

Are *Cedrus Atlantica* forests in the Rif Mountains of Morocco heading towards local extinction?

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Abstract

Cedrus atlantica (Atlas cedar) is a relict and endemic endangered species from northwestern African mountains, whose distribution range has undergone a dramatic reduction over recent decades. Long-term studies are needed for a better understanding of the development of its range as well as for assisting in the implementation of sustainable conservation measures. The multi-proxy analysis of a high-resolution fossil record of 180 cm depth allowed us to depict the final demise of an Atlas cedar population from the western Rif Mountains (Jbel Khesana), despite its high resilience during the last ~4000 years. Currently, Atlas cedar trees are not observed in Jbel Khesana but they still occur in the nearby area as scattered populations on a few mountain tops at altitudes higher than 1400 m a.s.l. Our data show an initial relatively stable period (~4000–2400 cal. yr BP) followed by a phase where both climatic and human-induced disturbances cause an alternate dominance of oaks and Atlas cedars (2400~1550 cal. yr BP). Then, the increasing aridity and human activities favoured the depletion of Atlas cedar forests (~1550–800 cal. yr BP). Our record shows that Atlas cedar forests have recovered after each deforestation event, which reveals a high resilience of the species until the mid-20th century, when they became extinct in the study area. The main driver of their local extinction may be attributed to the strong human pressure. Management measures of Atlas cedar in the Rif Mountains should aim at limiting intensive loggings and protecting the existing populations for their local regeneration.

Keywords

Cedrus atlantica, charcoal, extinction, geochemistry, late Holocene, Morocco, non-pollen palynomorphs, pollen, Rif Mountains

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Introduction

The Atlas cedar (*Cedrus atlantica* (Endl.) Manetti ex Carrière) is a relict and endemic tree species from northern African mountains of Morocco (Rif and Atlas ranges) and Algeria (Linares et al., 2011; M'hirit and Benzyane, 2006). The Rif Mountains are located in the northwestern part of Morocco and harbour 6.5% of the current range of Atlas cedar, namely, 12,138 ha (UICN, 2015). These Rifan populations have lost 49% of their area in the last three decades (Cheddadi et al., 2017; UICN, 2015). Future predictions for 2050 indicate that their distribution range will be restricted to the top of very few mountains, with expected local extinctions from areas at lower altitude (IRES, 2010; UICN, 2015). Atlas cedar populations seem to have gradually migrated upwards forced by climate change during the Holocene, like a number of tree species growing near treelines (e.g. Cheddadi et al., 2016; Heiri et al., 2006; Tinner and Theurillat, 2003; Walther et al., 2005). Model simulations indicate an upward shift of the lower limit of their range in the Rif Mountains by about 200 m (Cheddadi et al., 2017). Recent decline in these mountains, however, is considered to have been induced by human activities, mainly cropping, cutting and overgrazing (Ajbilou et al., 2003; Benabid, 1985; Coudel et al., 2016; Grovel, 1996; Hamelin and Nwankwo, 2013; Moore et al., 1998; Rejdali, 2004). Disentangling the impact of each factor on landscape is not an easy task, although essential to take the

appropriate managing measures to ensure the persistence of the modern populations (Allen et al., 2010; El-Baha et al., 2010; IRES, 2010; Vegas-Vilarrúbia et al., 2011).

Palaeoecological studies from the Mediterranean region have shown that the current tree flora is composed of very resilient and relict taxa that have experienced many abrupt and intense climate changes in the past (Carrión et al., 2010; Cheddadi et al., 2009; Magri, 2012; Magri et al., 2017; Petit et al., 2005; Terrab et al.,

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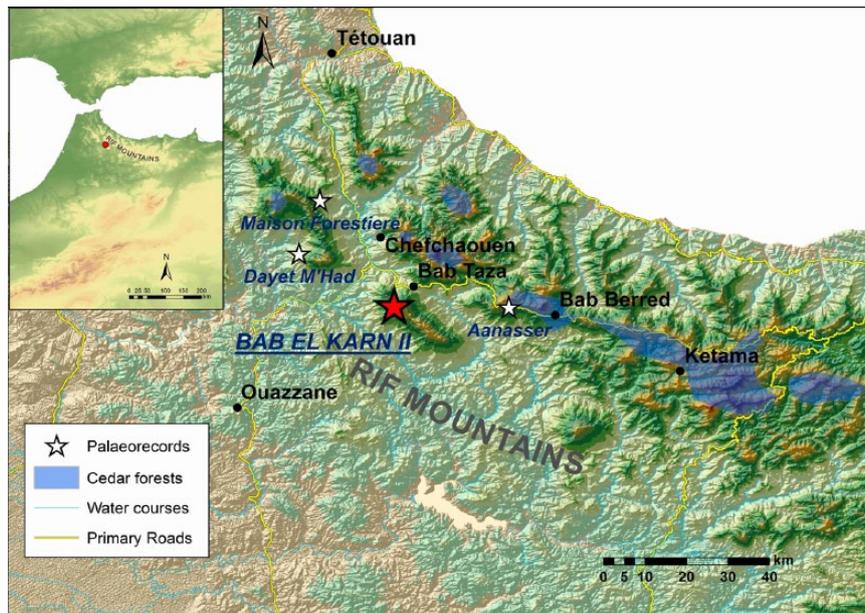


Figure 1. Location of Bab El Karn II (BEK II) mire (red star), showing some previous palaeoecological studies cited in the text (white stars) and the current Atlas cedar distribution range in the area (blue area).

2008), but also display local and regional extinction events in different areas (Dullinger et al., 2012; Postigo-Mijarra et al., 2010; Rubiales et al., 2012; Tinner and Ammann, 2005).

High-resolution (~20–50 years) multi-proxy records, such as in the present study, provide an accurate analysis of the vegetation changes and disturbances which lead to the current landscape. A wide range of palaeoenvironmental proxies is necessary to properly assess the landscape changes through time and to develop ad hoc future management strategies. In addition to traditional palynological studies, the identification of spores of both green algae and fungi, as well as the analyses of microcharcoals and geochemical elements contribute to more reliable environmental reconstructions (Bindler, 2006; Chambers et al., 2011, 2012; Cook et al., 2011; Cugny et al., 2010; Iglesias et al., 2015; López-Vila et al., 2014; Montoya et al., 2012; Mooney and Tinner, 2011; Silva-Sánchez et al., 2014, 2016; Van Geel, 2001).

Recent fossil records (Figure 1) collected in the Rif Mountains (Cheddadi et al., 2016, 2015; Muller et al., 2014, 2017) as well as the pioneering palaeoecological work of Reille (1977) allow the analysis of the forest dynamics in these mountains during the Holocene. The latter has been partially re-edited (Muller et al., 2014) with new ^{14}C dates which support a better evaluation of the chronological frame of the vegetation dynamics. Cheddadi et al. (2015) provided a focus on the spatial and temporal variation of human impact, setting the decline of Atlas cedar forests during medieval times and warning that this process is still underway. Cheddadi et al. (2016) show a record from the same wetland (Bab el Karn) as this study that spans the last 9000 years. These authors state the local extinction of *Cedrus atlantica* at ~2000 cal. yr BP, probably because of the combined effect of increasing aridity and anthropogenic disturbances. However, they express the difficulty in assessing which driver played the dominant role in the local extinction of the Atlas cedar populations. Here, we present a new core, Bab el Karn II, which spans the last 4000 years. We have carried out a high-resolution analysis of several environmental proxies (pollen and non-pollen palynomorphs (NPPs), fire, sedimentology and elemental geochemistry) with a main focus on the development of Atlas cedar forests and their relationship with climate and human activities.

The objective of the present study is threefold: (1) to provide an accurate record of the development of Atlas cedar forests in the western Rif Mountains, specifically in the Jbel Khesana; (2) to

clarify whether the long-term Atlas cedar forest changes are related to climate or anthropogenic disturbances; and (3) to help the decision-making process for future management and monitoring of the Atlas cedar forests.

