Considering that fire is an important element in Mediterranean environments, more sedimentary charcoal records are required in this area to know fire history during the Holocene in the NE Iberian Peninsula.

The potential of archaeopalynology for assessing human activities and use of space within settlements has been evidenced in this work. Nevertheless, some factors limited the task. Firstly, the limited sampled area in the spatial analysis. Obviously, the 32 m^2 studied represent only a small part of the total *ca.* 3000 m^2 of the site of La Draga. The lack of pollen samples before the season in 2012 limited the extent of the analysis. However, the analysis of samples recovered in Sector A in fieldwork seasons from 2014 to 2016 will provide in the near future interesting results to compare with the analysis in Sector D presented in this thesis. For this purpose, it will be also essential to integrate sedimentological data (ongoing sedimentological, geomorphological and geochemical analyses by E. Iriarte), dendrochronology and the study of phytoliths and starches.

Finally, the continuation of studies of new Holocene records and the development of archaeoecological projects is essential to confirm or discuss the hypothesis proposed in this PhD thesis. The study of new sequences in the future is necessary to enlarge the available datasets and to obtain new data about vegetation history and human-environment interactions during the Neolithic in the NE Iberian Peninsula.

7. ANNEX

7.1. Annex 1. Minimum count sums in archaeopalynology. Pollen and NPP quantification from the lake dwelling archaeological site of La Draga (Girona, Spain)

Minimum count sums in archaeopalynology. Pollen and NPP quantification at the archaeological lake-dwelling site of La Draga (Girona, Spain)

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Abstract

Quantification approaches are essential in archaeopalynology and before dealing with pollen analysis, some elements must be considered in order to evaluate the statistical representation of pollen, spores and other microremains. Pollen slides are not usually analysed in their totality, as it is important to choose of a representative part of the whole, in order to save time and to avoid redundant information. The site of La Draga offered the possibility of applying such a quantification analysis in a variable pollen record subjected to different formation processes and to different preservation conditions: waterlogged organic sediments representative of peat and lacustrine pollen records and aerial inorganic sediments representative of most archaeological sites in the Iberian Peninsula. Thus, this study presents the analysis of the reliability of different counts of pollen grains and non-pollen palynomorphs for the archaeological site of La Draga (Girona, Spain). The qualitative and quantitative variability of anthropic taxa (crops, weeds, ruderals and spores of coprophilous fungi) have been emphasised in relation with different pollen sums, in order to find the minimum pollen sum from which these taxa are qualitatively and quantitatively stabilised.

This study evidences that richness is the most crucial factor influencing the minimum reliable pollen sum. At the same time, richness is influenced by site formation processes, specifically by the combination of two factors: anthropogenic input of taxa causing higher richness, and the formation and preservation of the archaeological layers. In organic clayish archaeological layers preserved in waterlogged conditions, higher richness is documented, both in total PS and in anthropic taxa. Thus, variability of richness is seen to be the result of a combination of anthropic influence and taphonomic/site formation processes. In conclusion, the most commonly used pollen count size of 300 has been shown to be a reliable sum for terrestrial inorganic sediments and for non-anthropic contexts, while higher pollen counts (400 to 500) are required for organic wetland archaeological contexts, where anthropogenic taxa are overrepresented.

Keywords: lakeside settlement, archaeopalynology, pollen sum, quantification, pollen counts

1. Introduction

Although pollen analysis of archaeological deposits provides information about landscape configuration in specific historic periods, the most essential data provided by archaeopalynology resides in local or extra-local questions and in the intensity of human impact (Behre, 1988). Pollen analysis from archaeological sites contributes essential data to addresss archaeological issues (Diot, 1984-1985; López-Sáez *et al.*, 2003) due to the fact that human activities cause changes in the configuration of the pollen record. In that sense, an overrepresentation of herbaceous taxa and higher richness is commonly documented in archaeological deposits due to the anthropic inputs (Richard and Gery, 1993; Gauthier and Richard, 2009; Jeraj *et al.*, 2009), either intentional or unintentional. Therefore, special emphasis should be placed in quantification of pollen taxa related with farming practices (crops, weeds and ruderals) (Richard, 1997; Barbier *et al.*, 2001) and non-pollen palynomorphs linked with local human impact (spores of coprophilous fungi) (van Geel, 1978, 2001; van Geel *et al.*, 1981) when dealing with archaeological contexts.

Quantification approaches are essential in palynology, given the fact that pollen analysis is the quantitative and qualitative study of pollen grains and non-pollen palynomorphs (NPP) that are contained in sediment samples. Before commencing pollen analysis, some elements must be considered in order to evaluate the statistical representation of pollen, spores and other microremains. Pollen slides are not usually analysed in their totality, and a representative part of the whole must be chosen, in order to save time and to avoid redundant information. Previous authors have already addressed this question and, proposed different minimum pollen sums: 200 (Shackley, 1981; Dimbleby, 1985), 300 (Burjachs *et al*. 2003; D'Antoni 2008), 500 (Vuorela, 1992), 700 (Bennett and Willis, 2001), 1000 (Birks and Gordon 1985). Minimum count sums for NPP have also been discussed (Etienne and Jouffroy-Bapicot, 2014). Other studies developed a statistical sub-sampling tool, demonstrating the necessity of testing minimum count size in every deposit and even in every sample, rather than assuming that a minimum count size is applicable in every pollen assemblage (Keen *et al*., 2014).

Nevertheless, this kind of methodological analysis has rarely been applied in archaeological deposits. Bastin (1964) and Erdman (1969) considered that from 150 to 200 pollen counts the percentages of dominant taxa (>5%) do not substantially change, and it is often assumed that 300 pollen grains are enough to represent qualitative and quantitative data of the pollen assemblage (Barkley, 1934; Martin, 1963; Burjachs *et al*. 2003). Nevertheless, scarce attention has been paid to the specific quantification of anthropogenic and rare taxa, which are those offering essential information to comprehend human impact and to assess spatial differences indicating activity areas or different site formation mechanisms within the settlement.

The methodology must be adapted to the special features of the different deposits in which pollen analysis can be applied. The formation of archaeological sites obeys different processes, with several taphonomic agents involved. Problems of preservation due to corrosion of pollen and spores in dry environments are well known (Hall, 1981; Havinga, 1984; Morzadec-Kerfourn, 1977; Coûteaux, 1977; Lowe, 1982; Bui-Thi, 1985; Campbell, 1999), and these are the most common conditions for archaeological sites in the Iberian Peninsula (Carrión *et al.*, 2009). On the other hand, the unintentional anthropic contamination of occupation layers causes the overrepresentation of herbaceous taxa and this should be taken into account when dealing with landscape reconstructions (Richard, 1997).

