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Reconstructing the impact of human activities in a NW Iberian Roman mining landscape for the last 2500 years

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ABSTRACT

Little is known about the impact of human activities during Roman times on NW Iberian mining landscapes beyond the geomorphological transformations brought about by the use of hydraulic power for gold extraction. We present the high-resolution pollen record of La Molina mire, located in an area intensely used for gold mining (Asturias, NW Spain), combined with other proxy data from the same peat core to identify different human activities, evaluate the strategies followed for the management of the resources and describe the landscape response to human disturbances. We reconstructed the timing and synchronicity of landscape changes of varying intensity and form occurred before, during and after Roman times. An open landscape was prevalent during the local Late Iron Age, a period of relatively environmental stability. During the Early Roman Empire more significant vegetation shifts took place, reflected by changes in both forest (*Corylus* and *Quercus*) and heathland cover, as mining/metallurgy peaked and grazing and cultivation increased. In the Late Roman Empire, the influence of mining/metallurgy on landscape change started to disappear. This decoupling was further consolidated in the Germanic period (i.e., Visigothic and Sueve domination of the region), with a sharp decrease in mining/metallurgy but continued grazing. Although human impact was intense in some periods, mostly during the Early Roman Empire, forest regeneration occurred afterwards: clearances were local and short-lived. However, the Roman mining landscape turned into an agrarian one at the onset of the Middle Ages, characterized by a profound deforestation at a regional level due to a myriad of human activities that resulted in an irreversible openness of the landscape.

1. Introduction

The Roman period is well known for its large-scale impact on the landscapes and environment of central and southern Europe. It ranged from local imprints left by agriculture, animal husbandry and mining, to regional and even hemispheric-scale atmospheric metal pollution due to mining and metallurgy, which was detected in Greenland ice cores (Hong et al., 1994). Such a profound change in the scale of resource exploitation caused a restructuring of landscape management practices that was even more significant in mining areas, where the landscape was completely reorganised with new settlement patterns as a consequence of deep transformations of the territorial structures. One of the regions most affected was the north-western part of the Iberian Peninsula, due to its extensive gold resources (Domergue, 1987). The *Conventus Iuridicus Asturum* (mainly modern León and Asturias provinces in NW Spain) was rich in gold deposits, a strategic resource crucial for maintaining the Imperial coinage system, which was sustained by

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the *aureus*. The Roman extractive activities, which involved the harnessing and use of waterpower, triggered important geomorphological changes that resulted in the shaping of a completely new landscape, which is still clearly visible today. One of the most famous examples in NW Spain is found in Las Médulas (León) (Orejas and Sánchez-Palencia, 2002), a cultural landscape that was declared as an UNESCO World Heritage Site. Archaeological and archaeobotanical research has shown the various ways in which pre-Roman and Roman communities managed their surroundings through different modes of production (Sánchez-Palencia, 2000; López-Merino et al., 2008, 2010a; Sánchez-Palencia et al., 2011).

The chronology of the Roman gold mining activities in this area is not known precisely but it is generally accepted that it started after the conquest and territorialisation carried out under Augustus (27 BC–AD 14) and intensified in the Flavian period (late 1st century AD). The end of this imperial model of exploitation apparently took place towards the beginning of the 3rd century, at the end of the Early Roman Empire (Edmondson, 1989). Knowledge of Roman gold mining in Iberia has expanded greatly in recent decades, stemming particularly from the prolific work of Claude Domergue, who specialized in *Hispania* as the richest gold-producing region in the Ancient World (Domergue, 1987). In the León province, the techniques used (Domergue and Hérail, 1978), the working conditions (Orejas, 1994), the implications mining had for social processes (Orejas and Sánchez-Palencia, 2002), and even the environmental impact (López-Merino et al., 2010a) are now much better understood. In contrast, Roman gold mining in Asturias province (Fig. 1) has only been systematically studied using a landscape archaeology approach by Sánchez-Palencia (1983), leaving two published general syntheses that enumerate gold mining throughout the western half of the province (Sánchez-Palencia and Suárez, 1985; Sánchez-Palencia, 1995). Little is known about the impact of mining and other human activities on the landscapes of Asturias beyond the geomorphological changes brought about by hydraulic power.

One of the first indications of regional metalworking in the palaeoenvironmental record is the detection of atmospheric metal pollution. Although metal pollution linked to metallurgical activities has occurred for more than three millennia in NW Iberia (Pontevedra-Pombal et al., 2013), it climaxed during Roman times (Martínez Cortizas et al., 1997, 1999, 2002, 2013; Kylander et al., 2005). However, the impact of mining and metallurgical activities was not restricted only to metal pollution or the above-mentioned geomorphological changes. Studies of other historical mining areas of Europe (e.g., Mighall and Chambers, 1997; Monna et al., 2004a, 2004b; Jouffroy-Bapicot et al., 2007; Breitenlechner et al., 2010; Currás et al., 2012) also found ecological impacts such as forest clearance to promote agriculture and/or animal husbandry, and the use of wood resources for mining and metalworking, including charcoal production.

Recognizing the impact of past human activities, e.g., resource exploitation and management, on the environment and landscapes is essential for unravelling the origin, history and trajectories of current continental ecosystems (Birks, 2012), and key for the understanding of their response to a range of perturbations and their resilient behaviour (Dearing, 2006; Dearing et al., 2006). In this sense, multi-proxy palaeoecological studies have an important role in identifying and assessing the multiple intertwined forces that operate as long-term processes that control environmental transformation. We present a record of the last c. 2500 years of landscape change through the pollen study of a peat core sampled in La Molina (Asturias, Spain; Fig. 1); a mire located in an area where extensive gold mining and metallurgical activities took place during Roman times. As already mentioned, little is known about the impact of past human activities other than the geomorphological changes produced by mining activities. In order to redress this research gap and develop a complete picture of the complexity of

