Two millennia of plant community dynamics in north-eastern Algeria: the case of Nechaa Righia peat, El Kala National Park

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SUMMARY

A sedimentary sequence of length about 420 cm was extracted from the alder-peatland of Nechaa Righia in north-eastern Algeria's El Kala wetland complex, to clarify the relationship between past and present vegetation and understand climatic and ecological changes over the past two millennia in this key Mediterranean wetland. The pollen diagram, supported by A.M.S. radiocarbon dates, reveals a predominance of hygrophilous and aquatic taxa like *Alnus*, Cyperaceae and Juncaceae, indicating a wet environment. Regional vegetation includes mesophilic taxa such as *Quercus*, *Erica arborea* and *Myrtus*, suggesting a mixed landscape. Herbaceous taxa like Poaceae, Apiaceae and Fabaceae further illustrate the area's variety of plants. Indicators of anthropogenic activity such as *Olea*, *Vitis* or *Pistacia* highlight human impact on the landscape. Around 1890 ± 40 BP, during the Medieval Warm Period, the region featured cork oak forests and mesophilic vegetation consistent with the warmer climate conditions noted in other Mediterranean studies. This vegetation persisted through the Little Ice Age, characterised by cooler conditions, and remains today. Significant human activity began around 1275 ± 50 BP when Yemenites introduced new agricultural practices, supplanting Roman civilisation. Their cultivation of cereals and *Olea* species significantly shaped the vegetation landscape. These findings align with similar climatic variations reported in the Northern Hemisphere and in the Mediterranean region.

KEY WORDS: alder, climate change, ecosystem resilience, Mediterranean wetland, pollen, vegetation history

INTRODUCTION

Eastern Numidia, spanning 17,500 hectares, is a region remarkable for its ecological diversity and its critical role in biodiversity. This vast area, bounded by the Mediterranean Sea, the Oued Sybouse and the hills of the Tell Atlas, has featured the El Kala National Park since 1983. However, despite its protected status, the region faces significant threats from human activities and climate change (Rouibi 2022). The El Kala wetland complex, situated in the northeastern Tell Atlas, is a key ecological area bordered by the Oued Seybouse to the west, the Mediterranean Sea to the north, the Medjerda mountains to the south, and the Khroumirie mountains to the east (Chalabi-Belhadj 2008). The Oued El Kébir River, meandering through passes and transverse valleys, forms a series of small plains which are oriented east to west. These plains gradually decrease in size towards the river’s source in Tunisia, with altitudes ranging from 288 to 396 metres. Enclosed by a coastal dune belt and inland mountains, these plains collect runoff from various basins and sub-basins, contributing to the extensive El Kala wetland complex, which notably contains Algeria's most significant wet forests (de Bélair 1990). The geological substratum here is dominated by Oligo-Miocene sandstones, combined with clays, forming the Numidian flysch (Belouahem-Abed *et al*. 2011).

The El Kala region is distinguished by its exceptional ecological diversity, encompassing Mediterranean forests, wetlands and coastal ecosystems. The total area of wet forests in the El Kala region is estimated to be 3,924 hectares, with approximately 42 % represented by the alder forests of Righia (313 ha), Oum Laagareb (221 ha), Bourdim (123 ha) and Aïn Khiar (95 ha), along with the riparian forests of El Mellah lagoon (400 ha), the Mekhada marshes (197 ha), and lakes Tonga (167 ha) and Oubeïra (131 ha) (Kahli *et al*. 2018). According to Mathieu *et al*. (2013), these forests host a multitude of plant species including *Quercus ilex* (evergreen oak), *Pinus halepensis* (Aleppo pine) and *Cedrus atlantica* (Atlas cedar). These species play a vital role in biodiversity conservation and the maintenance of biogeochemical cycles. The variety of soils supporting these forests, ranging from sandy to clayey, has been highlighted by Benslama *et al*. (2010).