The site of La Draga (Girona, Spain) represents an exclusive Iberian site to discuss the topic of this study due to the fact that human impact has been previously attested (Revelles *et al.*, 2016) and because of the particular formation and preservation conditions of the site in the different sectors excavated. La Draga is located half-way along the eastern shore of Lake Banyoles (173 m asl.) (Girona, Spain) (Fig. 1). The climate in the Banyoles region is humid Mediterranean, with an annual precipitation of 750 mm and an annual mean temperature of 15 ºC. Current vegetation is dominated by a mixed evergreen oak, deciduous oak and pine forest. The site provides evidence of one of the earliest farming societies in open-air settlements in northeastern Iberia, dated to 7270-6750 cal BP (Bosch *et al.* 2012). It consists of a pile dwelling site where two different phases of early Neolithic occupation with distinctive constructive traditions have been documented; both dated within the late Cardial Neolithic according to pottery styles, and in the last three centuries of the 8th millennium cal. BP according to the radiocarbon dates. Phase I (7270–6930 cal. BP) is characterised by the collapse of wooden structures (carbonized in some points), which have been preserved in an anoxic environment. Phase II (7160–6750 cal. BP) presents several pavements of travertine stone. The levels in Phase II enjoyed less optimal conditions of preservation and the organic material is mainly found in a charred state, although some hard-coated uncharred material is found occasionally (Bosch et al., 2000, 2011; Antolín, 2013; Palomo et al., 2014).

Fieldwork was undertaken in multiple seasons from 1991 to 2014. From 1991 to 2005, the excavations concentrated on ‘Sector A’, where the archaeological level is above the water table and hence waterlogged conditions have not continued until the present. The archaeological level is in the phreatic layer in ‘Sector B’ and ‘Sector C’ is totally under water. New excavations from 2010 to 2012 focused on an area of 58 m^2 called ‘Sector D’, which is located to the south of ‘Sector B’ and displayed similar preservation conditions. The samples analysed in this work proceed from ‘Sector D’, which offers the possibility of comparing the pollen record from waterlogged conditions and from terrestrial inorganic clays transported by soil erosion events. For that reason, La Draga has been considered the best site to apply such a quantification analysis of pollen record variability subjected to different formation processes and to different preservation conditions: waterlogged organic sediments representative of peat and lacustrine pollen records and aerial inorganic sediments representative of most archaeological sites in the Iberian Peninsula.

This study aims to analyse the reliability of different counts of pollen grains and non-pollen palynomorphs from the archaeological site of La Draga (Girona, Spain). It will concentrate on the qualitative and quantitative variability of anthropic taxa (crops, weeds, ruderals and spores of coprophilous fungi) in relation with different pollen sums, in order to find the minimum pollen sum from which these taxa are qualitatively and quantitatively stabilised. In that sense, the main aims of this work are:

- Assess whether differences in terms of richness and evenness exist between samples and between archaeological layers in profiles at La Draga.
- Detect the reliable minimum pollen counts in different archaeological layers and the key factor of pollen count variability.
- Evaluate relationships between site formation processes and minimum pollen counts.

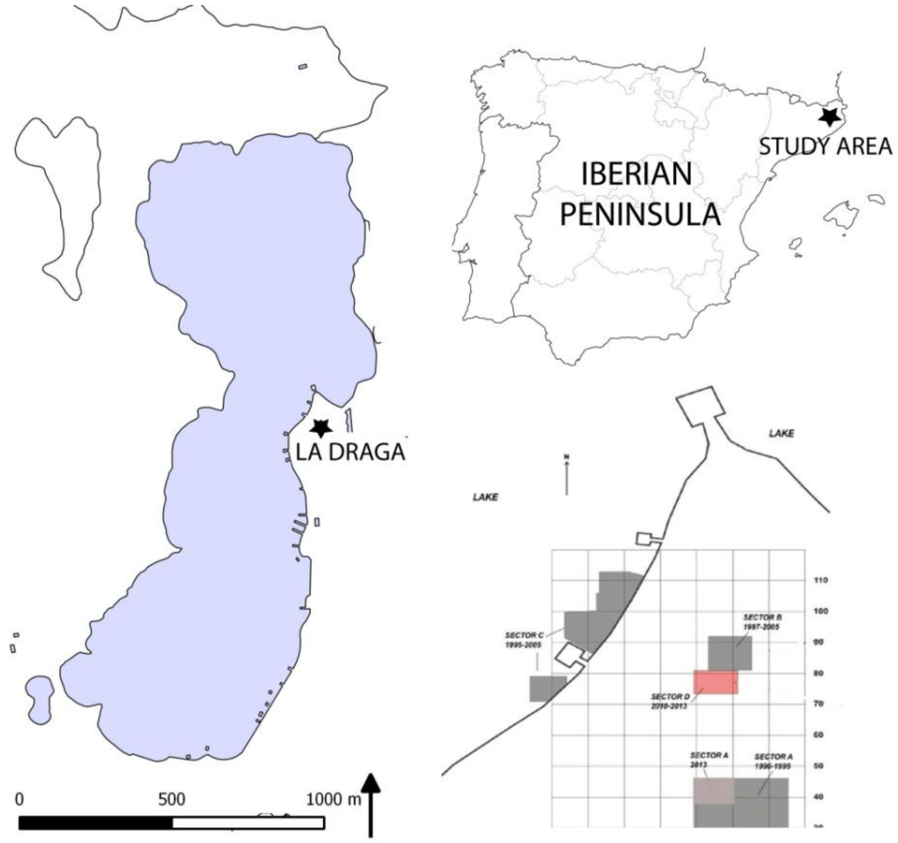

Figure 1. Location of La Draga and Sector D in the plan view of the site.

2. Materials and Methods

2.1. Sampling

West profile from 'Sector D' of La Draga (Fig.1) was chosen for sampling, because it represents the main sedimentary units in the archaeological record (6 of the 9 documented are represented there). Seven samples from west profile were used to carry out this analysis (one sample from Units I, II, IV, VI and IX, and two samples from Unit VII) (Table 1). Before the Neolithic settlement, the area was characterised as an aquatic environment poor in nutrients and rich in calcium (Layer IX). Layer VII, belonging to the 1st occupation, was formed by the precipitation of organic matter in a waterlogged environment as shown by the highest values of organic matter and pollen concentration. Afterwards, during the 2nd occupation, inorganic terrigenous clays were deposited in the context of soil erosion episodes caused by deforestation and transported by streams from uplands (Layers IV and VI). After the abandonment of the site, organic peaty layers were formed.

2.2. Pollen and non-pollen palynomorph analysis

The preparation of the samples followed standard methods (Burjachs *et al*., 2003) using treatment with HCl, NaOH, flotation in dense Thoulet liquor, HF (70%) and final mounting in glycerine. Pollen grains were counted using an Olympus Bx43 microscope fitted with ×10 oculars and ×40/60 objectives. Cyperaceae, *Typha latifolia* and *Typha/Sparganium* have been excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Reille (1992) and Cerealia-type was defined according to the morphometric criteria of Faegri and Iversen (1989). Non-pollen palynomorph (NPP) identification followed van Geel (1978, 2001), van Geel *et al*. (2003), Cugny (2011), Gelorini *et al*. (2011) and Revelles *et al*. (2016). Pollen concentration is expressed in pollen grains/gram of sediment following the volumetric method (Loublier, 1978).