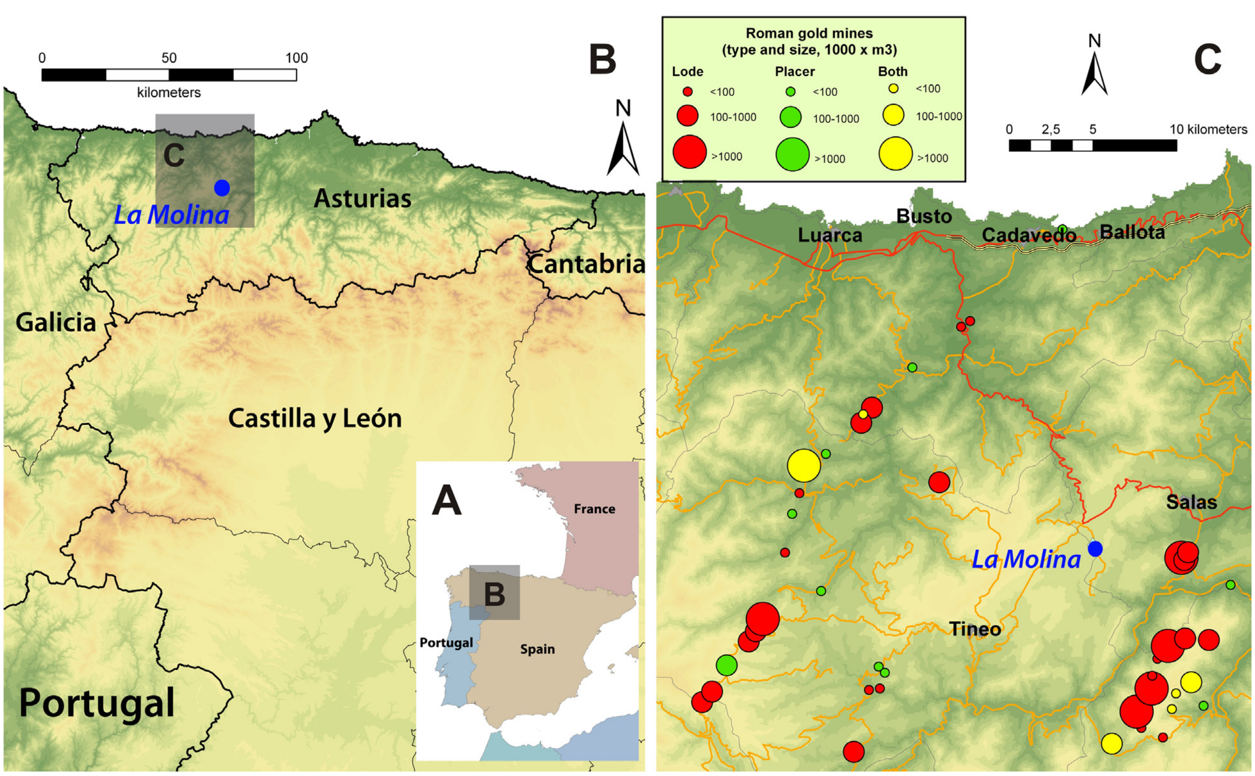

Fig. 1. A) and B) Location of La Molina mire in NW Iberia; C) local mining activity in Roman times (Perea and Sánchez-Palencia, 1995).

human intervention on this landscape, we synthesize the new pollen data with previous studies performed on the same peat core. The specific aims of this study were i) to identify different human activities, ii) to evaluate the strategies followed for the management of the resources at different cultural periods, and iii) to describe the landscape response to the human disturbances.

2. Setting and research background

2.1. Environmental and archaeological settings

La Molina is a Site of Community Importance (SCI) in the Natura 2000 network due to its ombrotrophic nature (habitat 7110 Raised bogs). The mire covers a surface of 32.8 ha and is located in the Alto de la Espina Range at 650 m a.s.l. (Concejo de Salas, Asturias, Spain; 43° 22′ 52.2″ N, 6° 19′ 38.4″ W; Fig. 1). The mire complex is represented by acidic, *Sphagnum*-dominated mesotopes, with the presence of *Sphagnum pylaisii*. The remaining forests in the area include oak (*Quercus robur*), hazel (*Corylus avellana*), beech (*Fagus sylvatica*), birch (*Betula alba*), and sweet chestnut (*Castanea sativa*). Most of the original area of forest has been replaced by pine and eucalyptus afforestation and heathlands dominated by *Erica* species, *Calluna vulgaris* and other shrubs (*Ulex* and other Genisteae). The use of some hillsides for agriculture and grazing has expanded the area covered by cereal crops and pasture.

The mire is close to a complex comprising four mines known as *Ablaneda* (Domergue, 1987), 5.5 km to the east (Fig. 2). These have been known since the mid-19th century, as well as the parallel canals that led to them at slightly different altitudes, hugging the quartzite cliff of *Peñausende* (Martínez Alcíbar, 1850; Schulz and Paillette, 1850; Paillette, 1852). Accidental breaching of one of these channels revealed a structure that closely resembled other examples from neighbouring areas such as Las Médulas (Sánchez-Palencia, 2000), merely 1 m wide and 30 cm deep (Camino Mayor, 1989a). A more recent study has offered a further overview of the mining complex, from the water reservoir at La Molina to the mines

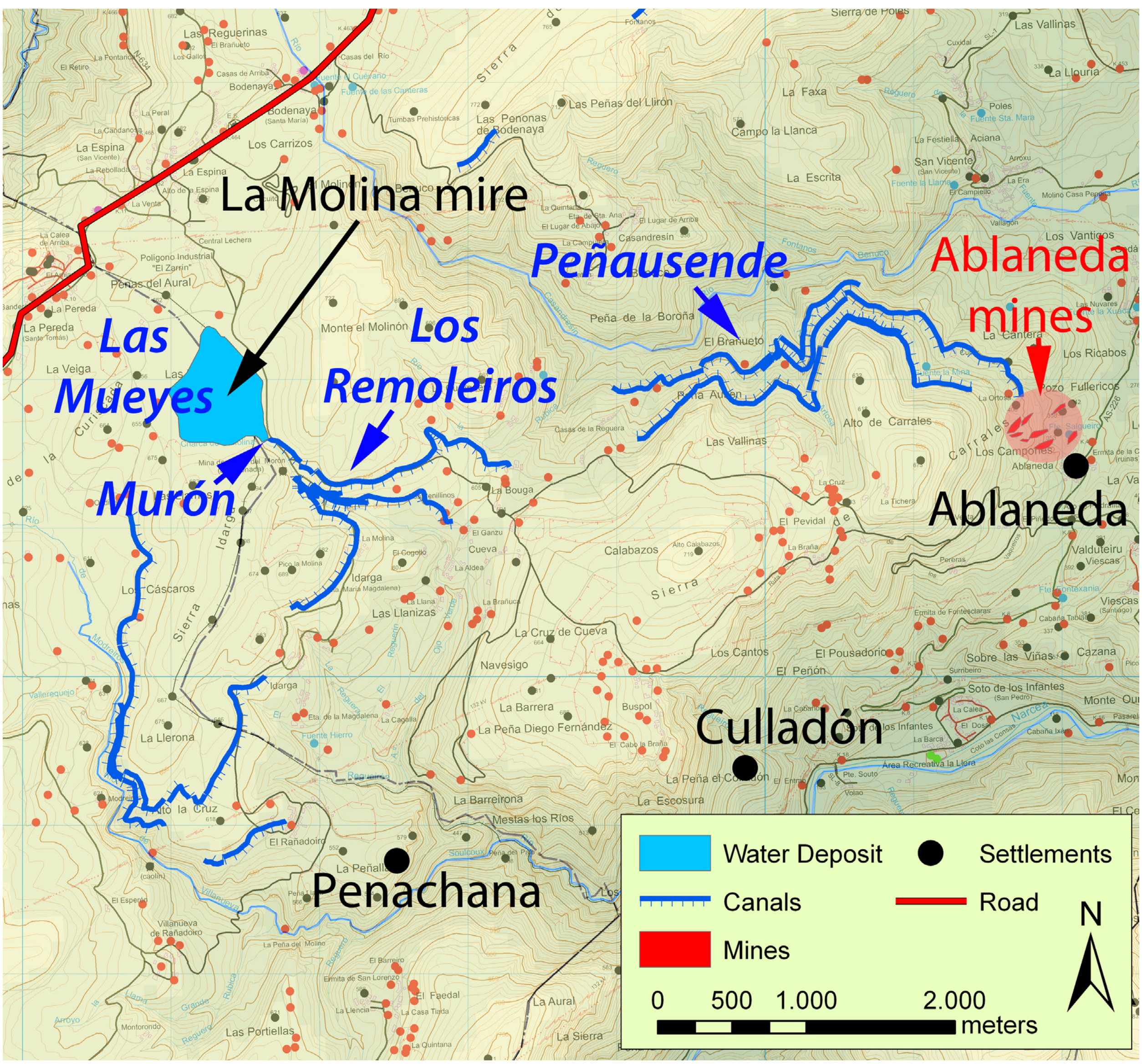

Fig. 2. Mining complex of Ablaneda, including the mines, the canals and the deposit at La Molina (*Las Mueyes*), as interpreted from high-resolution satellite imagery. Associated microtoponyms mentioned in the text are shown in italics. Settlements belong, surely or presumably -given the scarce data available and other regional morphologies-, to the Roman period, when the mine was active. The road is the itinerary of the medieval communication route which could presumably have existed also previously.