Despite its rich vegetation, the conservation of El Kala's flora faces increasing challenges including urbanisation, unsustainable agriculture and other human activities. Hamouda & Tahar (2012) emphasise that these pressures threaten the stability of the region's plant ecosystems. The relationship between pollen rain and vegetation is particularly important in this context. Phenological studies have revealed a synchronisation between pollen rain and plant flowering, determined by seasonal fluctuations in precipitation and temperature. This synchronisation is crucial for ensuring successful pollination and the reproduction of plant species. Research by Benhouhou *et al*. (2018) highlights the impact of this relationship on the conservation of plant biodiversity in the face of climate change challenges, offering valuable perspectives for guiding conservation efforts in the region.

The study of past vegetation provides context for ecological changes over time. As Ghit *et al*. (2018) emphasised, this type of analysis helps us understand how local ecosystems respond to climatic variations, human activities like logging and urbanisation, and historical geological events. Such understanding is crucial for informed environmental management and the preservation of valuable natural heritage.

The primary objective of our study is to clarify the relationship between past and present vegetation, to grasp the dynamics of vegetation over the past two millennia, and to understand climatic and ecological changes in the study area. This knowledge will underpin our aim to promote the conservation and sustainable management of the exceptional natural heritage of El Kala.

METHODS

Study area

The study was carried out in the Righia region, located within El Kala National Park (36° 49' 46" N, 8° 10' 53" E), focusing specifically on the alder-peatland ecosystem of Nechaa Righia (36° 49' 56" N, 8° 10' 28" E) (Figure 1).

Nechaa Righia is renowned for its dense swamp forests, which remain waterlogged throughout the year, making it a unique and vital wetland habitat (Zentar 2021). Covering an area of 300 hectares (Benslama 2007), the site lies at an elevation ranging from 16 to 30 metres above sea level (Belouahem-Abed *et al*. 2011).

This area hosts the largest alder forest in North Africa, which borders the southern dune massifs and has developed in the coastal depressions of the north-eastern part of the country. Nechaa Righia is part of the marshlands characterised by dark silts that have developed extensively in the flooded lowlands of the south-west, south and south-east of the Bouteldja forest, between the Cheffia mountains and the coastal dune massif, as well as at the eastern edge of Lake Oubeira, near Lake Tonga, and south of Lake Melah (Zentar 2021).

The local bioclimate is classified as "thermo-mediterranean". Climate data indicates average annual precipitation exceeding 700 mm, with a maximum of 944 mm at El-Kala (Benslama *et al*. 2010). The dry season lasts from May to September. The average annual temperature is 17.9 °C. Despite this, dense cork oak ecosystems remain present in the region, accompanied by deciduous vegetation (Benslama *et al*. 2010). The study conducted by Khallef *et al*. (2021) on the remote sensing of vegetation dynamics in El Kala from 1987 to 2016 revealed a 7.49 % loss of natural vegetation cover during this period. The El Kala National Park has undergone significant transformations in land use and vegetation cover, with reforestation but a decline in maquis areas. Factors such as fire, overgrazing, urbanisation and clearing have contributed to vegetation degradation. Climate variability and wildfires have also had a significant impact on the park's vegetation.

Among the notable ecosystems of the regional wetlands are the *Alnus glutinosa* forests, which thrive along waterways (known as riparian alder forests) and in the peatlands near lakes or within interdunal ridges (referred to as square alder forests). These unique habitats are partially integrated into the El Kala National Park and the Guerbès-Senhadja wetland complex. These areas sometimes benefit from indirect conservation measures focused on bird richness, as is the case for the alder forests of Tonga and Ain Khiar which were designated Ramsar sites in 1983, 2001 and 2002 (Belouahem-Abed *et al*. 2009). The floristic diversity of the El Tarf region reveals a complex ecological landscape, characterised by a remarkable predominance of Mediterranean floristic elements (50 %) and significant contributions from species with European affinity (20 %), cosmopolitan species (20 %) and tropical species (10 %) (Pech & Diaf 2022). This diverse landscape is shaped by a generously rainy and humid climate, which promotes exceptional biodiversity (Zentar 2021). The wetlands host a variety of tropical and European species such as *Marsilea diffusa*, *Utricularia exoleta*, *Dryopteris gongyloides* and *Cyperus corymbosus*, while traditional Mediterranean species like the cork oak, kermes oak, wild olive and tree heather (*Erica arborea*) contribute to firmly anchoring the regional floristic composition. This diversity reflects the