Material and methods

Study area and sampling

The mire of Bab el Karn II ($35^{\circ}1'23''\text{ N}$, $5^{\circ}12'24''\text{ W}$) is located in a seasonal ponded water area developed in a lithologically controlled plain on the northern slopes of Jbel Khesana (western Rif Mountains) at around 1200 m a.s.l. (Figure 1). The narrow plain area includes two hydrologically connected open mires (ca. 400 m²) that collect the runoff water of several streams. Jbel Khesana (1705 m a.s.l.) is composed of Cretaceous carbonate rocks and Neogene terrigenous rocks. The most common outcropping sediments consist of early to late Cretaceous flysch facies, alternating marls and limestones and fine terrigenous rocks, as well as Oligo-Miocene sandstones in the upper area of the mountain range (Service Géologique du Maroc, 1980). The climate in the Rif Mountains is characteristically Mediterranean, with more than 65% of the annual rainfall occurring in spring and autumn. Annual precipitation usually exceeds 400 mm, reaching more than 2000 mm in high-altitude areas of its western range (Charco, 1999). Atlas cedar grows between 1400 and 2300 m a.s.l. in areas which receive more than ca. 1400 mm annual rainfall within a wide temperature range (-5°C to 28°C) on every kind of soil (Moore et al., 1998; M'hirit and Benzyane, 2006). Current vegetation (Figure 2) in Jbel Khesana is dominated by deciduous oaks: *Quercus pyrenaica* in the highest elevations of the supramediterranean bioclimatic belt, and *Quercus canariensis* at lower altitude in the mesomediterranean one. At lower elevation, cork oaks (*Quercus suber*) give way to the thermomediterranean bioclimatic belt, where holm oaks (*Quercus ilex*) and olive trees (*Olea europaea*) are the main tree species. Today, Atlas cedar trees are not observed in Jbel Khesana but they still persist on nearby ranges at the highest altitudes. The vegetation by the mire is mainly composed of several genera belonging to Cyperaceae, like *Carex*, *Cyperus* or *Eleocharis*; and Poaceae, like *Molinia caerulea* or *Danthonia decumbens*; as well as other species like *Juncus heterophyllus*, *Ranunculus* spp., *Isoetes* sp. or *Sphagnum* sp. The surrounding

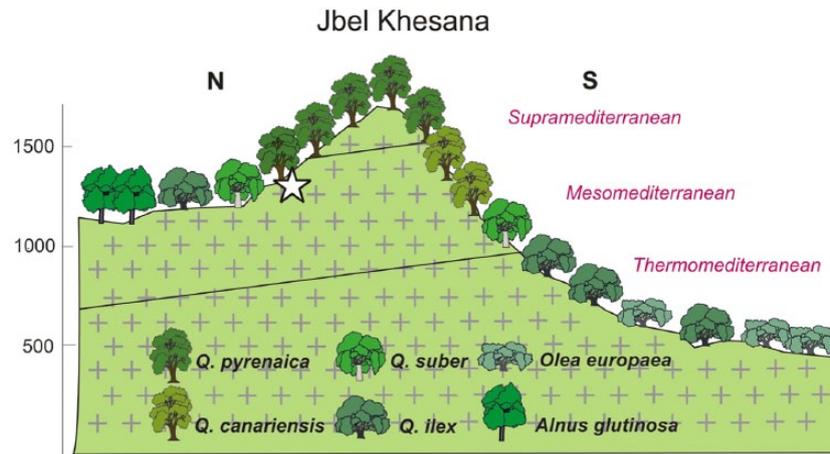


Figure 2. Schematic diagram showing the vegetation communities in the Jbel Khesana and the location of Bab el Karn II (white star).

Table 1. Results of Radiocarbon (^{14}C) dating of core samples, showing calibrated age ranges (2σ).

Depth (cm)	Lab code	^{14}C age	Age (cal. yr BP)		Probability
			Min.	Max.	
59	Beta-319029	1040 ± 30	918	989	89.1
			992	996	0.7
			1030	1049	5.1
100	Beta-319028	2000 ± 30	1881	2003	94.6
			2030	2032	0.4
127	Beta-319027	2160 ± 30	2057	2185	52.6
			2191	2207	2.2
			2229	2306	40.1
152	Beta-319022	2410 ± 30	2351	2496	81.2
			2596	2612	2.9
			2637	2684	10.9
			2404	2411	0.9
159	Beta-319023	2470 ± 30	2380	2393	1.7
			2426	2716	92.3
			3078	3094	4.2
171	Beta-319026	3010 ± 30	3107	3132	4.5
			3136	3257	74.3
			3290	3333	12
			3480	3538	23.1
175	Beta-319024	3340 ± 30	3544	3640	70.3
			3671	3678	1.4
			3834	3974	95

forest consists of deciduous oaks (*Quercus pyrenaica*) and isolated stands of *Quercus canariensis*. Shrubs like *Cytisus villosus*, *Erica arborea* or *Cistus salviifolius*; herbs like *Holcus lanatus*, *Rumex acetosella*, *Lamium flexuosum*, *Stellaria holostea* and so on; and ferns like *Pteridium aquilinum* develop specially in the clearings.

A core of 180 cm depth was extracted with a Russian corer and then sub-sampled at 1 cm intervals for the multi-proxy analyses.

Chronology

Eight radiocarbon datings were performed on bulk peat samples at the Beta Analytic Radiocarbon Dating Laboratory (Table 1). Ages BP were calibrated with the IntCal13 ^{14}C curve (Reimer et al., 2013). Confidence intervals of the calibrations and the age–depth model were calculated at 95% (2σ). An age–depth model was constructed for the fossil record (Figure 3) using calibrated ages and applying a smooth-spline solution with Clam 2.2 software (Blaauw, 2010).

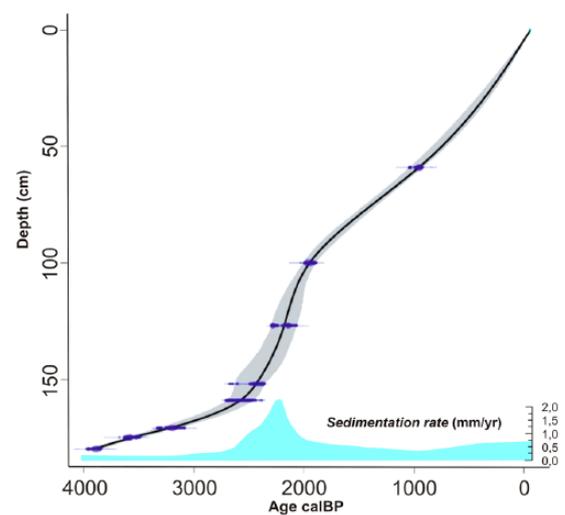


Figure 3. Age–depth model and sedimentation rate development calculated for the BEK II mire.

Pollen palynomorphs, NPPs and charcoal analysis

Samples were treated following the chemical methodology proposed by Faegri and Iversen (1989). The sediment was then concentrated in Thoulet solution for densimetric separation of pollen and NPPs (Goeury and de Beaulieu, 1979). Pollen concentration was estimated by adding a *Lycopodium* tablet to each sample (Stockmarr, 1971). Data processing and graphic representation was performed with TILIA and TGView programs (Grimm, 1992, 2004). Local pollen assemblage zones were determined with a cluster analysis made by CONISS (Grimm, 1987). Different keys (Faegri and Iversen, 1989; Moore et al., 1991) and pollen atlases (Reille, 1999) were used to identify pollen grains as well as the reference collection of the Archaeobiology Laboratory of CSIC (Madrid). *Pinus* and *Quercus suber* pollen differentiation follows Carrión et al. (2000a) and Carrión et al. (2000b), respectively. Ferns, hydro-hygrophilous taxa and NPPs were excluded from the total pollen sum (>500 pollen grains). The identification of NPPs is based on Van Geel et al. (1981, 1989, 2003) and Van Geel and Aptroot (2006) and nomenclature follows Miola (2012).