at *Ablaneda* (Fanjul Peraza and Menéndez Bueyes, 2003–2007). The name La Molina, which refers to local mills, is alternative to the local place name usually bestowed on this area – *Las Mueyes/Las Mueches*. The remains of a large stone wall, which closed off the reservoir, the *Murón* (Fig. 2), can barely be seen today (Camino Mayor, 1989b), because the stones have been reused. Measurements taken from the top of the wall to the lowest part of the mire basin indicate a depth of 4.5–5.0 m, making this the largest Roman water reservoir known in NW Iberia. Several channels leave the reservoir. They were probably used during different phases of mining and ran to various destinations within the mine (Fig. 2). Other channels also lead to the same area, but stem from another local stream (Fanjul Peraza and Menéndez Bueyes, 2003–2007).

2.2. Previous palaeoenvironmental research

López-Merino et al. (2011) studied the complex pattern of hydrological shifts in the mire during the last c. 2500 years using the records of hydro-hygrophytes and non-pollen palynomorphs (NPP) together with some geochemical data. This research showed that the mire was minerogenic in the local Late Iron Age (minerotrophic phase), but since Roman times it was subjected to hydrological changes due to a rise in the water-table, fluctuating between the presence of open water and phases of drawdown (transitional phase) (Fig. 3). The changes were most likely due to the direct use of the wetland as a water-reservoir for the canalisation system used for gold-mining. In post-Roman times it gradually evolved towards ombrotrophy (ombrotrophic phase), with increased grazing pressure more recently. Additionally, Martínez Cortizas et al. (2013) studied the same peat core using major, minor and trace lithogenic elements, trace metals/metalloids and stable Pb isotopes. This study indicated that La Molina preserved a very detailed record of atmospheric lead pollution and catchment soil erosion (i.e., mineral inputs to the mire) during the last c. 2500 years (Fig. 3). Atmospheric metal pollution follows an increasing trend during the Roman Period with several peaks, while the mineral inputs to the mire decreased showing also several phases. The detected seesaw pattern suggests significant variability at short-time scales – probably related to the local history of mining in NW Iberia.

3. Material and methods

3.1. Sampling and chronology

A 215 cm-deep core was collected in July 2005 using a Russian peat corer (50 cm long and 5 cm in diameter). Peat sections were placed in PVC tubes, protected in plastic guttering and stored under cold conditions (4 °C) prior to laboratory sub-sampling and analysis. The core was sectioned into continuous 1 cm-thick slices, except for the upper 4 cm of living vegetation. In this article we present data for the top 115 cm. For the whole sequence see López-Merino (2009). The core stratigraphy consists of four parts: I (115–87 cm), brown peat rich in mineral matter; II (87–43 cm), black peat with four layers rich in mineral matter (78–72, 69–65, 61–57 and 51–49 cm); III (43–4 cm), brown moss peat with decomposed *Sphagnum* remains; and IV (4 cm-top), the living vegetation.

The age–depth model, constructed with the aid of six AMS radiocarbon dates, was published by López-Merino et al. (2011), and constrained by Martínez Cortizas et al. (2013) assigning an age of AD 1975 to the near-surface peat which shows the largest Pb concentration and the recent lowest $^{206}Pb/^{207}Pb$ ratio as found in previous investigations in NW Spain (Kylander et al., 2005; Martínez Cortizas et al., 2012). The model was obtained using the Clam application developed by Blaauw (2010). The best fit was obtained with a fourth order polynomial (Supplementary Information). According to the model, the base of the 115 cm

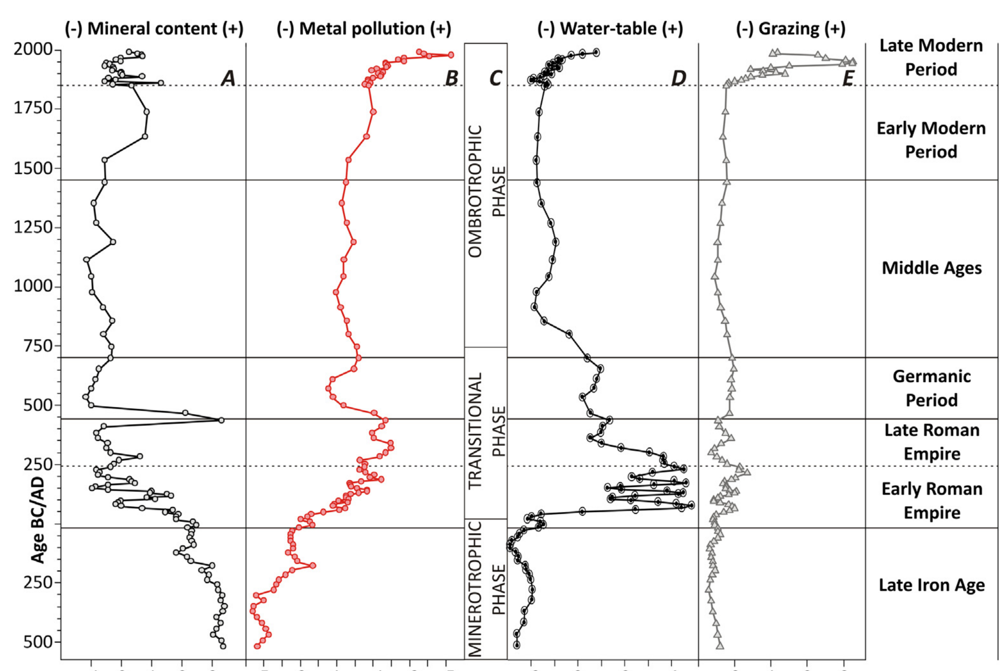

Fig. 3. Compilation of the main results obtained in previous studies on La Molina mire for the last c. 2500 years. A) Mineral content of the peat, a proxy for catchment soils erosion (PC1 factor scores of the geochemical data; Martínez Cortizas et al., 2013); B) atmospheric metal pollution index, proxy for mining and metallurgy (PC2 factor scores of the geochemical data, note that the *X* axis has been inverted, Martínez Cortizas et al., 2013); C) local wetland phases (López-Merino et al., 2011); D) water-table level index (sum of PC1, PC7, PC4, PC6, PC3 and PC8 factor scores of the hydro-hygrophytes and NPP data, as they are related to fluctuations in the water-table levels, data from López-Merino et al., 2011); E) grazing index (PC2 factor scores of the hydro-hygrophytes and NPP data, related to coprophilous fungi, López-Merino et al., 2011).