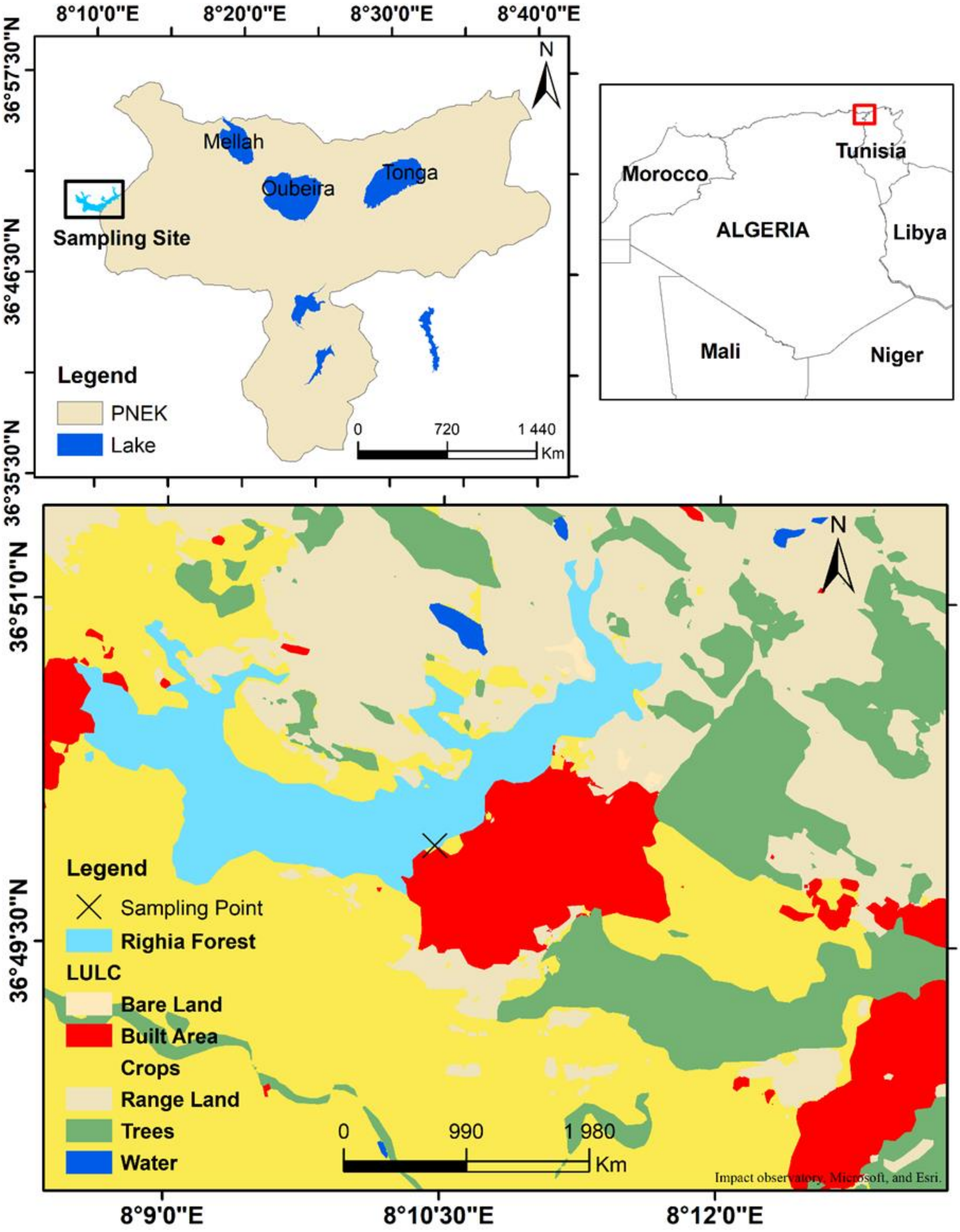

Figure 1. Location of the study area.

complexity of ecological interactions in the region (Benyacoub *et al*. 1998), highlighting the importance of preserving and studying these varied ecosystems for biodiversity conservation.