Microcharcoal was counted in the same slides used for pollen (Finsinger and Tinner, 2005; Mooney and Tinner, 2011; Tinner and Hu, 2003) and sorted into two size classes, namely, >100 and <100 μm , indicating local and regional fires, respectively. Charcoal accumulation rate (CHAR) was calculated by dividing the concentration of microcharcoals by the sedimentation rate of

each sample, obtained from the age–depth model (Long and Whitlock, 2002).

A synthetic diagram is included (Figure 4), in which some pollen and NPPs are grouped according to their ecological affinity (Table 2), with three charts showing the total pollen concentration and the CHAR on the right.

Pollen dispersal and deposition at local/regional scale

The local presence of Atlas cedar forests has usually been established in a minimum percentage of 1% (Demarteau et al., 2007; Hajar et al., 2008; Nour El Bait et al., 2014; Wright, 1952). This threshold value would be likely higher in the Rif Mountains, as pollen production increases responding to a higher moisture (Khanduri and Sharma, 2002). Percentages <1% are considered by Magri and Parra (2002) as extraregional and associated with long-distance transport of pollen grains by winds. In this work, we assume that pollen percentages of Atlas cedar >1% indicate its presence in less than 200 m (Wright, 1952) around our site.

Sedimentology and geochemical analysis

The sedimentological study consisted of stratigraphical characterisation, description of the sedimentary facies and a high-resolution geochemical analysis. The core was split into two halves and imaged with a high-resolution digital camera in a core scanner.

Elemental composition of sediments was analysed on the fresh core using an *Avaatech XRF* core scanner at a resolution of 1 cm and under two different working conditions: (1) with an x-ray current of 800 μ A, at 10 s count time and 10 kV x-ray voltage for the measurement of Al, Si, P, S, Cl, Ar, K, Ca, Ti, V, Rh, Cr, Mn and Fe; (2) with an x-ray current of 2000 μ A, 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 are semi-quantitative; only statistically significant chemical elements were considered. Geochemical data were analysed using multivariate statistics, in order to extract the geochemical signatures of the elemental composition of the sediments and the insights into underlying factors accounting for them. A principal component analysis (PCA; Hotelling, 1933) was applied to XRF data using SPSS software package, in correlation mode and by applying a varimax rotation. Prior to the analysis, the data were standardised (Z-scores) to avoid scaling effects and obtain average-centred distributions (Eriksson, 1999).

Results

Chronology

The age–depth model (Figure 3) is based on the data shown in Table 1 and was also used to calculate the sediment accumulation rate. It shows an overall increasing trend towards the top of the core (0.1–0.7 mm/yr), disrupted by a strong increase between ~2300–2000 cal. yr BP, reaching maximum values of 2.2 mm/yr ~2170 cal. yr BP.

Palynological record

Two main pollen zones were identified (Figure 4) which were divided into five subzones (Table 3), using a constrained cluster analysis (Grimm, 1987).

Sedimentary and geochemical records

The sedimentary units (Table 4 and Figure 5) consist of organic argillaceous marl, mixed siliciclastic (Si, Al, K) and carbonate (Ca) compounds, within which the organic content decreases towards the top. Edaphised terrigenous muds, sometimes Fe-rich,

with abundant root bioturbation traces, form the upper parts of these sedimentary intervals. In general, the arrangement of the sedimentary facies (SU1 to SU6) indicates a progressive shallowing tendency and more abundant desiccation intervals towards the top of the core (Table 4).

The elemental composition variations are summarised in four principal components (Figures 5 and 6), which explain 82.8% of the total variance. PC1 explains 37% of the variance. Al, Rb, Zr, V, K, Ti, Sr, Y and Nb show high positive loadings (higher than 0.5); Si and Pb have a moderately positive loading; and Mn, Ca and Br have a low negative factor loading, respectively (Figure 6). The high positive and moderate loadings of the lithogenic elements are indicative of the amount of fine-grained mineral matter (clay minerals) in the core sediments. The mineral fraction content and the record of factor scores (Figure 5) indicate that the amount of clay minerals is quite homogeneous and increases gradually because of the decrease of the organic matter content towards the top of the sedimentary units. In SU3 and SU4, the upper clay-rich interval shows a relative decrease in PC1 value (fine mineral matter) that is correlated with a significant presence of Fe, probably forming iron (hydro) oxides (Figure 5). There are two intervals with relatively low mineral content: (1) the lower organic half of SU1 (180–145 cm) with abundant coarse vegetal fragments; (2) an interval that encompasses SU3 and SU4, likely related to an increase in the input of carbonate sediment to the mire that may reflect an enhanced soil erosion episode (see Ca/Ti ratio and PC4 curves in Figure 5).

PC2 explains 19.2% of the variance. Fe, P and Br show high positive loadings, and Pb and Mn show moderate positive loading (Figure 6). Rb has a low negative factor loading. Factor scores (Figure 5) are positive in SU5 and SU6 (40–0 cm). In SU4 (63–40 cm), they shift sharply to negative values and then gradually become less negative until the bottom of the core, where they remain around 0. Fe and Mn are redox-sensitive elements, while P and Br are related to the presence of vegetal organic matter (Leri and Myneni, 2012). The surface enrichment in Fe and Mn is probably related to vadose oxic conditions in the upper sections of the record, which involve more favourable conditions for oxidised, less mobile forms of these elements to form (Chesworth et al., 2006). Br presence is related to the processes controlling organic matter enzymatic halogenation (Biester et al., 2006; Leri and Myneni, 2012) and dehalogenation under reducing conditions within the soils (Van Pée and Unversuch, 2003).

PC3 explains 17.3% of the variance, and it reflects the inverse relationship between lithogenic Si and Al (moderate positive loading) and biophilic and organically bound elements such as S and Zn (high negative factor loadings) (Figure 6). The record of the scores can be divided into two sections: >140 and <6 cm, with positive scores (Figure 5).

PC4 explains 9.3% of the variance. Ca and Mn show high positive factor loadings (Figure 6). The origin of Ca is likely related to the presence of terrigenous carbonate sediments derived from the marly Cretaceous rocks that outcrop along Jbel Khesana slopes. The record of the scores can be divided into three sections: (1) >154 and 55–16 cm, with negative scores (except from one sample at 129 cm); (2) 154–75 cm, with scores around zero; (3) 75–55 and 15–0 cm, with positive scores (Figure 5).