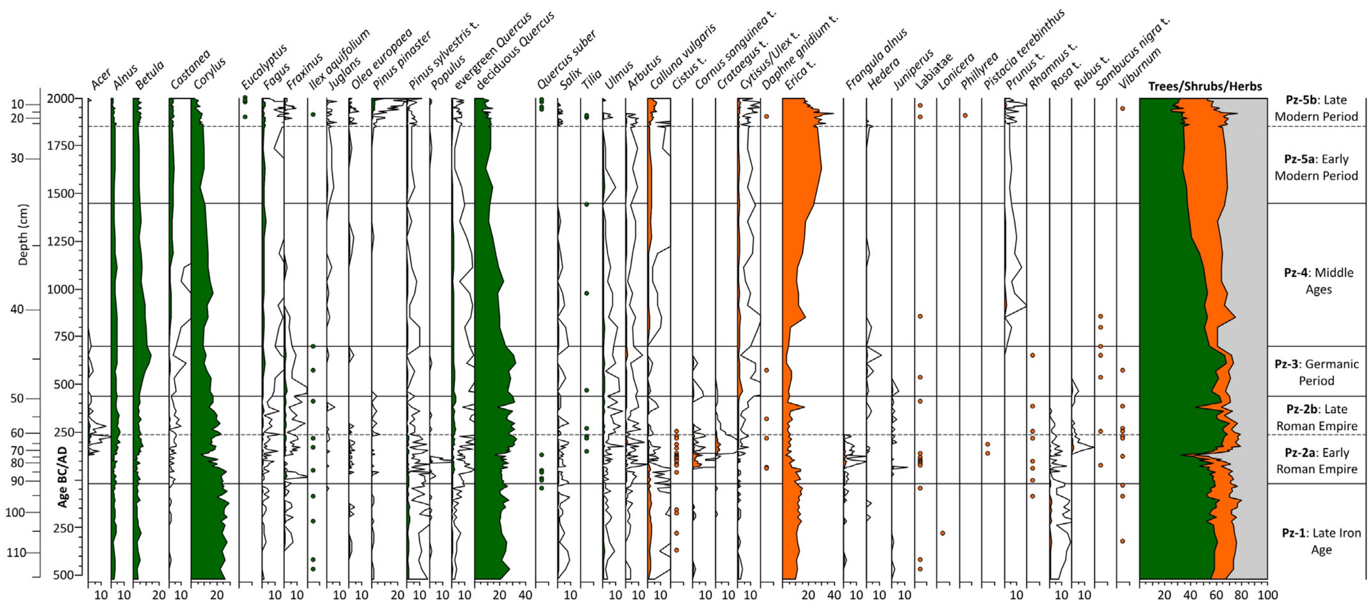

Fig. 4. Percentage pollen diagram of La Molina mire (woody vegetation) plotted against age. The filled silhouettes show the percentage curves of the taxa, the white silhouettes show the ×10 exaggeration curves. Dots represent percentages below 0.5%.

section dates to the local Late Iron Age (c. 2500 cal yr BP) and the sequence extends up to the present day without any sedimentary hiatus recorded.

3.2. Pollen analysis

Palynomorphs were isolated following the classic procedure (Moore et al., 1991) with concentration in heavy liquid. Pollen counting was conducted at 400× magnification, and a minimum of 400 terrestrial pollen grains were considered in the pollen sum, the lowest pollen sum being 435. Pollen identification was aided by the reference collection of the Laboratory of Archaeobiology at the CCHS (Madrid), standard identification keys (Moore et al., 1991) and the photographic atlas (Reille, 1992) of European pollen flora. Additionally, *Pinus pinaster* and *Quercus suber* types were identified following the criteria provided by Carrión et al. (2000a, 2000b). The analysis was conducted in 101 samples taken every 1 (from Roman times onwards) or 2 (late Iron Age) cm. The core has a particularly good resolution for the Roman period, with 40 pollen samples spanning c. 20 BC to AD 440, providing nearly decadal resolution. The pollen and the summary diagrams (Figs. 4–6) have been plotted against age using Tilia. The pollen sequence was divided into five pollen zones (Pz-1 to Pz-5) according to the local cultural periods. Palynological richness was estimated by rarefaction analysis using the open software PAST 3.01 (Hammer et al., 2001). The number of grains selected for standardization in the rarefied sample was the lowest pollen sum (435).

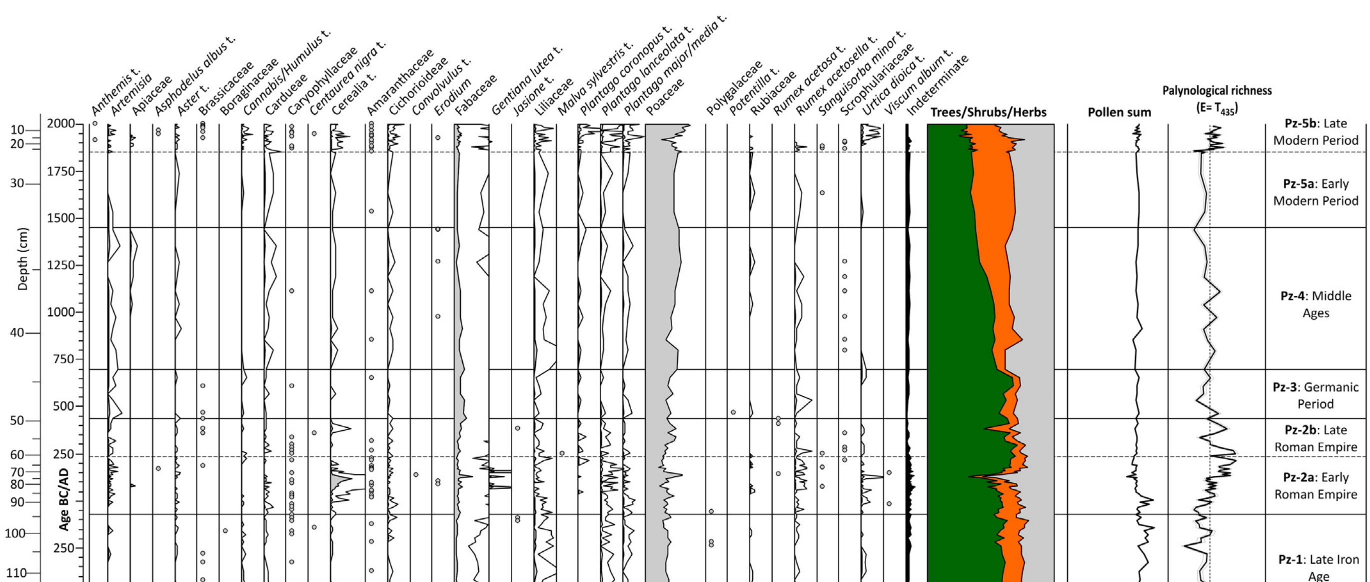

Fig. 5. Percentage pollen diagram of La Molina mire (herbs) plotted against age. The filled silhouettes show the percentage curves of the taxa, the white silhouettes show the ×10 exaggeration curves. Dots represent percentages below 0.5%. Palynological richness calculated by rarefaction analysis is also shown, as well as the total land pollen sum.

Previous data have been used in this study to develop a more complete picture of the environmental and landscape changes since the local Late Iron Age. Firstly, the grazing index obtained by López-Merino et al. (2011) after a principal component analysis (PCA) applied on the hydro-hygrophytes and non-pollen palynomorphs record was adopted. This principal component is associated to positive loadings of *Cercophora*-type, *Chaetomium*, *Podospora*-type, *Sordaria*-type and *Sporormiella*-type. These NPP are ascospores of coprophilous fungi, indicating herbivore pressure on the mire, and their curves follow a comparable pattern with the one exhibited by the principal component scores. Secondly, the atmospheric metal pollution index obtained by Martínez Cortizas et al. (2013) after a PCA on geochemical data has also been used. The extracted principal component is mainly related to changes in the $^{206}Pb/^{207}Pb$ ratio, indicating metal (Pb) pollution. The correlation between these indexes with selected pollen types (deciduous *Quercus*, *Corylus* and *Erica* t.) was assessed using Pearson's correlation coefficients, for different cultural phases from the Late Iron Age to the Germanic period (Table 1). Metal pollution factor scores were first multiplied by -1 for the calculation of Pearson's correlation coefficients and for Fig. 7, so the larger the positive score of a sample the higher the metal pollution is. This was done to make the interpretation of the results more intuitive.