In each sample, 1000 pollen grains were counted, and successive and accumulative counts of 50 pollen grains were entered in a spreadsheet. Non-pollen palynomorph counts are subordinated to pollen counts, differing between a minimum NPP sum of 94 (in sample 40), and a maximum of 2634 NPP (in sample 3). The taxa included in the evaluation of anthropic taxa variability were: Poaceae, Cerealia-type, Asteraceae tubuliflorae, Asteraceae liguliflorae, *Aster*-type, *Centaurea*, *Vitis*, *Artemisia*, Chenopodiaceae, *Plantago*, *Plantago major-media* type, Apiaceae, Fabaceae (*Vicia* and *Hedysarym* types), Lamiaceae, *Cirsium*-type, *Galium*-type, *Sedum*, *Rumex*, Brassicaceae, *Cercophora*-type (HdV-112), *Sordaria*-type (HdV-55A), *Podospora*-type (HdV-368), *Rhitydospora* (HdV-171), *Apiosordaria verruculosa* (HdV-169), *Trichuris* sp., ascospores UAB-33, UAB-34B (cf. *Delitschia*) and UAB-36.

2.3. Numerical analysis

The importance of variability in richness (amount of different taxa) and evenness to evaluate pollen count accuracy is noteworthy when dealing with archaeological deposits, where anthropic inputs of taxa increase the diversity of crops and ruderal herbs rarely recorded in off-site natural deposits. Thus, evenness and richness were calculated by Past 3.01 software (Hammer et al., 2001) for every pollen count (in absolute data in both total pollen sum and anthropic taxa datasets) in order to test their stabilisation. To determine the reliable pollen counts statistically, the Spearman's rank correlation coefficient was used (by Past 3.01), with a confidence level over 0.95, comparing absolute data from the different pollen counts (50 to 950) against the total pollen count of 1000.

Once the reliable minimum count is determined for every sample, both in total pollen sum (PS) and in anthropic taxa (AT), a Spearman correlation is applied to the variables Minimum count (PS), Minimum count (AT), Richness (PS), Richness (AT), Evenness (PS), Evenness (AT), Organic matter and Pollen concentration. A p value <0.05 indicates strong evidence against the null hypothesis, that is against the fact that the variance of reliable pollen counts is independent of other variables. These variables were submitted to correlation analyses in order to test correlation and covariance between them and to assess the key factor determining the reliable minimum pollen counts in the different archaeological layers. Finally, the variability of the Cerealia-type curve by applying different pollen counts is evaluated by correlation (linear r Pearson), testing the pollen count from which the most important pollen taxon in terms of human impact in Neolithic times is stabilised and shows reliable results.

Table 1.Sedimentological description of archaeological layers from the site of La Draga. See Revelles et al. 2016 for more detail about LOI analysis.

Phase	Layer	Sample	OM/CaCO3/Mineral	Description
Post-Neolithic	I	3	20.3/38.3/41.3	Peat, affected by modern agricultural works in some points of the site (i.e. south profile).
	II	9	15.7/23.7/60.5	Base of the peat layer, covering archaeological layers.
La Draga 2nd phase	IV	23	6.1/50/43.9	Greyish terrigenous clay among travertine stone structure.
	VI	30	6/45.7/48.2	Greyish terrigenous clay below travertine stone pavement.
La Draga 1st phase	VII	37 38	18/27.9/54 31.8/29.7/38.4	Dark organic clay below collapse of wooden structures.
Pre-Neolithic	IX	40	2.8/88.9/8.2	Lake marl, natural sediments before Neolithic settlement.

3. Results and Discussion

3.1. Minimum pollen counts in the site of La Draga

Pollen counts were considered statistically reliable once they exceeded a Spearman's rank correlation coefficient of 0.95. The results, both for total pollen sum and for anthropic taxa, are shown in Table 3 and in Fig. 2. The highest reliable pollen counts were evidenced in samples 3 (550 in PS/400 in AT), 9 (450/400), 37 (550/550) and 38 (500/400); and lowest pollen counts in samples 23 (300/100), 30 (400/300) and 40 (350/300). In case of anthropic taxa in sample 23, despite a pollen count of 100 reached 0.95, a higher pollen count was required to represent the richness of the sample (in a 100 pollen count only 8/15 taxa were recorded). For that reason, a 300 pollen count (13/15 taxa) was chosen for sample 23 to be submitted to posterior numerical analysis.

The numerical analyses applied show, in general, the qualitative and quantitative stabilisation of data from a pollen sum of 300-550, and counting more pollen grains only provided redundant information. Nevertheless, some differences can be observed between samples and between sedimentary units. In that sense, samples in less organic layers and with lower values of richness and pollen concentration (S-23, S-30, S-40), that is, from inorganic clays (Layers IV and VI) and from carbonate lacustrine clays (Layer IX) show reliable data (Spearman's correlation over 0.95) from lower pollen sums (300-400). On the other hand, samples with higher values of pollen concentration and richness (S-3, S-9, S-37, S-38), that is, from peat (Layers I and II) and organic clays (VII) always show stabilisation from 450-550 pollen grains counted. This study also evidences similar quantitative and qualitative stabilisation of data in total pollen sum (PS) and anthropogenic taxa (AT), but always with lower sums in the case of anthropogenic taxa (about 400 pollen count in organic rich layers and about 300 in inorganic layers).

As mentioned above, it is often assumed that 300 pollen grains are enough to represent qualitative and quantitative data of the pollen assemblage. Considering reliable pollen sums over 0.95 in Spearman's correlation ratio, only 'Sample 23' from the Layer IV presents 300 as a reliable pollen count. Nevertheless, the sum of 300 shows high Spearman's values in many samples, over 0.90 in PS in S-9 (Layer II), S-30 (Layer VI) and S-40 (Layer IX) and over 0.95 in AT in S23 (Layer IV), S30 (Layer VI) and S40 (Layer IX) (Table 3). That means that a 300 pollen sum in some archaeological layers from La Draga is reliable, specifically in inorganic layers (IV, VI and IX).

Thus, the standard 300 pollen sum is confirmed as a reliable pollen count in inorganic clay levels, the most representative type of sediment in archaeological sites in the Iberian Peninsula (Carrion et al. 2009). On the other hand, a minimum count of 450-500 pollen grains is required to obtain reliable data in pollen and NPP analysis of organic clays and peat levels, showing higher richness.