Discussion

Model simulations suggest that the range of Atlas cedar in the Rif Mountains has decreased by about 75% between 1960 and 2010 (Cheddadi et al., 2017). During the coming decades, Rifan *Cedrus atlantica* forests are predicted to disappear because of the increasing aridity and temperatures, as they will not have enough space to migrate upwards in search of suitable climatic conditions (IRES, 2010; Thomas, 2013; UICN, 2015). For a better

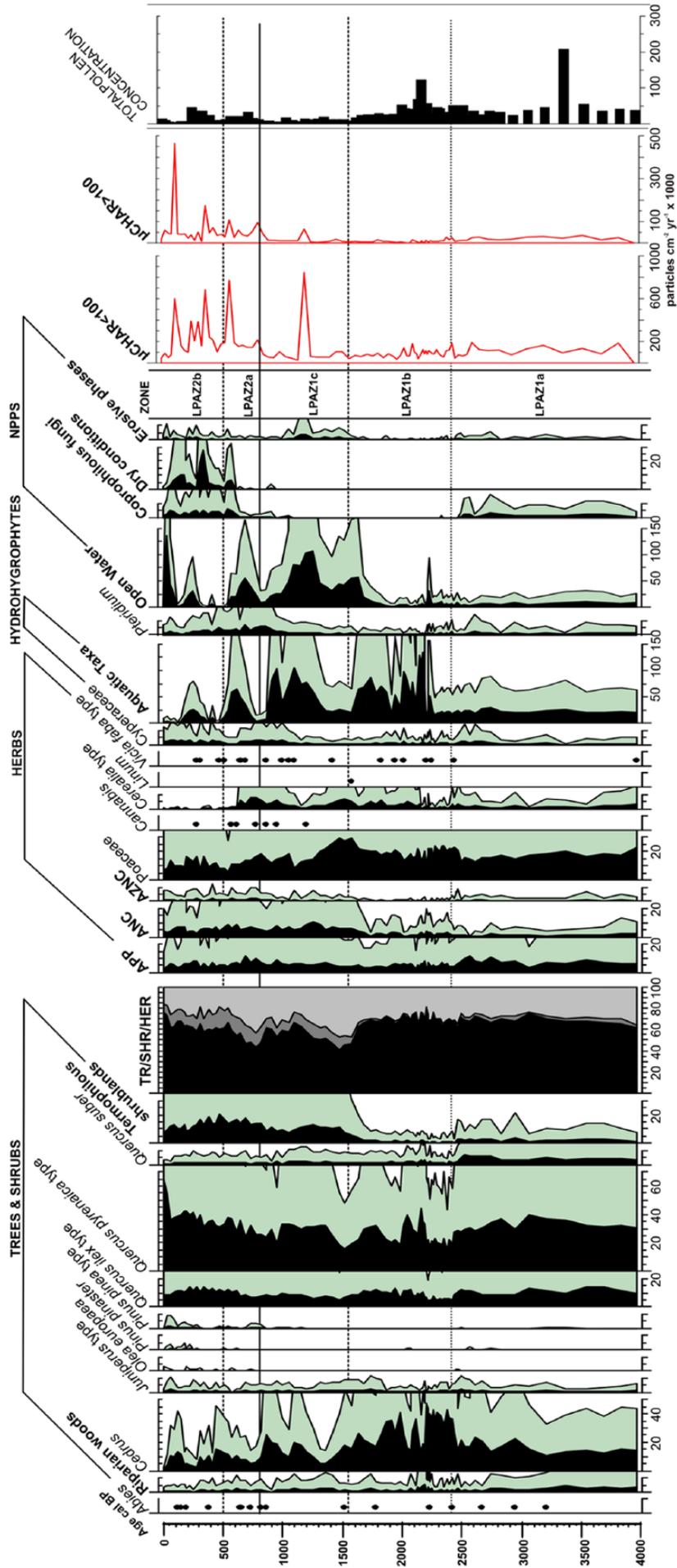


Figure 4. Summary diagram including selected pollen types, NPPs, CHAR and Total Pollen Concentration. APP:Anthropogenic Perennial Pastures;ANC:Anthropogenous Nitrophilous Communities;AZNC:Anthropozoogenous Nitrophilous Communities.

Table 2. Groups of pollen and non-pollen palynomorphs according to their ecological affinities.

Group	Pollen and NPPs
Riparian woods	<i>Alnus, Fraxinus, Prunus, Salix, Sambucus, Ulmus, Hedera</i>
Thermophilous shrubland	<i>Arbutus, Buxus, Cistus, Cytisus, Daphne, Ephedra fragilis, Erica arborea, Helianthemum, Ilex, Lamiaceae, Myrtus, Phillyrea, Pistacia, Viburnum</i>
Anthropogenic Perennial Pastures (APP)	<i>Allium, Apiaceae, Artemisia, Brassicaceae, Campanula, Caryophyllaceae, Fabaceae, Liliaceae, Rosaceae, Saxifraga, Scrophulariaceae, Viola</i>
Anthropogenic Nitrophilous Communities (ANC)	<i>Anthemis, Asphodelus albus, Aster, Boraginaceae, Cardueae, Centaurea cyanus, Cichorioideae, Erodium, Malva sylvestris</i>
Anthropozoogenic Nitrophilous Communities (AZNC)	<i>Chenopodiaceae-Amaranthaceae, Plantago spp., Rumex spp.</i>
Aquatic taxa	<i>Myriophyllum, Ranunculaceae</i>
Open water	<i>Botryococcus, Debarya, Mougeotia, Spirogyra, Zygnema</i>
Coprophilous fungi	<i>Gelasinospora sp. (HdV 1), Gelasinospora cf. retispora (HdV 2), Chaetomium sp. (HdV 7A), Sordaria-type (HdV 55), Cercophora sp. (HdV 112), Sporormiella sp. (HdV 113), Coniochaeta cf. Lignitaria (HdV 172), Podospora-type (HdV 368)</i>
Dry conditions	<i>Pleospora sp. (HdV 3B), Trigocladium opacum (HdV 10)</i>
Erosive phases	<i>Glomus, Pseudoschizaea circula</i>

understanding of the long-term drivers which have led Atlas cedar populations to local extinction, we evaluate the main driving factors involved in the Atlas cedar forests' sensitivity since the early Holocene. Ultimately, this palaeoecological study should lead to setting up management measures and conservation policies which could avoid their potential extinction in North Africa.

Background: Climate-induced expansion and decline of Atlas cedar forests from the early to the middle Holocene (~9000–4000 cal. yr BP)

Previous studies in the Rif Mountains (e.g. Cheddadi et al., 2015, 2016, 2017; Muller et al., 2014; Reille, 1977) spanning a broader period have shown the overall landscape development in the Rif Mountains (Morocco) since the early Holocene. The analysis performed in the same wetland under study (Cheddadi et al., 2016), encompassing the last 9000 years, shows for this first period humid and temperate conditions, nuanced by high seasonality (Brayshaw et al., 2011; Jalut et al., 2009; Magny et al., 2012). The forest landscape was dominated by semi deciduous oaks (*Quercus canariensis*, *Quercus pyrenaica*), with a significant presence of *Cedrus*, likely more widespread at higher altitudes, and *Quercus ilex*, probably more widespread at lower altitudes.

During the middle Holocene, ~7000 cal. yr BP, the climate became wetter and probably cooler, with a lower seasonality (Cheddadi et al., 1998; Magny et al., 2012; Vanni re et al., 2011), thus promoting a marked development of Atlas cedar forests, which reached their maximum expansion ~6000 cal. yr BP. From this date onwards, the Atlas cedar forests underwent a steady decline, likely related to increasing aridity (Alba-S nchez et al., 2015; Jalut et al., 2009; Magny et al., 2012; Tabel et al., 2016) which allowed their replacement by oaks, especially semi-deciduous ones, also favoured by local fires (Cheddadi et al., 2016). No evidence of human impact was found in this record, but minor evidence was reported in relatively nearby sites (Muller et al., 2014) at this time, which so far prevents connecting this shift to human activities in the area.

Therefore, at the end of the middle Holocene, ~4500/4000 cal. yr BP, forests were dominated by oaks, with a significant expansion of Atlas cedar forests, which would have migrated to higher altitudes in search for more humid climatic conditions.

Resilience of Rifan forests within a low human-disturbed landscape (~3900–2400 cal. yr BP)

The beginning of the late Holocene in the Jbel Khesana is characterised by a wide expansion of the forests, mainly composed of semi-deciduous oaks, with a noteworthy presence of *Cedrus*

which may have composed an ecotone rather than a mixed Atlas cedar-oak forest.