4. Results

4.1. Pz-1: Late Iron Age (115–90 cm; c. 500–20 BC)

The arboreal pollen component is dominated by *Corylus* and deciduous *Quercus*, with the continuous presence of *Alnus* and *Betula*. Other mesophytes such as *Fraxinus*, *Fagus*, *Castanea*, *Salix* and *Ulmus* are also present, although with low values. Shrubs are abundant, with *Erica* t., *C. vulgaris* and *Rosa* t. being the most important taxa (Fig. 4). Poaceae is the main herbaceous component. *Plantago lanceolata* t. and *Plantago major/media* t. are present, as well as other herbs such as Liliaceae, Fabaceae, *Rumex acetosella* t., Cardueae and Cichorioideae. Cerealia t. presents low values and a discontinuous record (Fig. 5).

4.2. Pz-2: Roman times (90–50 cm; c. 20 BC–AD 440)

Deciduous *Quercus* and *Corylus* are still the most abundant trees, and other mesophilous trees such as *Fraxinus*, *Ulmus* and *Acer* have higher percentages than previously recorded. Additionally, cultivated and mesothermophilous taxa such as *Castanea*, *Juglans*, evergreen *Quercus*, *Q. suber*, *Arbutus*, *Olea europaea* and *P. pinaster* are present, but with low values (Fig. 4). Although tree percentages are relatively important, deciduous *Quercus* and *Corylus* values show a seesaw pattern (Fig. 6). Amongst the shrub component, *Erica* t., *C. vulgaris* and *Rosa* t. values are lower than those previously detected (Fig. 4). Herbaceous types such as *Urtica dioica* t., *R. acetosella* t., *Artemisia* and Fabaceae occur in higher values than in Pz-1 (Fig. 5).

Some differences between the Early Roman Empire (Pz-2a, c. 20 BC-AD 240) and the Late Roman Empire (Pz-2b, AD c. 240–440) are noticeable. During Pz-2a, *Frangula*, *Cornus sanguinea* t., *Crataegus* t., *Rubus* t. and Cerealia t. present relatively high percentages (Figs. 4 and 5). During Pz-2b, Cerealia t. is less abundant, as well as the aforementioned shrubs. *Rosa* t. values decrease and *Cytisus/Ulex* t. values increase.

4.3. Pz-3: Germanic period (50–43 cm; AD c. 440–700)

Deciduous *Quercus* is the most abundant tree pollen type. *Corylus* and *Fraxinus* decrease in value, while *Betula*, *Fagus* and *Castanea* increase. Other tree species maintain low percentages, i.e., *Alnus*, *Acer*. Shrubs are not abundant, as during Pz-2, although *Cytisus/Ulex* t. present higher percentages than previously recorded. *Erica* t., *C. vulgaris* occur in very low values (Fig. 4). Fabaceae and *Artemisia* show increased representation among the herbaceous component. Cerealia t. is almost absent in this pollen zone (Fig. 5).

4.4. Pz-4: Middle Ages (43–32 cm; AD c. 700–1450)

Tree cover gradually diminishes through this zone, as indicated by the lower percentages of deciduous *Quercus*, *Betula* and *Ulmus*. However, *Castanea* percentages increase again (Fig. 4). The most notable feature is the spread of shrubs. As in Pz-3, *Cytisus/Ulex* t. has significant values, while *Erica* t. and, to a lesser extent, *C. vulgaris* percentages increase. *Prunus* t. appears for the first time (Fig. 4). Percentages of herbs such as Poaceae, *Artemisia*, *Aster* t., Cardueae, Cichorioideae, Liliaceae, *Plantago lanceolata* t. and *Plantago major/media* t. all increase. Cerealia t. appears constantly during this zone (Fig. 5).

4.5. Pz-5: Modern Era (<32 cm; AD >1450)

Tree percentages are the lowest they have been throughout the whole sequence, while *Erica* t. shows high values, and other shrubs such as *C. vulgaris*, *Cytisus/Ulex* t. and *Prunus* t are also present (Fig. 4). Some differences exist between the Early Modern (Pz-5a, AD c. 1450–1850) and Late Modern (Pz-5b, AD >1850) periods. During Pz-5a, tree percentages are low and the values of Poaceae, Liliaceae, *Plantago* sp., Cardueae and *R. acetosella* t. are important. Cerealia t. is also present (Fig. 5). However, during Pz-5b *Erica* t. values show a decreasing trend, while *P. pinaster* and herbs (i.e., *Plantago lanceolata* t., *Plantago major/media* t., *Plantago coronopus* t., *U. dioica* t.) percentages increase, along with Cerealia t. and the appearance of *Eucalyptus* (Figs. 4 and 5).

4.6. Palynological richness

The results of the rarefaction analysis show a varied distribution along the record (Fig. 5). The average is 28.08 pollen types, although values range from 19.90 to 35.79 pollen types. During Pz-1, palynological richness values are usually lower than the average. However, a seesaw pattern begins to be evident from c. 300 BC onwards. During Pz-2a, this pattern is more evident and palynological richness values show an increasing trend from the average values to 35.79 pollen types. Palynological richness decreases unevenly during Pz-2b, reaching average or lower than the average values in Pz-3, and they are more or less constant during Pz-4 and Pz-5a. Elevated palynological richness is detected in Pz-5b.

5. Discussion

The multi-proxy approach applied here enable us to reconstruct landscape change since the local Late Iron Age and to recognise the role played by different human activities, such as mining/metallurgy, cultivation, animal husbandry and deforestation. Two main periods could be distinguished: the first one characterised by the reversible effects of the human activities on the woodlands, the second one a non-regeneration of the tree cover.

5.1. Reversible effects of human impacts on the vegetation from the Late Iron Age to Germanic times

During the local Late Iron Age (Pz-1) hazel and oak were the most important components of medium altitude woodlands surroundings the La Molina mire. Additionally, shrubs such as *Erica* t. and *C. vulgaris*, together with *Rosa* t. and grasses, indicate an