Coring and dating

The collection and analysis of sediment core samples followed a rigorous methodology. A Russian corer was used to collect samples from peat bogs. The cores were extracted alternately from adjacent and parallel holes to ensure that an adequate quantity of material for pollen and dating analyses, particularly high-resolution pollen analysis, was collected (Reille 1990). The cores were transported promptly to the laboratory and stored in the shade at room temperature to prevent any damage.

Chronology

For the 14C dating, two bulk peat samples from the same core were selected. The dating analyses were performed at the radiocarbon laboratory in Lyon, France, using the AMS spectrometry method. The obtained dates were calibrated using Chronomodel 2.0.18 (Lanos & Dufresne 2019) (Table 1, Figure 2).

Table 1. AMS radiocarbon dating of the studied core.

Dated sample levels (cm)	Dated material	Lab code	Calibrated C14 (Yr BP)	Calibrated C14 (Yr AD) 95.4 % probability (2-sigma)
265–270	Peat	LY-9403	1275 ± 50	658 - 876
395–400	Peat	LY-9404	1890 ± 40	28 - 231

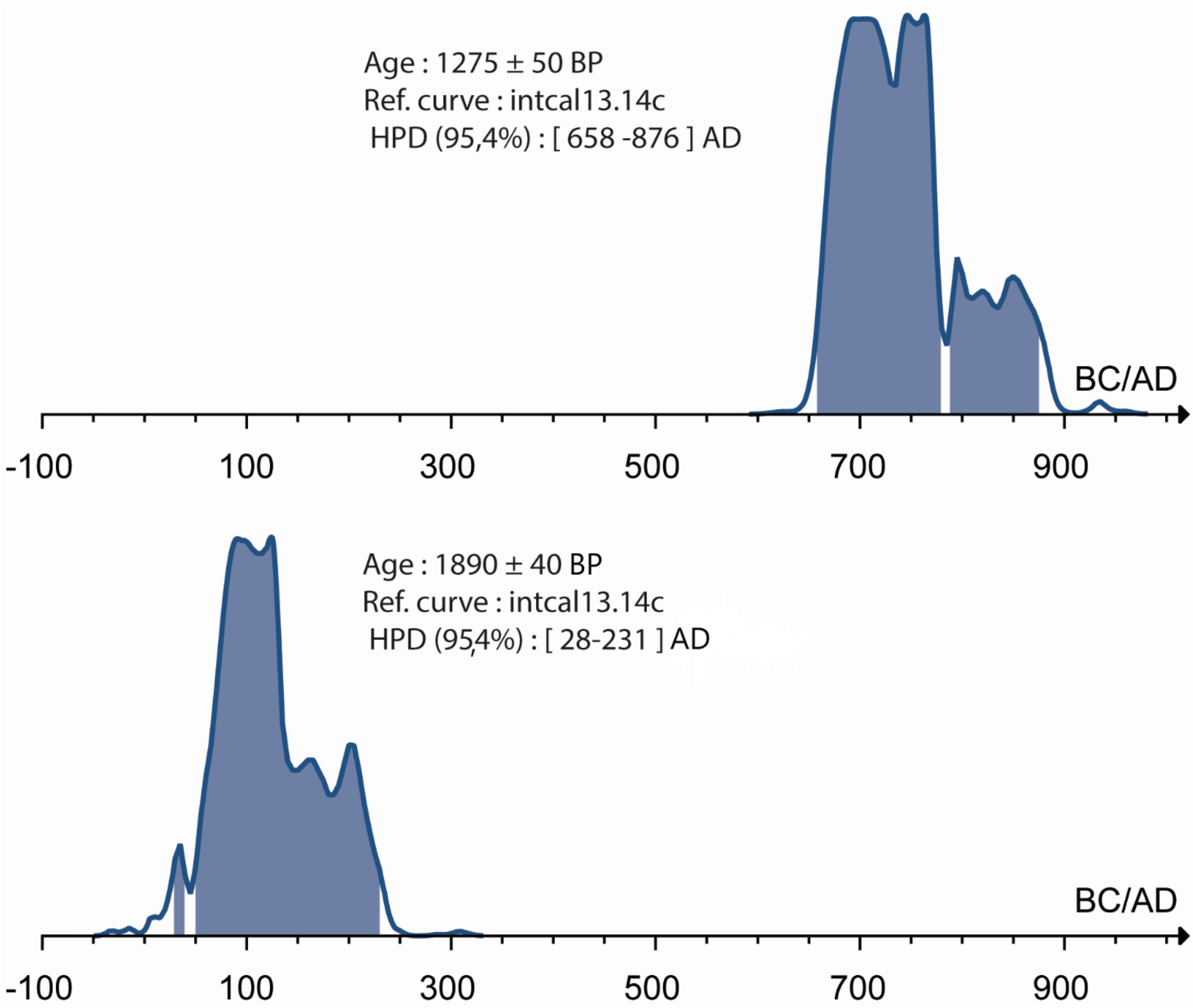

Figure 2. Distribution of calibrated dates from Nechaa Righia.

Palynological analysis

In the laboratory, careful sampling of the cores was performed by removing the surface polluted by coring and conducting a stratigraphic description. For pollen analyses, 41 samples were taken at 10 cm intervals along the core (420 cm length), adjusting the mass according to the types of sediment to be analysed, following the method of Faegri & Iversen (1989) and Benslama (2007). Once the samples were chemically prepared, counting and identification of pollen grains were performed under a microscope, using a reference collection and pollen atlases (Beug 2004, Reille 1992, Reille 1998). At least 300 pollen grains were counted at each level to ensure the statistical representativeness of each analysed spectrum. The data were expressed as relative frequencies compared to the total pollen sum and visualised graphically using TILIA and TG View (Grimm 1991). The counts of hygrophilous and aquatic plants were excluded from the total pollen sum to improve the graphical representation of other pollen taxa. The zoning of the obtained diagram was established through a preliminary clustering analysis using the CONISS software (Grimm 1987), considering notable frequency variations of major forest and herbaceous taxa.