Table 2. Pollen concentration (PC, grains/g), Richness and Evenness by 1000 total count

Sample	Layer	PC	Taxa	Richness	Evenness
3	I	3323	Pollen Sum	46	0.39
			Anthropic	17	0.47
9	II	7198	Pollen Sum	38	0.38
			Anthropic	16	0.39
23	IV	6206	Pollen Sum	34	0.43
			Anthropic	15	0.51
30	VI	6705	Pollen Sum	44	0.39
			Anthropic	13	0.47
37	VII	25078	Pollen Sum	48	0.29
			Anthropic	26	0.51
38	VII	46117	Pollen Sum	45	0.31
			Anthropic	22	0.63
40	IX	9771	Pollen Sum	29	0.18
			Anthropic	8	0.50

Table 3. Spearman correlation (rho) results in Pollen sum (PS) and anthropic taxa (AT)

Count size	S3 (PS/AT)	S9 (PS/AT)	S23 (PS/AT)	S30 (PS/AT)	S37 (PS/AT)	S38 (PS/AT)	S40 (PS/AT)
50	0.64/0.75	0.75/0.69	0.83/0.89	0.70/0.78	0.59/0.73	0.63/0.63	0.66/0.81
100	0.73/0.84	0.83/0.82	0.90/**0.95**	0.79/0.80	0.70/0.72	0.78/0.87	0.79/0.82
150	0.82/0.86	0.88/0.83	0.91/0.97	0.84/0.80	0.79/0.77	0.87/0.92	0.84/0.89
200	0.83/0.86	0.82/0.82	0.94/0.98	0.87/0.92	0.79/0.77	0.86/0.90	0.84/0.89
250	0.88/0.92	0.86/0.89	0.94/0.98	0.87/0.90	0.84/0.78	0.88/0.92	0.83/0.91
300	0.88/0.90	0.91/0.92	**0.95**/0.99	0.91/**0.95**	0.84/0.77	0.88/0.91	0.91/**0.96**
350	0.88/0.91	0.93/0.93	0.96/0.98	0.93/0.95	0.87/0.79	0.88/0.91	**0.96**/0.96
400	0.92/**0.95**	0.94/**0.96**	0.98/0.99	**0.96**/0.99	0.89/0.86	0.90/**0.96**	0.96/0.96
450	0.94/0.95	**0.95**/0.97	0.98/0.99	0.96/0.99	0.91/0.88	0.93/0.96	0.96/0.95
500	0.94/0.97	0.96/0.98	0.98/0.99	0.97/0.99	0.94/0.94	**0.96**/0.97	0.96/0.95

550	**0.96**/0.97	0.97/0.98	0.98/0.99	0.98/0.99	**0.95**/**0.95**	0.96/0.97	0.96/0.95
600	0.96/0.97	0.97/0.98	0.98/0.99	0.99/0.99	0.95/0.95	0.97/0.97	0.97/0.96
650	0.96/0.97	0.97/0.98	0.99/0.99	0.99/1.00	0.97/0.97	0.97/0.98	0.98/0.96
700	0.97/0.97	0.98/0.99	0.99/0.99	0.99/1.00	0.97/0.97	0.98/0.98	0.98/0.96
750	0.97/0.99	0.98/0.99	0.99/0.99	1.00/1.00	0.97/0.97	0.99/0.99	0.99/0.96
800	0.98/1.00	0.99/0.99	0.99/1.00	1.00/1.00	0.98/0.99	0.99/0.99	0.99/0.99
850	0.99/1.00	0.99/1.00	0.99/1.00	1.00/1.00	0.98/0.99	0.99/0.99	0.99/0.99
900	1.00/1.00	1.00/1.00	0.99/1.00	1.00/1.00	0.99/0.99	0.99/0.99	0.99/1.00
950	1.00/1.00	1.00/1.00	1.00/1.00	1.00/1.00	1.00/0.99	1.00/0.99	1.00/1.00
1000	1.00/1.00	1.00/1.00	1.00/1.00	1.00/1.00	1.00/1.00	1.00/1.00	1.00/1.00

3.2. Richness, Evenness and site formation processes

Correlation between pollen counts, richness, evenness, organic matter and pollen concentration are shown in Table 4. The strongest correlation exists between pollen count (in PS) and richness (p=0.007), as well as between pollen count (in AT) and richness (p=0.014). A correlation was also documented between pollen count (PS) and organic matter (p=0.05), richness and organic matter (p=0.05 in PS; p=0.012 in AT) and between minimum pollen count in PS and AT (p=0.021). In that sense, richness emerges as the most determining factor in the definition of statistically reliable minimum pollen counts, with a correlation (linear Pearson r^2) of 0.83 in PS and 0.77 in AT (Fig. 4), and richness could be influenced by site formation processes (due to the richness-organic matter correlation) (Table 4).

The highest richness, both in anthropogenic taxa and in the total assemblage, is documented in samples from the Layer VII (samples 37 and 38) (Table 2). The lowest richness in both records is documented in Layers IV and IX (samples 23 and 40, respectively). Distribution of pollen taxa within the total pollen assemblage is assessed by the calculation of Evenness. Lowest values are documented in sample 40 (Layer IX, carbonate sands previous to the Neolithic settlement), consistent with the dominance of deciduous *Quercus* in the pollen assemblage (53%) (Revelles et al., 2016). Evenness is also quite low in samples 37 and 38 (Layer VII) due to the same oak dominance. In the remaining of samples, pollen taxa are more equally distributed. Anthropic taxa show higher evenness, therefore, an equal distribution within the pollen assemblage in all the samples.

Richness was evidenced as the main factor influencing count sizes and richness variability seems to be caused by variations in organic matter content in sediments. In that sense, inorganic clays and carbonate lacustrine clays showed lower richness and lower count sizes. The formation dynamics of the archaeological layers affected pollen assemblages, and in consequence, richness and minimum pollen sums to obtain reliable data. Organic clays and peat, with higher organic matter content show higher richness and pollen sum. In addition to the anthropogenic input of taxa, the taphonomic factor should be considered to comprehend the variability of richness. In that sense, better identification at species or genus level can be achieved in well-preserved material, while in worse preservation conditions the diagnostic elements may not be well preserved. Another factor to be considered is the site formation process. Lower richness, pollen concentration and organic matter are documented in layers formed by rapid depositions of eroded soils (terrestrial inorganic clays of Layers IV and VI). In contrast, the formation of layers by local precipitation of organic matter in a calm waterlogged/subaerial environment (Layers I, II, VII) leads to more organic sediments and richer pollen spectra. In conclusion, a combination of human input to the settlement and taphonomic processes is the cause of richer and more diverse pollen assemblages and, thus, higher pollen sums required.