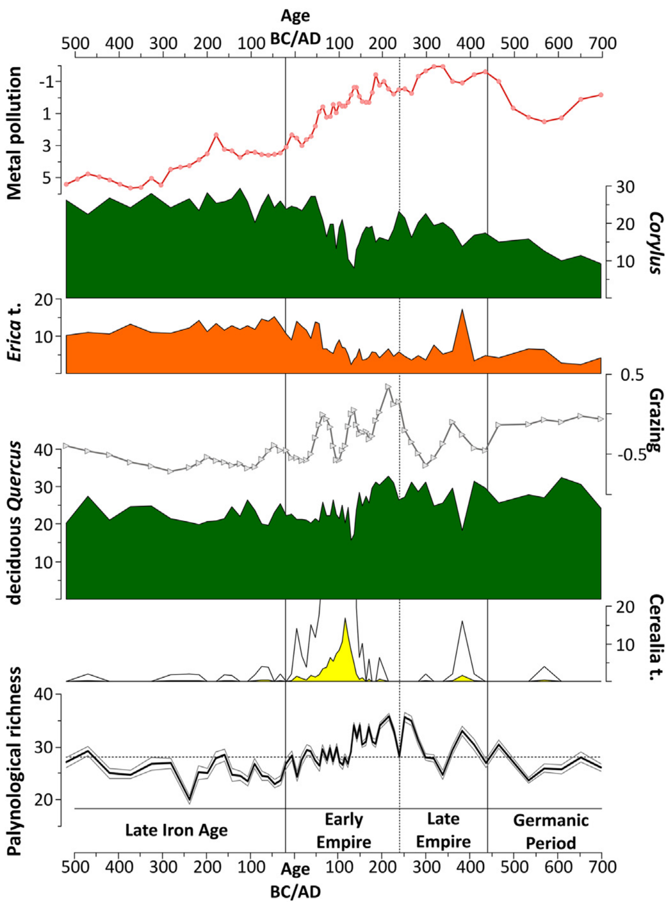

Fig. 6. Chronology of the environmental changes detected in La Molina mire from c. 500 BC to AD 700 (from top to bottom): Metal pollution index (note that the *X* axis has been inverted, Martínez Cortizas et al., 2013); *Corylus* percentages; *Erica* t. percentages; grazing index (López-Merino et al., 2011); deciduous *Quercus* percentages; Cerealia t. percentages; and palynological richness.

already open landscape, probably due to local human activities. Despite the relative landscape stability during the first half of Pz-1, two small-scale clearance events were detected (Fig. 6). The first one (c. 300–160 BC) supposed a minor decrease in deciduous *Quercus* pollen, suggesting a small opening of oak woodlands surrounding La Molina, due to mining/metallurgical activities and agricultural and pastoral farming, as indicated by small peaks in atmospheric metal pollution, Cerealia t. pollen and grazing index. The second event (c. 120–30 BC) had a more sizeable impact on forest cover, although it was still a small-scale, local woodland clearance. Increases in the values of Cerealia t. and grazing index are linked to this clearance that produced a decrease of, first, hazel and, second, oak. Both clearances could be related to the development of larger, more complex settlements at the end of the Iron Age (Marín Suárez, 2011).

The overall picture is more complex during the Roman period (Pz-2), and not only in terms of human activities. The presence of mesothermophilous taxa such as evergreen *Quercus*, *Q. suber*, *Arbutus* and *Olea europaea* increased, probably due to the warmer temperatures characterising the Roman Warm Period. A reconstructed temperature index from Penido Vello (PVO), a mountain blanket bog located 100 km west of La Molina, shows warmer conditions in NW Spain at this time (Martínez Cortizas et al., 1999). A shift in the hydrology of the mire can be detected at the beginning of the Early Roman Empire (Pz-2a, c. 20 BC–AD 240), representing a large perturbation in the mire system, which triggered a rapid decrease in the mineral matter flux from the mire's catchment

Table 1
Pearson's correlation coefficients of selected pollen taxa, metal pollution and grazing for the Late Iron Age, Early and Late Roman Empire and Germanic Period. Note that metal pollution values haven been multiplied by −1, so the larger the score of a sample, the higher the metal pollution is. This has been done to make the interpretation of the results more intuitive.

Cultural period	Taxa	Metal pollution	Grazing
Germanic period	Deciduous *Quercus*	−0.47	0.21
(AD c. 440–700)	*Corylus*	0.05	−0.65
	Erica t.	−0.41	−0.42
Late Roman Empire	Deciduous *Quercus*	−0.04	−0.23
(AD c. 240–440)	*Corylus*	0.34	−0.37
	Erica t.	−0.09	0.27
Early Roman Empire	Deciduous *Quercus*	**0.51**[a]	**0.42**[b]
(c. 20 BC–AD 240)	*Corylus*	**−0.69**[a]	**−0.46**[b]
	Erica t.	**−0.76**[a]	**−0.54**[a]
Late Iron Age	Deciduous *Quercus*	−0.14	−0.06
(c. 500–20 BC)	*Corylus*	0.01	0.03
	Erica t.	**0.49**[b]	0.14

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

(López-Merino et al., 2011). Four synchronous phases with increases in atmospheric metal pollution are distinguished, following a marked seesaw pattern as that shown by the water-table level and geochemical index of soil erosion (Martínez Cortizas et al., 2013) (Fig. 3). Additionally, *Frangula*, *C. sanguinea* t., *Crataegus* t. and *Rubus* t. are well represented (Fig. 4), probably linked to a higher wetland water-table level as they are commonly found on river banks and in disturbed areas. The above-mentioned evidence combined with the archaeological record of a channel network in the surroundings and the remains of a dam (Camino Mayor, 1989a, 1989b; Fanjul Peraza and Menéndez Bueyes, 2003–2007; Fernández Mier, 1999) (Fig. 2), strongly suggest that the mire was intentionally flooded – leading to an increase in bioproductivity and thus an increase in the organic matter content of the peat. This human perturbation was linked to mining activities, because water was necessary to open lode deposits and to wash the ore down sluices, where gold particles could be separated from the remaining ore. This was achieved by hydraulic force obtained using water-canalisation systems (*corrugi*) and water deposits (*piscinae* or *stagna*). The hydrological shift in La Molina may have been amplified by wet events such as those reconstructed in PVO for the Roman period (Schellekens et al., 2011).

Some taxa such as *Corylus* and *Erica* t., as well as the grazing index also show a marked seesaw pattern during Early Roman Empire chronology (Pz-2a) (Fig. 6). Phases with increases in atmospheric metal pollution, pointing to changes in the intensity of mining/metallurgy, are coeval with decreases in tree pollen percentages indicating episodes of woodland clearance (Fig. 6). Those episodes, which coincided with increased atmospheric metal pollution and grazing pressure, were mostly connected with decreases in *Corylus* and *Erica* t (Fig. 7). Pliny the Elder, who served as procurator in *Hispania*, described the way Romans used the wood for gold mining (outlined in Reher et al., 2012). Timber was used for shoring in galleries or pits, a technique called *aurum canalicium*. This technique was infrequently used in the region, although some beams have been found in mining contexts close to La Molina mire, such as the Boinás site (Villa Valdés, 1998). Pliny also documented the use of heather, which was employed to retain the gold in the washing channels (*agogae*) and burned afterwards in order to extract the gold particles caught in the branches. Heather (*Erica* t.) values decrease synchronously with the peaks in metal pollution, most likely indicating its use for gold extraction. In fact, the relationships between *Corylus* and *Erica* t. with metal pollution show large Pearson's correlation coefficients for the Early Roman Empire