Aquatic taxa show constant percentages throughout this phase (Figures 4 and 7), denoting some water availability during the summer season (Tabel et al., 2016). The low occurrences of green algae, considered as open water indicators, suggest temperatures too low for their growth (Cook et al., 2011). The negative values of both PC2, interpreted as an indicator of meteorisation in oxic conditions of the sediments because of the mire desiccation and subaerial exposure, and PC3 that reflects the relative input of lithogenic versus organic sediment in the mire, support our interpretation. Both principal components point to a relatively deep wetland within stable and wet climatic conditions. This is consistent with previous studies in the area describing a dry climate at lower altitudes, but more humid upslope, forcing Atlas cedar to migrate towards higher elevations (Cheddadi et al., 2016, 2017; Mart n-Puertas et al., 2010).

Human activities are attested by the constant record of *Cerealia* which may be considered as locally grown (L pez-S ez and L pez-Merino, 2005), and coprophilous fungi which indicate the presence of cattle as well as the development of grazing activities in the area. They could be likely linked to fire occurrences which affect mostly the shrub communities (Figure 7). Cereal cultivation has been detected in the fossil record since at least 7000 years ago in Northern Morocco (Ballouche and Marinval, 2003; L pez-S ez et al., 2013; L pez-S ez and L pez-Merino, 2008), but it seems to have been most developed in coastal areas and lowlands. Hence, human impact on Rifan forests seems to be quite slight in these early phases of the late Holocene (Cheddadi et al., 2016, 2015, 2017; Kaplan et al., 2009; Muller et al., 2014). In our record, the forest ecosystem remains almost unaltered, with the exception of a minor retreat of oak forests ~3000 cal. yr BP, along with a subsequent expansion of Atlas cedars, grasslands and thermophilous shrubland (Figures 4 and 7). Such landscape change may be related to specific clearing events, as a result of a scant increase of the human use during the Phoenician occupation, of the high-altitude forests (Cheddadi et al., 2015, 2016, 2017; Reille, 1977; Taiqui and Cantarino, 1997). From this date (~3000 cal. yr BP) onwards, accumulation rates show an increasing trend (0.15–0.71 mm/yr) revealing an increasing erosion process derived from these activities, specifically fire and grazing, after a period of greater stability.

Alternate dominance of oaks and Atlas cedars in Rifan forests within an increasingly disturbed landscape (~2400–1550 cal. yr BP)

Atlas cedar forests reach their maximum extent ~2400 cal. yr BP, likely favoured by cold temperatures and the weakening of human impact on the area, as indicated by the disappearance of

Table 3. Description of pollen zones.

Subzone, depth (cm)/age (cal. yr BP)	Trees/shrubs	Herbs	NPPs	Pollen concentration/ CHAR
LPAZ1a, 180–149 cm/~3900–2400 cal. yr BP	AP: 61–74% <i>Quercus pyrenaica</i> (30–39%), <i>Quercus ilex</i> (10%), <i>Cedrus</i> (15%), Riparian woods (<4%) <i>Pinus</i> spp. and <i>Abies</i> (<1%) By ~3000 cal. yr BP, retreat of oak forests (56.5–49.4%), maximum of <i>Cedrus</i> (22.3%) and spread of thermophilous shrubland (4.3%)	Poaceae (15–20%) APP (8%) ANC (0.2–2.8%) AZNC (0–1.8%) Cerealia (2–3%)	Coprophilous fungi (2–3%) Open Water indicators (9%) Aquatic taxa (20–24%)	Relatively high Pollen concentration (maximum ~3300 cal. yr BP) Medium levels of CHAR
LPAZ1b, 149–81 cm/~2400–1550 cal. yr BP	AP: 62–80% Initial phase with <i>Cedrus</i> (27–48%) dominant compared with <i>Quercus pyrenaica/canariensis</i> (27–21%), followed by alternating peaks between <i>Quercus pyrenaica/canariensis</i> and <i>Cedrus</i> .	Poaceae (13–22%) APP (6–3%) ANC (1–4%) AZNC (<1%) Cerealia (>6%) ~ 1755 cal. yr BP <i>Vicia faba</i> appears sporadically	Coprophilous fungi almost disappear Maxima of Aquatic taxa and Open Water indicators but general low levels up to the top	Relatively high Pollen concentration (maximum ~2110 cal. yr BP) Low levels of CHAR
LPAZ1c, 81–53 cm/~1550–800 cal. yr BP	AP: 53–70% Initial (16%) and final (19%) minima of <i>Quercus pyrenaica/canariensis</i> Alternating minima of <i>Cedrus</i> ~1300 and 1000 cal. yr BP Riparian woods (<3%) Wide increase of Thermophilous shrubland (4–11%)	Poaceae (29–12%) APP (4.5–5.8%) ANC (6.5–5%) AZNC (<1%) Cerealia (5.4–4.7%) <i>Vicia faba</i> , <i>Linum</i> and <i>Cannabis</i> appear sporadically	Coprophilous fungi in the last samples Maxima of Aquatic taxa/ Open Water indicators Maximum of Erosive Phases indicators Final occurrence of Dry Conditions indicators	Low levels of Pollen Concentration Maximum of CHAR ~1100 cal. yr BP
LPAZ2a, 53–37 cm/~800–500 cal. yr BP	AP: ca. 60–70% <i>Quercus pyrenaica/canariensis</i> (24–37%), <i>Quercus ilex</i> (8–11%) Minima of <i>Cedrus</i> (ca. 5–10%) Riparian woods (1–2%) Significant increase of Thermophilous shrubland (9–15%)	Poaceae (18–11%) APP (10–6.5%) ANC (4–6%) AZNC (1–2%) Cerealia (8–0.4%) <i>Vicia faba</i> and <i>Cannabis</i> appear sporadically	Coprophilous fungi in the top samples Significant values of Aquatic taxa and Open Water indicators Final peak of Dry conditions indicators	Higher levels of Pollen Concentration Initial minor peak and a final sharp one of CHAR
LPAZ2b, 37–0 cm/~500 cal. yr BP–present	AP >90% Sharp increase of <i>Quercus pyrenaica/canariensis</i> (38–65%). <i>Cedrus</i> almost disappears Riparian woods (<1%) Thermophilous shrubland (20–7%)	Poaceae (5–7%) APP (5–3%) ANC (ca. 4%) AZNC (ca. 2%) Cerealia, <i>Vicia faba</i> and <i>Cannabis</i> become exceptional	Maxima of Coprophilous fungi Open Water and Dry conditions indicators Low levels of Aquatic taxa	High levels of Pollen Concentration, Maxima of CHAR

CHAR: charcoal accumulation rate; ANC: Anthropogenic Nitrophilous Communities; AZNC: Anthropozoogenic Nitrophilous Communities; AP: arboreal pollen; APP: Anthropogenic Perennial Pastures.

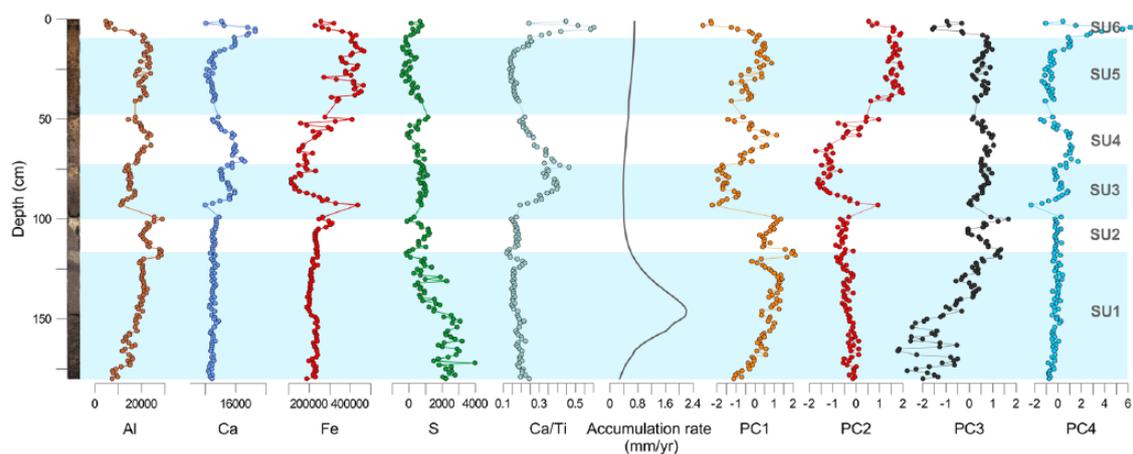
coprophilous fungi and the lower percentages of Anthropozoogenic Nitrophilous Communities (AZNC) and *Cerealia* (Figures 4 and 7). In spite of this, the synchronous retreat of oak forests could have also been triggered by thinning or felling, allowing a further development of grasslands. Such forest opening allowed the pollen transport from the cedar forests located at higher altitudes (Millerón et al., 2012). The medium levels of CHAR along with the increasing sedimentation rate (0.8–1.3 mm/yr), and particularly the high values of PC1, related to fine terrigenous sediment input because of enhanced soil erosion, also point to such a forest clearance (Figure 7).