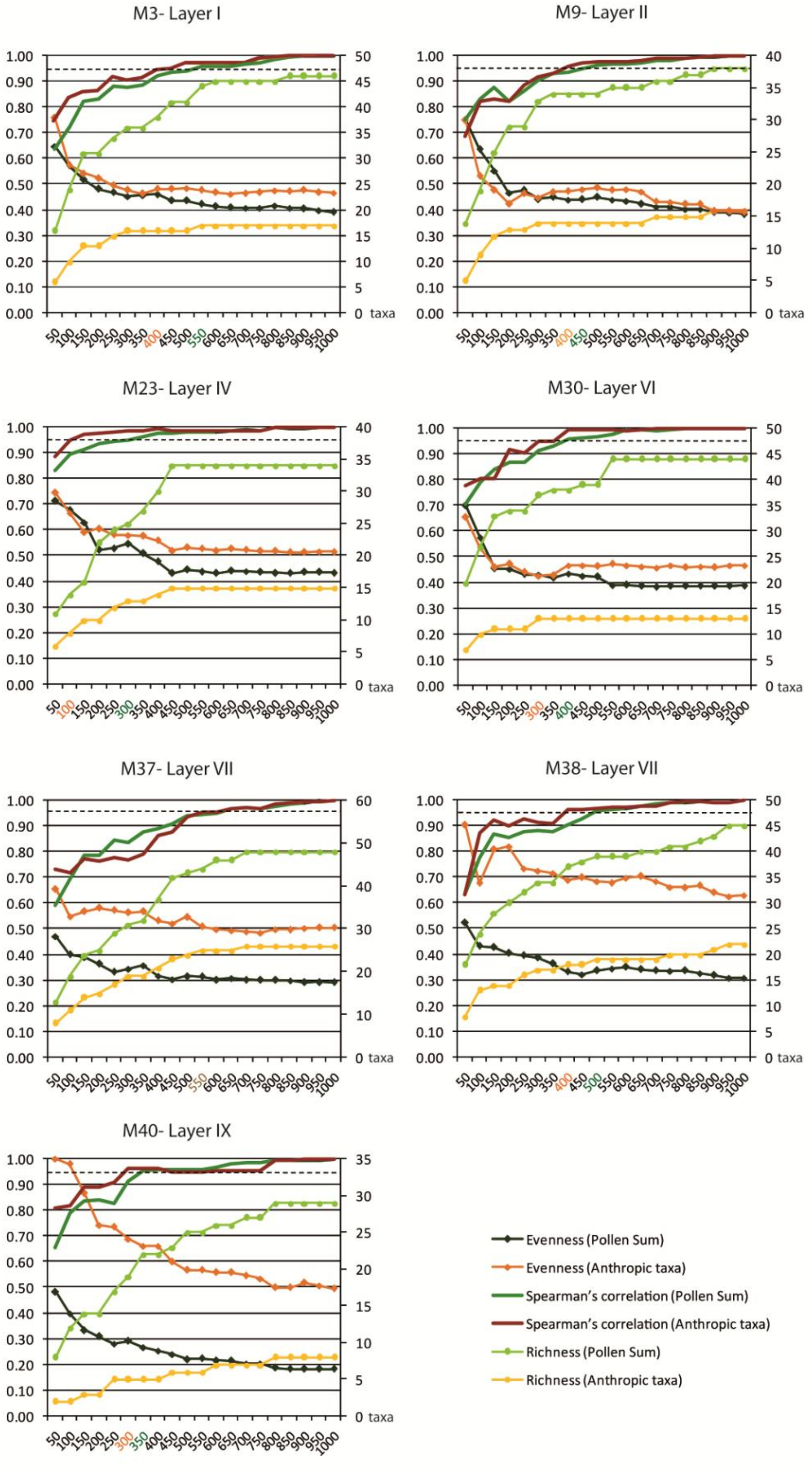

Figure 2. Spearman's correlation, Evenness and accumulative Richness in different pollen counts in each sample.

Table 4. Spearman correlation (statistic/p value) between minimum counts, richness, evenness, OM and PC.

	Count (PS)	Richness (PS)	Count (AT)	Richness (AT)	OM	PC	Evenness (PS)	Evenness (AT)
Min. Count (PS)		**0.007**	**0.021**	**0.03**	**0.05**	0.67	0.58	1
Richness (PS)	0.93		0.06	**0.03**	**0.05**	0.92	0.96	0.83
Min. Count (AT)	0.89	0.78		**0.014**	0.057	0.4	0.46	0.87
Richness (AT)	0.83	0.83	0.93		**0.012**	0.44	0.8	0.42
OM	0.77	0.77	0.77	0.89		0.59	0.95	0.51
PC	0.2	0.05	0.38	0.36	0.21		**0.04**	0.23
Evenness (PS)	-0.24	0.03	-0.33	-0.12	0.04	-0.8		0.65
Evenness (AT)	0	0.11	0.12	0.38	0.33	0.54	-0.22	

3.3. Anthropogenic taxa in archaeological deposits

Anthropogenic taxa variability must be considered in archaeological deposits, especially in a Neolithic settlement, when the adoption of farming practices led to the appearance of new species in archaeobotanical assemblages associated with agriculture. The most significant anthropogenic taxa is Cerealia-type, especially considering that the input of this taxa would have had an anthropic origin in the context of storage of cereals/chaff (Antolín et al., 2014; Revelles, 2016) and not by pollination from crop fields, which would have been too far away to be so overrepresented in the pollen record at the archaeological site. In that sense, the linear R correlation of Cerealia-type curves with different pollen counts shows that after 200 pollen grains the representation of Cerealia-type is stabilised ($p=0.049$), and reaches a high correlation after 300-pollen count ($r^2=0.89$) (Fig. 3).

In conclusion, anthropogenic taxa display stabilisation with lower pollen counts when compared with the total pollen sum. Therefore, 300 and 400 pollen counts are reliable for anthropogenic taxa representation in inorganic poor layers and in organic rich layers, respectively.