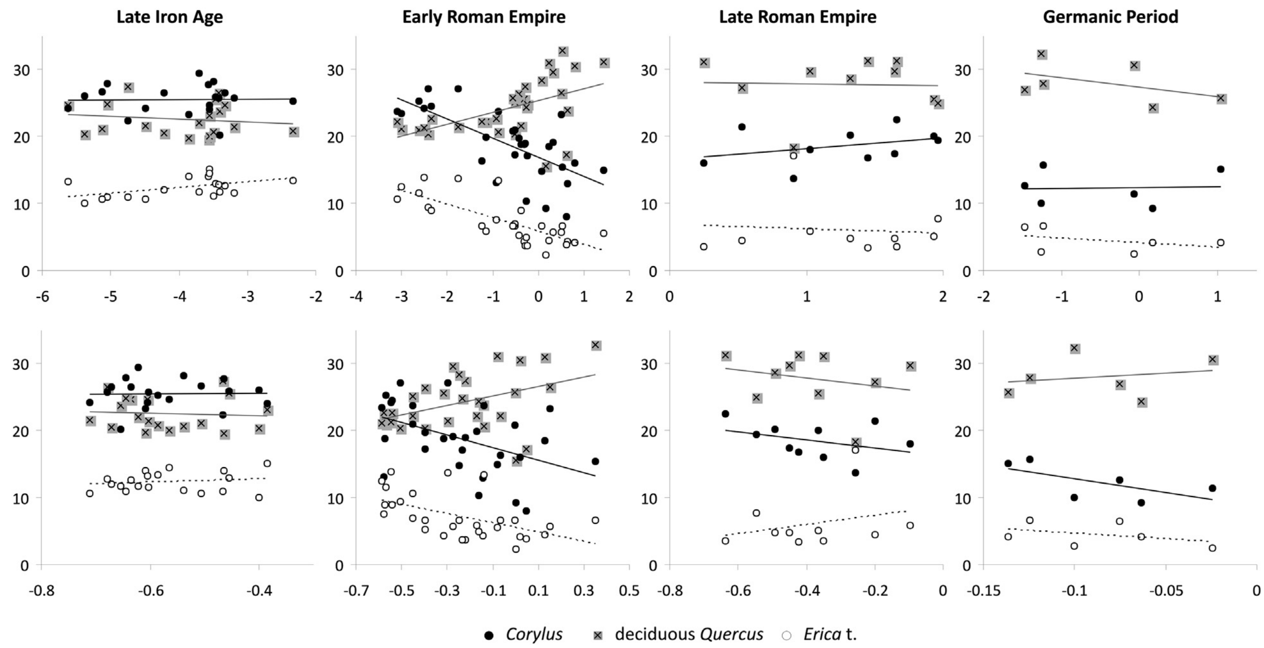

Fig. 7. Correlation between indicators of metal pollution and grazing with deciduous *Quercus*, *Corylus* and *Erica* t. for the Late Iron Age, Early and Late Roman Empire and Germanic Period. Note that metal pollution values haven been multiplied by −1, so the larger the score of a sample, the higher the metal pollution is. This has been done to make the interpretation of the results more intuitive. Pearson's correlation coefficients for the same indicators are in Table 1.

(Table 1); the larger the metal pollution the larger the decreases in hazel and heather were. Similarly, the relationship between hazel and heather with the grazing index shows strong correlations during the Early Roman Empire (Table 1, Fig. 7), because more intense phases of grazing pressure are coincident with the largest decreases in hazel and heather. These relationships are not detected either before or after this period (Fig. 7, Table 1).

The two phases of decline in deciduous *Quercus* pollen percentages detected during the Early Roman Empire (Pz-2a) are more difficult to interpret, although they are probably related to the disturbance of the woodland cover with repeated clearances due to the presence of local human activities. They could have been related to crops sown very close to the mire, because they coincide with Cerealia t. peaks (Fig. 6). However, the Cerealia t. signal could also be linked to the higher water-table of the mire, as some wild grasses produce pollen of cereal size and grow in aquatic environments (e.g., *Glyceria*; Joly et al., 2007). Although the fact that deciduous oaks occupy deeper soils suitable for cultivation cannot be neglected, a combination of both processes could explain the large percentages of Cerealia t. Additionally, it is likely that the increase in *Castanea* percentages and the appearance of *Juglans* indicate the cultivation of chestnut and walnut (Fig. 4) at a regional scale. Unfortunately, there is no record of Roman settlements in the vicinity (Rodríguez Otero, 1992; Fernández Mier, 1999), whose inhabitants would have farmed locally, except for an inscription found beside the mines (CIL II, 5739). Nonetheless, not far from La Molina mire an old branch of the Way of Saint James pilgrimage route (Fig. 2) passes by, which could have been a communication route in ancient times. The intensification of agricultural *indicia* and the significant presence of Roman activity in the area allow us to expect new sites to be found in the immediate surroundings with further archaeological research.

For the Late Roman Empire (Pz-2b, AD c. 240–440), any differentiation in the use of resources linked to mining activities is less evident, as the decline of hazel and heather are no longer coeval (Fig. 7, Table 1). The mire water-table was much lower (Fig. 3), in agreement with archaeological evidence that gold mining was only important during the Early Roman Empire (Domergue, 1990). Even so, atmospheric metal pollution was still high and probably related to metallurgy more broadly rather than specifically to gold mining, although other mines far from La Molina could have been exploited. Metalworking, together with farming activities, would explain the woodland decline. In fact, a woodland clearance event affecting both deciduous *Quercus* and *Corylus* is coincident with a peak in grazing pressure and cereal cultivation along with indication of metal pollution (Fig. 6). Additionally, *Juglans* pollen is almost absent, but *Castanea* has similar values to those recorded during the Early Roman Empire, suggesting that it continued to be cultivated (Fig. 4).

The Germanic period (Pz-3, AD c. 440–700) was also a phase of change in land use. The seesaw pattern, which started to disappear in the Late Roman Empire, is no longer evident either for forest clearances, atmospheric metal pollution, soil erosion or water-table fluctuation (Figs. 3, 6 and 7). Permanent grazing is the most prominent feature while Cerealia t. is almost absent. Forest clearance took place to create pasture rather than for cultivation. Nevertheless, the effect of human activities on the woodland cover was not so strong as to prevent some regeneration, a pattern also observed during the local Late Iron Age and Roman periods. This indicates that human activities, although quite intense in some phases, were probably of local scale. The human impact on woodlands was not strong enough to trigger irreversible changes after the perturbations, principally the intense mining activities detected during the Early Roman Empire. The same conclusion can be extracted from the rarefaction analysis. Palynological richness values increased during the Early Roman Empire, when local human impact was more intense, although from the Late Roman Empire to Germanic times they gradually return to values similar to those found during the Late Iron Age (Figs. 5 and 6). In the study performed on a peat core from the Ayoó de Vidriales mire (Northern Iberia Plateau; Morales-Molino and García Antón, 2014) an increase in the palynological richness with increasing human disturbance was also found.

The archaeobotanical work performed in the Las Médulas Roman mining landscape (Léon province) on pre-Roman, Roman and post-Roman archaeological sites showed the importance of *Castanea*, higher presence of both Cerealia t. pollen and carpological remains of emmer (*Triticum dicoccum*), barley (*Hordeum vulgare*), broomcorn millet (*Panicum miliaceum*) and broad beans (*Vicia faba*), and lower values of mesophilous trees in Roman times (López-Merino et al., 2010a). After Roman times, cereal crops decreased and local grazing indicators increased, as shown by the lower percentages of Cerealia t. and the higher values of coprophilous fungi (López-Merino et al., 2008). Unfortunately, there are not many continuous palynological records on natural archives with good chronological control and high-resolution for these chronologies, close to Roman mining areas, to develop a more general picture of the impact of human activities. One exception is located in the Teleno Mountains close to Las Médulas: the Xan de Llamas mire at 1500 m asl (Morales-Molino et al., 2011). It shows a deforestation phase with a high incidence of fires from c. 2850 to 1300 cal yr BP, i.e., from the Iron Age to Germanic times. After this phase woodlands recovered. Hence, even in places such as Las Médulas in which the impact of mining was very dramatic at many scales, forests recovered when the extractive activities ceased.