An important shift occurs ~2100 cal. yr BP, when moisture seems to increase apparently throughout the western Mediterranean region (Cheddadi et al., 1998; Damnati et al., 2016; Martín-Puertas et al., 2010), expressed by a series of peaks of oak forests and aquatic taxa, alternating with those of Atlas cedar and Poaceae, which extend until ~1550 cal. yr BP without a significant modification of the ratio arboreal pollen/non-arboreal pollen (AP/NAP) (Figure 4). Thus, deciduous oaks (*Quercus pyrenaica* and/or *Quercus canariensis*) seem to be closely related to water availability (Cheddadi et al., 2016), revealed by the coeval high values of aquatic taxa. As already commented, oak forest could decline during drier phases, reducing

the canopy cover which would favour grasses and Atlas cedar pollen grains to reach the mire. *Cedrus atlantica*, however, appears to be more sensitive to temperatures in these mountains, since rainfall usually exceeds 700 mm (Castelló et al., 2016; Charco, 1999; Lenoir et al., 2008), especially at higher altitudes. The peaks reached by cedar get steadily lower during this period (Figures 4 and 7), because of a progressive upward shift to out-compete oak forests. PC4 and the terrigenous fraction suggest that the water table has fluctuated with several shallow phases, which gradually impacted the organic content towards the top (Figures 5 and 7). Although wet conditions are prevailing, a number of periods with shallowing mire (SU2 and SU3) spanning ~200 years can be observed. The very high sedimentation rate between ~2300 and 2000 cal. yr BP, reaching maximum values of 2.2 mm/yr at ~2170 cal. yr BP, suggests the nearly filling up of the mire accommodation space which became subjected to more frequent desiccation periods (Figure 7). This process has been enhanced by the increase of the carbonate constituent of the sediment, which derives from the weathering of the upstream tertiary marls, likely as a result of the erosion of the original soils triggered by agricultural activities (see Ca/Ti ratio and PC4 in Figures 5 and 7). This is consistent with the intensification of cereal cultivation which corresponds to the

Table 4. Description of sedimentary units.

Unit	Depth (cm)	Age	Description	Interpretation
SU6	10–0	~145 cal. yr BP to present	Moderate sedimentation rate : 0.7 mm/yr Two sedimentary facies: 1. 3–0 cm: Brownish grey and relatively less organic Fe-rich mud 2. 10–3 cm: Brownish grey organic mud that gradually becomes more organic Modern root bioturbations in the upper half	Shallow ephemeral mire. Presence of desiccation/weathering events at the top
SU5	46–10	~725–145 cal. yr BP	Increasing sedimentation rate: 0.5–0.7 mm/yr Two sedimentary facies: 1. 23–10 cm: More Fe-rich 2. 46–23 cm: Dark grey organic mud that gradually becomes less organic Fe-rich root bioturbations in the upper half	Shallow ephemeral mire. Presence of abundant desiccation/weathering intervals.
SU4	70–46	~1300–725 cal. yr BP	Quite constant sedimentation rate: 0.4–0.5 mm/yr Two sedimentary facies: 1. 57–46 cm: More Fe-rich 2. 70–57 cm: Dark grey organic mud that gradually becomes less organic Root bioturbations near the top	Relatively shallow perennial to ephemeral open water mire. Presence of desiccation events at the top, ca. 725 cal. yr BP
SU3	95–70	~1900–1300 cal. yr BP	Quite constant sedimentation rate: 0.4 mm/yr Two sedimentary facies: 1. 77–70 cm: More siliciclastic grey clays 2. 95–77 cm: Dark grey organic mud The sediments are slightly bioturbated near the top	Relatively shallow perennial open water pond. Presence of desiccation events ca. 1.9–1.7 cal. yr BP
SU2	113–95	~2170–1900 cal. yr BP	Low sedimentation rate: 0.4–0.5 mm/yr Two sedimentary facies: 1. 102–95 cm: Greenish siliciclastic clays 2. 113–102 cm: Organic mud Not bioturbated and/or edaphised sediments	Relatively shallow perennial open water pond. Absence of desiccation events
SU1	180–113	~3900–2170 cal. yr BP	Highest sediment accumulation rate: ~2.2 mm/yr Three sedimentary facies: 1. 120–110 cm: More siliciclastic mud 2. 145–120 cm: Organic muds 3. 180–145 cm: Organic-rich facies (plant fragments) Not bioturbated and/or edaphised sediments	Relatively deep and perennial open water pond. Absence of desiccation events

**Figure 5.** Sedimentary sequence of BEK II mire including core image, lithostratigraphic units (SU), geochemical stratigraphy of the most significant chemical elements, accumulation rate and principal components derived from PCA analysis (PC).

onset of the Roman Period in northern Morocco (Cheddadi et al., 2015; Taiqui and Cantarino, 1997). Mountain forests seem to remain fairly unconnected with this increasing human impact, likely because of the long distance of the site from the main inhabited areas. Cork oak forests, by contrast, show a quite significant retreat, as a probable result of initially drier climatic conditions and the increasing regional human impact, related both to cereal cultivation and the recurrent fires, pointed out by CHAR (Figures 4 and 7). This landscape feature persisted

without major changes until the decline of the Roman Empire ~1550 cal. yr BP.

The fall of Atlas cedar forests in Jbel Khesana (~1550–800 cal. yr BP)

This period (~1550–800 cal. yr BP) begins with a remarkable wide deforestation event, which led to a major expansion of grasslands, likely related to a drier climate, but also to an increase