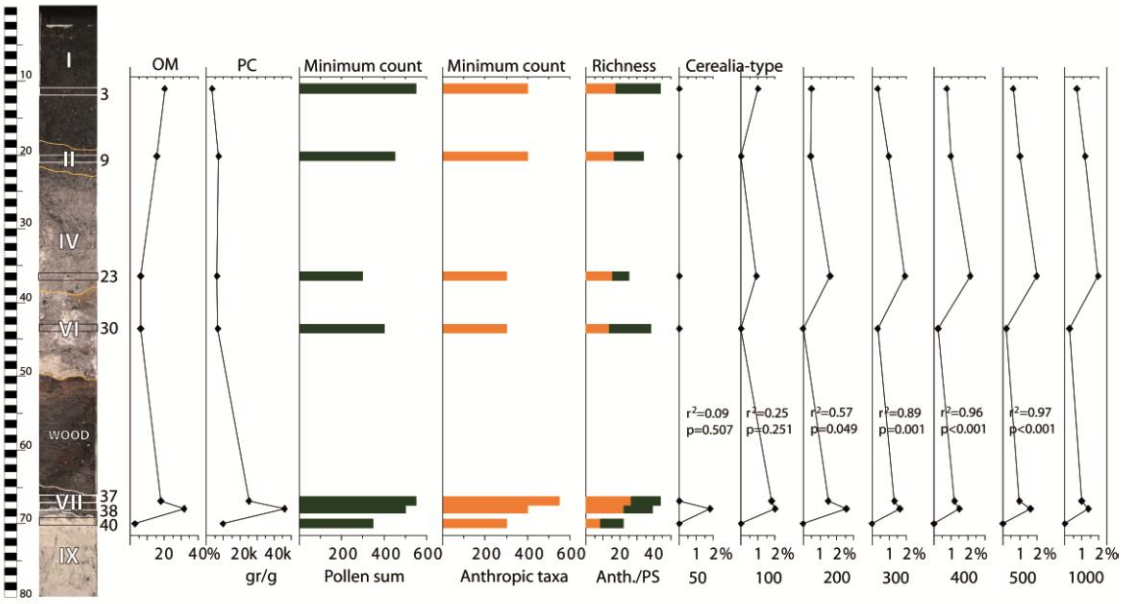

Figure 3. Relationship among organic matter (OM), pollen concentration (PC), minimum counts and richness (pollen sum in green, anthropic taxa in yellow) and correlation of representation of Cerealia-type in several sums by linear r Pearson.

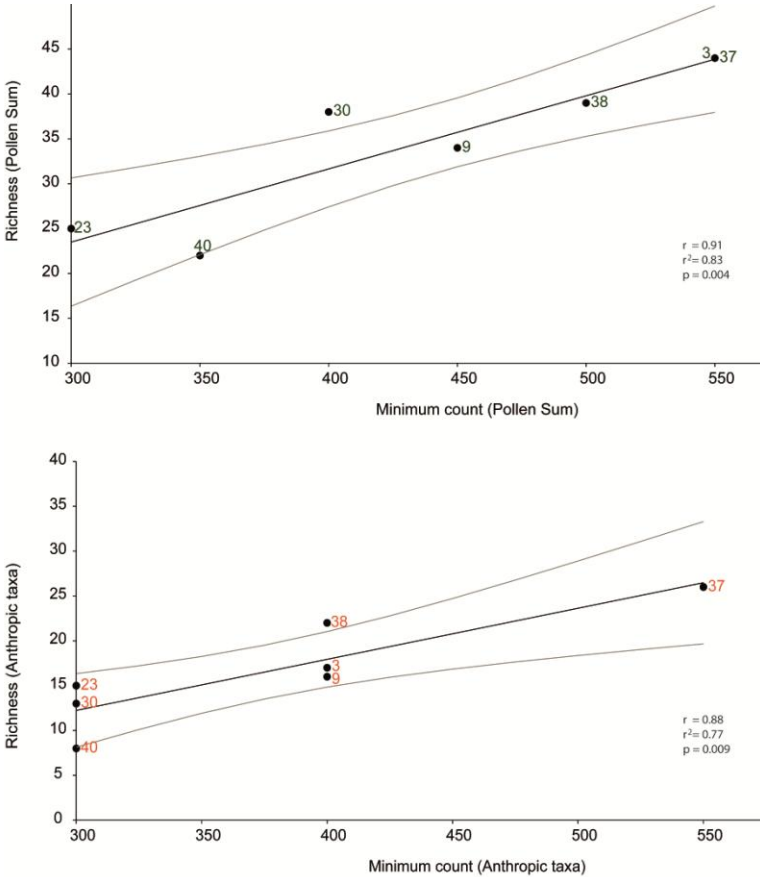

Figure 4. Richness- Minimum counts linear r Pearson correlation (A, pollen sum; B, anthropic taxa)

4. Conclusions

This work has shown the importance of carrying out quantification in palynology in order to produce reliable results through archaeopalynology. This study evidenced that richness is the most crucial factor influencing the minimum reliable pollen sum. At the same time, richness is influenced by site formation processes, specifically with the combination of two factors: the anthropogenic input of taxa cause higher richness, and also the formation and preservation of the archaeological layers. In organic clayish archaeological layers preserved in waterlogged conditions higher richness is documented, both in total PS and in anthropic taxa. Thus, variability of richness is evidenced as a result of a combination of anthropic influence and taphonomic/site formation processes.

In conclusion, the most commonly used pollen count size of 300 has proved to be a reliable sum for terrestrial inorganic sediments and for non-anthropic contexts, while higher pollen counts (400 to 500) are required for organic wetland archaeological contexts, where anthropogenic taxa are overrepresented.

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7.2. Annex 2. Original papers

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All the papers listed below can be found in the attached CD in PDF format:

- Revelles, J., Antolín, F., Berihuete, M., Burjachs, F., Buxó, R., Caruso, L., López, O., Palomo, A., Piqué, R., Terradas, X., 2014. Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain). Environ. Archaeol. 19 (3), 298–310.

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Other material:

-Doctoral Thesis (PDF)

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List of figures (thesis)[5]

List of tables (thesis)

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[5] Enumeration of figures and tables correspond to sections 1, 2, 3, 5 and 6. Scientific papers (section 4) and Anex 7.1. have their own lists (see next page).

List of figures (Scientific Papers and Annex 7.1.)

4.1.1. Revelles et al. 2015. Mid-Holocene vegetation history and Neolithic land-use in the Lake Banyoles area (Girona, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2015, 435: 70-85.

Figure 1. Location of the coring site and surrounding archaeological sites. Source for vegetation map: Mapa Forestal de España (Zona 10). Climogram: precipitation and temperatures data in 2013 recorded in the station of Banyoles.

1. Cova de Reclau Viver, Cova d'en Pau, Mollet III, Cova de l'Arbreda, Cova d'en Costa, Cau del Roure.
2. Cau d'en Salvador, Cova dels Encantats de Serinyà, Cau d'en Quintana.
3. Worked wooden remains, probably a canoe, recovered by underwater surveying.

Figure 2. Age-depth model based on six AMS radiocarbon dates. Estimation of age along the entire profile by a smooth spline technique using Clam 2.2 (Blaauw, 2010). From Revelles et al. (2014).

Figure 3. X-ray fluorescence (XRF) scanner data of the Lake Banyoles SB2 core. Element concentrations (Ti, Ca and Br), expressed as counts per second (CPS), and Ti/Ca, Ti/Br and Ca/Br ratios are indicated. Sedimentary facies/subunits, pollen zones and archaeological cultural periods are also included.

Figure 4. A. Percentage pollen diagram. Selected arboreal pollen taxa and sedimentary charcoal accumulation rate from the SB2 core (Lake Banyoles) are plotted to a calibrated year cal BP scale. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points (also in Figs. 4B and 6). B. Percentage pollen diagram. Selected non-arboreal pollen taxa from the SB2 core (Banyoles) plotted on a calibrated year cal BP scale.

Figure 5. Macro-remain diagram of absolute frequencies plotted to a calibrated year cal BP scale. Individual occurrence of taxa is represented by points.