The changes in vegetation described above are consistent with those recorded in pollen diagrams from other later prehistoric and Roman mining and/or metalworking regions in Europe (i.e., Le Roux et al., 2004; Mighall et al., 2010, 2012). At all sites woodland clearance associated with metal pollution and arable and livestock farming commenced in the Late Iron Age and intensified during the Roman period. Miners and/or metallurgists appear to have exploited local woodland, a hypothesis that is also supported by anthracological data (Ludemann et al., 2004; Ludemann, 2010). Any preference for particular tree species appears to have been simply controlled by local availability: the most abundant trees and shrubs were exploited, such as hazel and heather in the case of La Molina. Phases of forest regeneration also typically occur when mining activities cease: at La Molina percentages of *Corylus*, *Erica* t., and occasionally *Quercus* increase in between the phases of metal pollution. As pointed out by other studies in other historical mining areas, the impact of mining on woodlands was short-lived (Monna et al., 2004a, 2004b; Breitenlechner et al., 2010; Mighall et al., 2012; Reher et al., 2012).

5.2. Non-regeneration of forests since the Middle Ages

In the palaeoenvironmental record of La Molina mire the episodes of forest clearances detected from the Late Iron Age to Germanic times were small-scale and short-lived, after which forests recovered. Thus, although mining and metallurgy exerted a large control on the resources and a new regime to manage the landscape, such activities did not trigger major changes at a landscape scale, neither during the intense rise of Roman mining/metallurgical activities nor after they ceased, because the Visigothic lifestyle that developed after the Late Roman Empire was a subsistence farming structure mainly based on livestock and fruit trees (i.e., oak and chestnut) (Valbuena-Carabaña et al., 2010). Thus, relatively extensive woodland still persisted until the Middle Ages.

The transition between Germanic times (Pz-3) and the Middle Ages (Pz-4, AD c. 700–1450) led to the onset of a continuous, gradual and permanent deforestation (Fig. 4), which fits with the widespread reduction of the forest cover since Medieval times detected in other high-resolution studies performed in NW Spain: for example, at AD c. 700–800 in the Ancares, Courel and Xistral Mountains (Muñoz Sobrino et al., 1997, 2001; Mighall et al., 2006), at AD c. 600–700 in the Monte Areo and Bocelo Ranges (López-Merino et al., 2010b; Silva Sánchez et al., 2014), and at AD c. 500–1000 in the Monte Paradela (Carrión et al., 2010; Kaal et al., 2011; López-Merino et al., 2012). This loss of woodlands is one of the most dramatic changes in the vegetation history of NW Spain (Martínez Cortizas et al., 2005). Previously forested areas seem to have been occupied by the characteristic heathlands that compose the NW Iberian landscape today (Kaal et al., 2011). The high percentages of *Erica* t., *C. vulgaris*, *Cytisus/Ulex* t. and *Prunus* t. found in the pollen record of La Molina also support this interpretation (Fig. 4). But grasslands, as inferred by the higher percentages of Poaceae, were also very important. Although indicators of local grazing activities (i.e., coprophilous fungi) are not significant in La Molina record during the Middle Ages (Fig. 3), transhumance livestock was notable at a regional scale and is considered to be one of the main drivers for the deforestation process in the whole Spanish territory (Gil Sánchez, 2011). Although no microcharcoal information is available for the La Molina peat record, which would have been interesting to support the regional scale character of the forest decline and the grassland expansion, the study done by Mighall et al. (2006) in the nearby Pena da Cadela bog (PDC, 974 m asl, Xistral Mountains), located c. 100 km west of La Molina, shows an increase in the microcharcoal content since c. 700 AD, which supports the broad-scale of the Middle Ages deforestation process in NW Iberian landscapes.

Consequently, the Middle Ages supposed a large-scale, progressive change in the landscape, as deforestation occurred at a broader scale across the whole Iberian Peninsula for many purposes in a time of instability, characterised by Christian/Muslims wars and invasions, which impeded forest regeneration. The principal causes were related with mobile livestock, mainly sheep, which triggered the burning of woodlands for the creation of extensive pastures, but also shipbuilding and caulking, charcoal extraction, and the intensification of cultivation (Valbuena-Carabaña et al., 2010). However, at the mire local scale the changes that happened at the onset of Roman times in La Molina seem to have been crucial for the future dynamics of the mire. Changes caused by higher water-table levels were irreversible, triggering a shift towards a new trophic status (ombrotrophy) (Fig. 3). Thus, responses at regional and local scales were related to different environmental stressors, highlighting the complexity of landscape trajectories.

Since the Middle Ages other human activities were also important in shaping the landscape surrounding La Molina. These include the consolidation of the cultivation of sweet chestnut (Conedera et al., 2004) since Pz-4, as well as the widespread pine and eucalyptus afforestation across NW Iberia (Sande Silva, 2007) and the local equine and bovine grazing during the last two centuries around and on the La Molina mire itself (Pz-5b). Additionally, the La Molina record shows a rise in atmospheric metal pollution, starting in the Early Modern period and increasing dramatically since the onset of the Industrial Revolution (Fig. 3), which is the same as that typically detected for other records in NW Spain (Martínez Cortizas et al., 2002, 2012; Kylander et al., 2005; Olid et al., 2010). This was the first time in more than 2000 years that atmospheric pollution reached values higher than those detected during Roman times. Interestingly, palynological richness presents more or less constant values during the Middle Ages (Pz-4) and the Early Modern period (Pz-5a), while values sharply increase at AD c. 1850 (P-5b, Fig. 5). Palynological richness seems to be more sensitive to local perturbations on the landscape rather than to regional ones: the first increase during the Early Roman Empire is linked to the local mining, while the most recent increase is coeval with the local afforestation with pines and eucalyptus (Fig. 4).

6. Conclusions

The palynological study of La Molina mire has proved to be a powerful tool to identify and reconstruct landscape changes related to human activities since the Late Iron Age in NW Iberia. The mire studied, La Molina, is particularly well suited for this purpose because it is located in an area of the Spanish Asturias province that was intensively mined for gold in Roman times. Gold mining used hydraulic power and the intense fluctuations in the mire's hydrology started at the beginning of the Early Roman Empire (c. 20 BC-AD 240), when Roman domination began in the area, pointing to its use as a water reservoir in new extraction works. Synchronous clearances of the local woodlands to extract wood resources to develop mining/metalworking and to open spaces for cultivation and livestock grazing were also detected. The most striking feature is that the use of natural resources seems to have been much more complex and variable during Roman than in pre-Roman (local Late Iron Age) and post-Roman (Germanic Period) times. This fact suggests different strategies of landscape management and socio-environmental interactions. In fact, the exceptionally detailed record for the Early Roman Empire period enabled the identification of these contrasting strategies, e.g., different forest clearances for several purposes. The use of hazel and heather seems to have been linked for mining/metalworking during the Early Roman Empire.

Although the impact of mining and other human activities from the late Iron Age to Germanic times, and mostly during the Early Roman Empire, was intense and affected the landscape, these early effects were seemingly reversible, because the forest regenerated after mining ceased. These forest clearances were local and short-lived. In contrast, the onset of the Middle Ages involved a non-return change, because deforestation was generalised across the landscape as a whole and linked to many different human activities.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jas.2014.07.016.

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