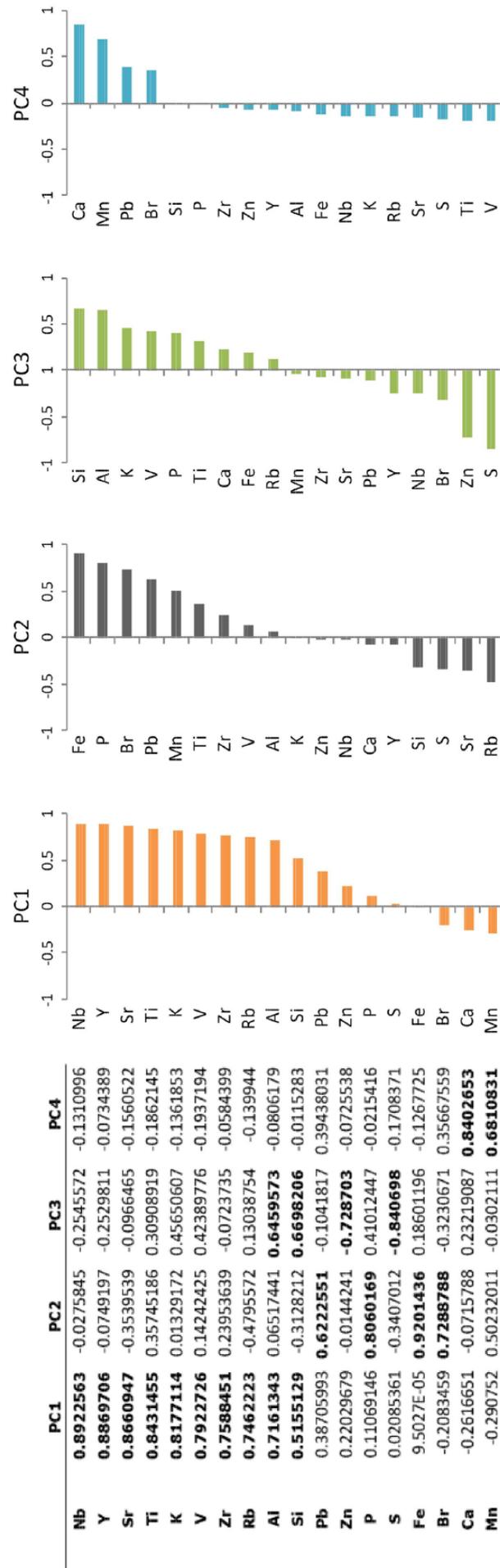


Figure 6. Loadings of the analysed elements on the principal components obtained by PCA analysis. High and moderate loadings are marked in bold.

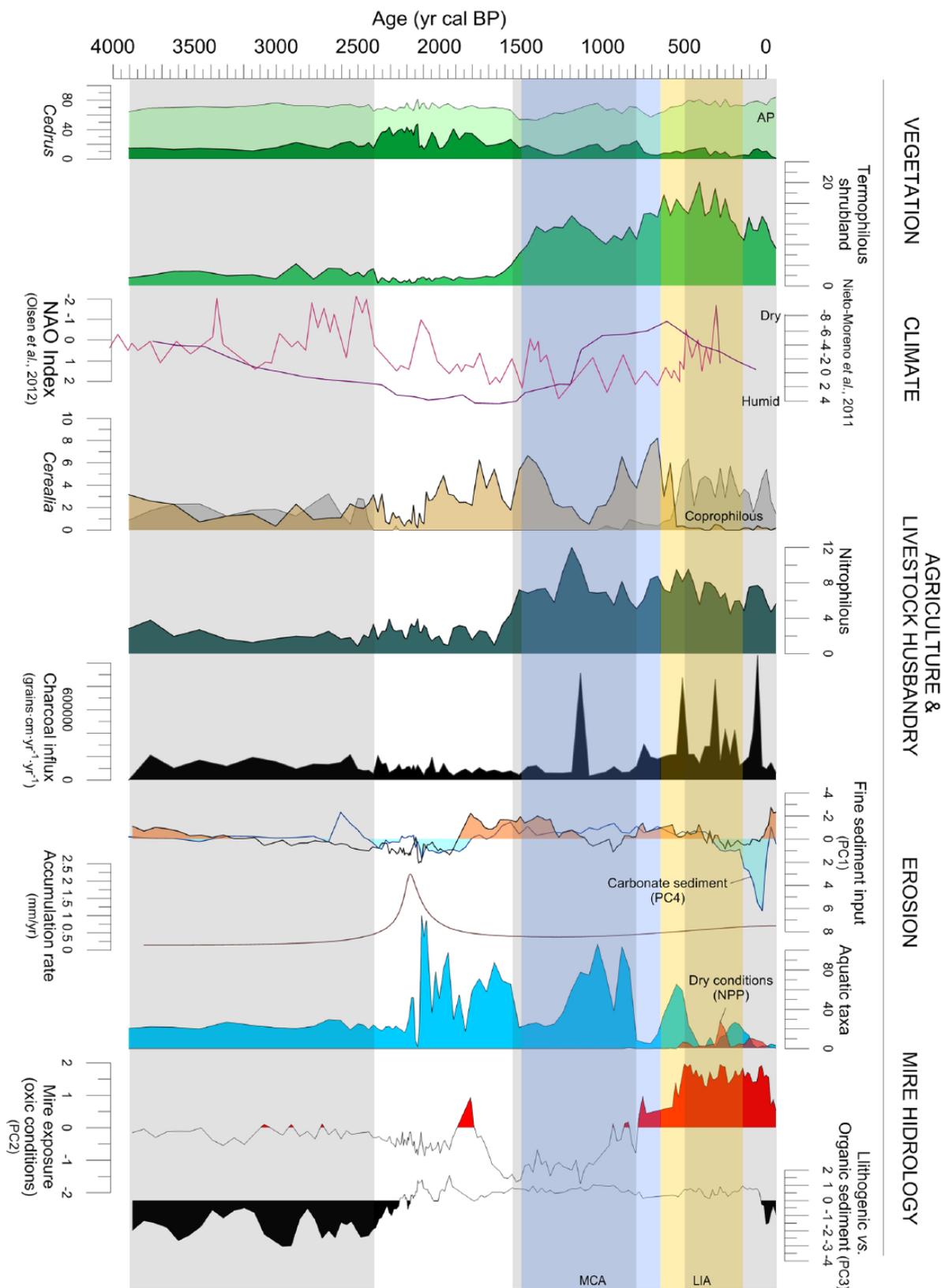


Figure 7. Main environmental changes over the last ~4000 years in the BEK II mire. AP: Arboreal Pollen; for the explanation of the pollen groups: Thermophilous shrubland, Coprophilous and Nitrophilous (Anthropogenic Nitrophilous Communities, ANC) go to Table 2; NAO Index from a climate proxy reconstruction from Greenland (Olsen et al., 2012); Dry versus humid climate conditions from the first eigenvector of the west Balearic-Algerian Basin 306G core (Nieto-Moreno et al., 2011); MCA and LIA from Martín-Puertas et al., 2010; Charcoal influx as the total input of microcharcoals.

of temperature, as suggested by open water indicators (Cook et al., 2011; Quamar, 2015; Van Geel, 2001). They also point to an increasing seasonality against the more continuous water availability indicated by aquatic taxa (Amami et al., 2010; Oertli et al.,

2010). This corresponds to the onset of the Medieval Climate Anomaly (~1400–700 cal. yr BP; Martín-Puertas et al., 2010), a period characterised by drier and warmer climatic conditions (Esper et al., 2007; Nieto-Moreno et al., 2015, 2011). The strong

deforestation of Atlas cedar forests coincides also with a political instability between the end of the Byzantine period and the arrival of the Arabs (AD ~650–900/~1300–1050 cal. yr BP), leading to the establishment of the Idrisid dynasty during the 8th century, when an increasing consumption of forest resources triggered a major break in the regional landscape history (Cheddadi et al., 2015; Taiqui and Cantarino, 1997). Furthermore, after ~1300 cal. yr BP, PC1 and PC2 indicate an increase of the relative fine terrigenous input against organic matter (Figure 7), which can be interpreted as the start of a new shallowing sequence, as a result of drier conditions.

Also striking is the disconnection between the development of oak and Atlas cedar forests (Figure 4), pointing to the end of the competition between the two species with a further upward shift of the latter. The sharp drop of oak occurrences is no longer counteracted by Atlas cedars but rather by a wide spread of thermophilous shrubland and grasslands which is consistent with an increasing aridity trend, as well as a recovery of cereal cultivation, which had declined at the end of the previous period. It could also be linked with a slightly higher occurrence of fires, shown by CHAR values, either as a consequence of a longer dry season, or as a result of clearings to open new lands for cultivation. In this sense, Atlas cedars do not seem to have a high flammability, especially when they are old (Slimani et al., 2014). Thus, the retreat of oak forests could instead have been induced by a drier climate and an intensification of agricultural activities, while Atlas cedar forests could have been exploited for timber.