Figure 6. Pollen categories compared with non-pollen palynomorphs categories, sedimentary charcoal and geochemical data. Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*), riparian forest (*Ulmus*, *Fraxinus*, *Salix*, *Alnus*), evergreen sclerophilous trees (*Quercus ilex-coccifera*, *Olea*, *Phillyrea*), shrubs (*Erica*, Cistaceae, *Vitis*, *Hedera helix*, *Crataegus*), Grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Plantago*, Chenopodiaceae, Lamiaceae), Cultivars (Cerealia-type), Spores of coprophilous fungi (*Sordaria* type, *Podospora* type, *Cercophora* type, *Rhytidospora*), and Algae (*Spirogyra*, *Zygnema*, *Closterium*, *Mougeotia*).

Figure 7. Pollen categories compared with climate data. Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*) and evergreen sclerophylous trees (*Quercus ilex-coccifera*, *Olea*, *Phillyrea*).

4.1.2. Revelles and van Geel, 2016. Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia). *Review of Palaeobotany and Palynology*, 2016, 232: 81-97.

Figure 1. Location of the coring site and surrounding archaeological sites. Isolines indicate 1mdifferences in altitude. 1) Worked wooden remains, probably a canoe, recovered by underwater surveying, and dated in 3200–3180 cal BP (Bosch et al., 2012).

Figure 2. A. Percentage NPP diagram. Fern spores and plant remains are plotted to a calibrated year BP scale. Hollow silhouettes show values exaggerated ×5. Values below 1% are represented by points (also in Figs. 2B, C and 3). B. Percentage NPP diagram. Fungal spores are plotted to a calibrated year BP scale. C. Percentage NPP diagram. Aquatic organisms, unidentified palynomorphs and zoological remains are plotted to a calibrated year BP scale.

Figure 3. Synthetic diagram comparing selected NPP taxa and categories expressed in percentages (silhouettes) and absolute concentration (particles/g) (lines), with macrofossils, sedimentology and pollen data from a previous work.

4.2.1. Revelles et al. 2014. Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain). *Environmental Archaeology*, 2014, 19 (3): 298-310.

Figure 1. Map showing the location of the study area in the Iberian Peninsula (A), the location of Banyoles in Catalonia (B) and the location of La Draga site and the SB2 core in Lake Banyoles surroundings (C).

Figure 2. Relative proportions among the number of seed and fruit remains recovered in systematic samples from Phase I in sector D of La Draga (right). Percentage charcoal diagram of the two occupation phases (Caruso and Piqué 2014). Relative frequencies of the main taxa from wood and charcoal analysis (left). Taxa classified as others: *Salix* sp., *Populus* sp., *Clematis* sp., Rosaceae/Rosoideae, Rosaceae/Maloideae, *Rubus* sp., cf. Leguminoseae, Monocot, *Cornus* sp., *Populus* sp., *Juniperus* sp., *T. baccata*, *Acer* sp., *A. glutinosa*, *A. unedo*, *Fraxinus* sp., *Pinus* type *sylvestris-nigra*, *Prunus* cf. *avium-cerasus*, *Ulmus* sp.

Figure 3. Age–depth model based on six AMS radiocarbon dates. Estimation of age along the entire profile by a smooth spline technique using Clam 2.2 (Blaauw 2010).

Figure 4. Percentage pollen diagram. Selected pollen taxa and sedimentary charcoal accumulation rate from SB2 core (Banyoles) are plotted to a calibrated year cal BP scale. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points. Pinus is AP overlayed. Valid for Fig. 5

Figure 5. Pollen categories compared with climatic data (GISP2 and Alboran Sea). Categories: broadleaf deciduous trees (deciduous *Quercus*, *Corylus*), riparian forest

(*Ulmus*, *Fraxinus*, *Salix*), evergreen sclerophilous trees (*Q. ilex–coccifera*, *Olea*, *Phyllirea*), shrubs (*Erica*, Cistaceae,*Vitis*), grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Urtica*), weeds (Chenopodiaceae, Brassicaceae, *Plantago* spp., *Plantago major-media*, *Rumex*). GISP2 values are 50-year smoothed.

4.2.2. Revelles (2016). Archaeoecology of Neolithisation. Human-environment interactions in the NE Iberian Peninsula during the Early Neolithic. *Journal of Archaeological Science: Reports*, 2016, http://dx.doi.org/10.1016/j.jasrep.2016.02.004

Figure 1. Left) Location of the study area in the NE Iberia and location of sitesmentioned in Fig. 2: 1 - Besós (Barcelona), 2/5 - Bosc dels Estanyons, Forcat, Riu dels Orris and Planells de Perafita (Andorra), 6 - Monte Areo (Asturias), and 7 - Conquezuela (Soria). Right) Pollen records analysed around Lake Banyoles.

Figure 2. Summary pollen diagram for SB2 (silhouette) and La Draga (histogram) and correlation with patterns of human impact in other pollen records in NE Iberia and in Iberian Peninsula. Hollow silhouettes show values exaggerated ×3. Values below 1% are represented by points. Categories: shrubland (*Erica*, Cistaceae, *Heliathemum*, *Vitis*, *Hedera helix*, *Crataegus*, *Sanguisorba*, *Rhamnus*), grasslands (Poaceae, *Artemisia*, *Filipendula*, Asteraceae, Apiaceae, *Galium*-t, *Plantago*, Lamiaceae) and weeds (*Plantago major-media*, Chenopodiaceae, *Rumex*, Brassicaceae).

4.3.1. Revelles et al. 2016. Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain). *Review of Palaeobotany and Palynology*, 2016, 225: 1-20.

Figure 1. Map with the location of the study area in the Iberian Peninsula, the position of Banyoles in Catalonia and the location of La Draga on the eastern shore of Lake Banyoles.

Figure 2. Plan view and cross section of Sector D at La Draga. Red rectangles in the plan view mark the spatial distribution of the three sequences analysed. In the cross section, red rectangles show columns of the West and South profiles; red points, subsamples retrieved in the field from West II profile.

Figure 3. Percentage pollen diagram of the West, West II and South profiles. Values below 1% are represented by points.

Figure 4. A. Non-pollen palynomorphs diagram. Fungal spores from the West, West II and South profiles are represented. Values below 1% are represented by points. B. Non-pollen palynomorphs diagram. Fern spores, algae, insects and unidentified remains from theWest, West II and South profiles are represented. Values below 1% are represented by points.

Figure 5. Macrofossil absolute frequency diagram.

Figure 6. Principal component analysis showing ordination of taxa. Main groups of taxa were surrounded and new types (UAB) marked in different colour.

Figure 7. Diagram comparing AP/NAP ratio, LOI results, values of pollen concentration and absolute frequencies (grains, spores or particles/g of sediment) of some NPP taxa and categories. Hollow bars represent values of new types classified as having probable coprophilous or carbonicolous/lignicolous origins.

4.3.2. Revelles et al. (submitted) Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia). Journal of Archaeological Science (submitted).

Figure 1. Location of the site (left) and location of Sector D within the site of La Draga (right)

Figure 2. Plan view, cross section and location of samples (pollen, NPP, Macrofossils and LOI in brown; parasitological analysis in orange).

Figure 3. Architectural wooden assemblages in the 1st phase at La Draga based on the distribution of horizontal boards and vertical posts.

Figure 4. Percentage pollen diagram of samples from Level VII in Sector D. Values <1% are represented by dots. Pollen concentration is expressed in pollen grains/cm^3.

Figure 5. Percentage NPP diagram of samples from Level VII in Sector D. Values <1% are represented by dots. Algae in blue, fungi soil-erosion indicators in orange, carbonicolous-lignicolous fungi in dark brown, coprophilous fungi in light brown.

Figure 6. Macrofossil diagram of samples from Level VII in Sector D. Values plotted consist of absolute frequencies/5 cm^3 of sediment and single occurrences are represented by dots.

Figure 7A. Distribution of pollen taxa with higher measures of positive and negative autocorrelation using Local Moran analysis (by SpaceStat4 software). Red and blue dots represent positive autocorrelation (high values surrounded by high values and low values surrounded by low values, respectively). Orange dots represent negative autocorrelation (high values surrounded by low values) (also in Fig. 7B).

Figure 7B. Distribution of NPP taxa with higher measures of positive and negative autocorrelation using Local Moran analysis (by SpaceStat4 software). Purple dots represent negative autocorrelation (low values surrounded by high values).

Figure 8A. Kriging interpolation maps of LOI results (OM, $CaCO^3$ and other mineral) and pollen record features (Undeterminable, PC, Richness). Best fitting model and correlation are plotted for each taxa (e: exponential; ewn: exponential with nugget; g: Gaussian; gwn: Gaussian with nugget) (also in Figs. 8B,8C and 8D).

Figure 8B. Kriging interpolation maps of selected pollen taxa.

Figure 8C. Kriging interpolation maps of selected NPP.

Figure 8D. Kriging interpolation and Local Moran analysis maps for parasites *Trichuris trichiura* and *Ascaris* sp. Red and blue dots represent positive autocorrelation (high values surrounded by high values and low values surrounded by low values, respectively).

Figure 9. Graph showing the results of Detrended Correspondence Analysis and interpolation by Inverse distance weighting analysis (IDWA) (Past software), plotting the row scores of the first and second axis on the *x,y* coordinates.

Figure 10. Kriging interpolation and Local Moran analysis maps for all archaeological remains and grinding stones. Purple dots represent negative autocorrelation (low values surrounded by high values).

List of tables (Scientific Papers and Annex 7.1.)

4.1.1. Revelles et al. 2015. Mid-Holocene vegetation history and Neolithic land-use in the Lake Banyoles area (Girona, Spain). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2015, 435: 70-85.

Table 1. Prehistoric occupations framed in chronocultural periods according to probability intervals established by means of sets of high reliability dates (Barceló, 2008).

Table 2. Radiocarbon dates, SB2 core (Banyoles). Calibration to years cal. BP was performed with Clam 2.2 (Blaauw, 2010) based on the data set IntCal13.14C (Reimer et al., 2013).

Table 3. Lithofacies defined for the SB2 core Unit 2 sequence, including sedimentary facies and main compositional parameters (mineralogical content (%) and geochemical content of selected elements (cps)) and depositional environments and/or process interpreted for each subunit.

4.1.2. Revelles and van Geel, 2016. Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia). *Review of Palaeobotany and Palynology*, 2016, 232: 81-97.

Table 1. Radiocarbon dates, SB2 core (Lake Banyoles) (from Revelles et al., 2014, 2015). Calibration to years cal. BP was performed with Clam 2.2 (Blaauw, 2010) based on the data set IntCal13.14C (Reimer et al., 2013).

4.2.1. Revelles et al. 2014. Landscape transformation and economic practices among the first farming societies in Lake Banyoles (Girona, Spain). *Environmental Archaeology*, 2014, 19 (3): 298-310.

Table 1. Radiocarbon dates, SB2 core (Banyoles). Calibration to years cal. BP was made using Clam 2.2 (Blaauw 2010) based on the data set IntCal13.14C (Reimer et al. 2013).

Table 2. Pollen subzones description.

4.3.1. Revelles et al. 2016. Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain). *Review of Palaeobotany and Palynology*, 2016, 225: 1-20.

Table 1. Sedimentological description of archaeological layers from the site of La Draga.

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Table 4. Results of principal component analysis, considering relationship between samples (variables) and NPP taxa (objects).

4.3.2. Revelles et al. (submitted) Use of space and site formation processes in a Neolithic lakeside settlement. Pollen and non-pollen palynomorphs spatial analysis in La Draga (Banyoles, NE Iberia). Journal of Archaeological Science (submitted).

Table 1. Results of Loss on Ignition analysis.

Table 2. Results of parasitological analysis.

Table 3. Moran's I results of selected pollen, NPP, parasites and macrofossil taxa.

Table 4. Eigenvalues and percentages of Correspondence Analysis and Detrended Correspondence Analysis.

Table 5. Correlation by Spearman's rs between OM, Richness, Undeterminable pollen, AP and selected taxa.

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4.1.2. Revelles and van Geel, 2016. Human impact and ecological changes in lakeshore environments. The contribution of non-pollen palynomorphs in Lake Banyoles (NE Iberia). *Review of Palaeobotany and Palynology*, 2016, 232: 81-97.

Plate I. Types UAB-1, UAB-2, UAB-3, UAB-4, UAB-5, UAB-7, UAB-8, UAB-10, UAB-11, *Kretzschmaria deusta* (HdV-44), UAB-12, UAB-13, UAB-14, UAB-15, UAB-16, UAB-20 and UAB-21. All scale bars are 10 µm.

Plate II. Types UAB-17, UAB-18A, UAB-18B, UAB-22, UAB-25, UAB-29, UAB-30 A, UAB-30B, UAB-31.

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Plate IV. *Sordaria* (HdV-55A), *Podospora* (HdV-368), *Rhytidospora* (HdV-171), *Cercophora* (HdV-112), HdV-361, HdV-224, HdV-128 undiff., HdV-182 and Type 988. All scale bars are 10 µm.

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4.3.1. Revelles et al. 2016. Pollen and non-pollen palynomorphs from the Early Neolithic settlement of La Draga (Girona, Spain). *Review of Palaeobotany and Palynology,* 2016, 225: 1-20.

Plate I. Types UAB-1, UAB-2, UAB-3, UAB-4, UAB-5, UAB-7, UAB-8, UAB-9, UAB-10, UAB-11, *Kretzschmaria deusta* (HdV-44), UAB-12, UAB-14, UAB-15, UAB-18A, UAB-18B, UAB-20, UAB-21, UAB-26, UAB-27, UAB-30A, UAB-30B, UAB-31. All scale bars are 10 µm.

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Plate IV. Clusters of *Glomus* and *Chaetomium* fruit bodies.