Later, ~1150 cal. yr BP, a marked peak of CHAR appears to have caused a deeper impact on grasslands and thermophilous shrublands than on mountain forests (Figures 4 and 7). Furthermore, fires could also have enhanced the erosion of the catchment area, as indicated by *Glomus* and *Pseudoschizaea circula*. Enhanced erosion is also marked by positive scores in PC4 (Figure 7), likely related to the reduction of the forest cover as well as to the development of agricultural activities.

A new wet phase (~1030 cal. yr BP), indicated by a high occurrence of aquatic taxa, allowed a recovery of the forest ecosystem where both Atlas cedar and oaks almost reached their previous occurrences. However, a new regression of the Atlas cedar forests took place ~980 cal. yr BP, likely more related to human disturbances. In this sense, timber trade between Al-Andalus and the Maghreb is well dated since the 10th century AD (Rodríguez Trobajo, 2008). Then, Atlas cedars recovered again with extended populations around the studied site. At the end of this period, the significantly high proportion of shrubs (>10%) suggests a 'matorralization' process (Barbero et al., 1990) for the last millennium in Jbel Khesana.

Cereal cultivation remains a strong human activity during this period, except ~1080 cal. yr BP, at the end of the Idrisid dynasty (AD 790–930). Grazing activities are attested only in the top samples, from 980 cal. yr BP onwards, with very low values of coprophilous fungi.

Final extinction event of Atlas cedar forests in Jbel Khesana (~800 cal. yr BP-present)

Atlas cedar forests undergo a sharp decrease likely related to new loggings. The initial event may coincide with the political rule of the Almohad dynasty (AD ~1150–1250/~800–700 cal. yr BP), which built a great number of mosques, presumably with Rifan *Cedrus atlantica* wood (Park and Boum, 2005). The use of Atlas cedar timber for buildings in Al-Andalus is also reported by various sources (Rodríguez Trobajo, 2008). Lower water levels and more frequent desiccation intervals are indicated by the more pervasive vadose oxic meteorisation (PC2) of the mire sediments, the low values of aquatic taxa and the higher occurrence of Cyperaceae. In spite of these drier conditions, cropping activities reach their maximum intensity within the record. Both CHAR and

coprophilous fungi show significant values, indicating a higher incidence of fires and the intensification of grazing activities. The latter reach their maxima after the final abandonment of cereal cultivation in the area, ~550 cal. yr BP. This significant change in land-use, coeval with a noteworthy climate event, allows us to carry out a detailed diachronic analysis of this final subzone, despite the lack of a radiocarbon dating. Climatic conditions probably became cooler with the onset of the 'Little Ice Age' (Esper et al., 2007; Martín-Puertas et al., 2010; Nieto-Moreno et al., 2015). The final minimum (~600 cal. yr BP) in the first eigenvector of the west Balearic-Algerian Basin 306G core, indicating dry climatic conditions (Nieto-Moreno et al., 2011), as well as the shift towards negative values (~500 cal. yr BP) of the NAO Index (Olsen et al., 2012), allows us to set the abandonment of cereal cropping at this date (Figure 7). The slight expansion of aquatic taxa matches this event, although a more intense seasonality seems to have been established, as indicated by the increasing values of Dry conditions indicators (Figure 4) and the positive ones of PC2, related to a greater mire exposure (Figure 7). The LIA is considered to have been drier in Morocco, especially during its first half, than in Europe (Nieto-Moreno et al., 2011; Touchan et al., 2011). Some authors (Taiqui and Cantarino, 1997) also describe a period of social crisis between 15th and 16th centuries which would have led to the prevalence of transhumance and nomadism against cropping activities. In any case, this event would have favoured the recovery of all arboreal taxa, especially oaks, while *Cedrus* populations retreated. Nevertheless, it triples its values from ~665–375 cal. yr BP, after a significant retreat ~510 cal. yr BP likely related to the construction of new settlements like the town of Chefchaouen (AD 1471/479 cal. yr BP). Its percentages (5–15%) indicate that the species was present or growing a few hundred metres from the site likely further upwards from the core site. Previous lower resolution studies (Cheddadi et al., 2016, 2017; Muller et al., 2014; Reille, 1977) depict the virtual demise of *Cedrus* from most pollen records during medieval times and even before. The present high-resolution analysis shows, in contrast, a significant resilience of Atlas cedar forests in the area. The successive loggings, carried out ~340, 280, 220 and 105 cal. yr BP, were always counteracted by subsequent recoveries up to 12%, reporting the local persistence of Atlas cedar forests close to the site. Meanwhile, the expansion of oak forests was favoured by the retreat of the thermophilous shrubland, as a result of a higher occurrence of fires, with maxima of CHAR. Fires would have also favoured the spread of grasslands in order to supply the increasing livestock density (Figure 7). These traditional agrosilvopastoral uses shaped a dehesa-like landscape which has persisted until very recent times (Ballouche, 2013; Cheddadi et al., 2015).

A major landscape change took place with the onset of the Colonial Period (AD 1912–1956) and the subsequent independence of Morocco from France and Spain. First of all, Atlas cedar forests disappeared completely ~1950 cal. yr AD from the Jbel Khesana, most probably as a consequence of loggings carried out by the Spanish government (Ajbilou et al., 2003; Araque and Garrido, 2015). A further regeneration could have been ultimately unachievable because of the high incidence of the subsequent human activities in the area, including logging, slash-and-burn farming ('sbir') and overgrazing (Coudel et al., 2016; Rejdali, 2004; Taiqui, 2005), which triggered a strong soil erosion (Moore et al., 1998), along with increasing temperatures and aridity. This enhanced soil erosion is also pointed out by the high levels of PC1 and PC4, related to the increase of sediments coming from the slope bedrock (marls) weathering (Figure 7).

Thus, the local extinction of Atlas cedar forests in Jbel Khesana seems to have been mainly induced by an increasing human pressure, particularly during the 20th century, rather than by a climatic constraint, although recent warming and increasing aridity have

increased their vulnerability. Both current temperature and rainfall amount still remain appropriate for the development of these forests in the area (Ajbilou et al., 2003; M'hirit and Benziane, 2006). In this sense, Rifan *Cedrus atlantica* forests show a distinct pattern from the rest of their distribution range in the north of Africa (Allen et al., 2010; Castelló et al., 2016; Cheddadi et al., 2017; Linares et al., 2013; Slimani et al., 2014; UICN, 2015).

Conclusion

In the present study, we show that high-resolution multi-proxy analyses are essential for evaluating local extinctions of endangered forest species.

Over the last 4000 years, with a reduced human influence, the climate seasonality and increasing aridity were the main drivers for the upslope migration of the Atlas cedar towards more humid conditions. Then, the increased aridity and human pressure over time favoured the spread of a thermophilous shrubland and the depletion of Atlas cedar forests, in a process that lasted until ~800 cal. yr BP. Sequential deforestation events in relation with timber exploitation took place over recent centuries with subsequent recoveries of the forest, until the final local extinction of the species in the middle of the 20th century.

In summary, human pressure, either directly, by intensive loggings, or indirectly, strongly limits the species regeneration through overgrazing and the use of fire. Our data show that the increasing human pressure has been the main driver of the extinction of Atlas cedars in the studied area. Our findings have significant implications for current and future management and conservation of Atlas cedars in the Rif Mountains, beyond the unpromising forecasts linked to climate change. Conservation measures in Atlas cedar forests growing at altitudes about 2000 m a.s.l. could ensure the future of this endangered species (IRES, 2010). There should be a high priority for preserving their regeneration as well as for limiting the intensive loggings. Cropping activities, especially related to *Cannabis* cultivation, have become a major threat to Atlas cedar populations as main drivers of deforestation and soil erosion. More sustainable activities are required. In this sense, low-intensity levels of livestock grazing are especially advised to avoid an excessive fuel accumulation which could lead to widespread wildfires.

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