RESULTS

Stratigraphical data

The stratigraphy of Nechaa Righia core reveals five layers that differ in colour, the degree of organic matter decomposition, and the presence of sand and clay (Table 2).

Palynological data

Palynological analysis of 41 samples collected from the Nechaa Righia core indicated the presence of pollen and spores with a good degree of preservation. The pollen diagram in relative frequency presents the evolution of the main taxa encountered during the analysis (Figure 3).

A pollen zone is defined by a series of pollen assemblages from adjacent levels that do not show significant differences among them. The zoning step is crucial as it allows for organising the description of the pollen diagram and, consequently, the reconstructed vegetation history. Three main zones were identified, as presented in Figure 3 and Table 3.

Pollen zone A (305 cm–405 cm)

In this zone, a strong presence of *Alnus* suggests favourable conditions for its development. Concurrently, a low presence of *Erica* indicates some plant diversity, although *Erica* is less dominant. These observations support previous studies that highlighted the ability of *Alnus* to thrive in marshy and humid environments (Schoenenberger *et al*. 1970, Géhu *et al*. 1993).

Pollen zone B (260 cm–305cm)

In this zone, the decline in the presence of *Alnus* could be the result of environmental changes or human intervention. The increase in Poaceae in this zone may reflect changes in local hydrology or environmental conditions, such as fluctuations in the water regime which could have favoured drying out, allowing Poaceae to develop in that area. Additionally, the increase in grasses may be a response to possible local deforestation. This

Table 2. Morphological description of the core taken from Nechaa Righia.

Depth	Description
0–25 cm	Clayey; fine and soft; barely visible lamellar structure; many slightly decomposed organic debris; very moist.
25–105 cm	Fibrous texture; non-clayey; lamellar structure; much recognisable organic debris; very moist; wood debris present at depths of 35 cm and 95 cm.
105–180 cm	Little organic debris, sand or clay but a lot of highly degraded organic matter; soft; lamellar structure; some wood debris at 175 cm depth.
180–245 cm	Fibrous texture; non-clayey; organic; very soft (degraded peat) with scattered wood debris; sand grains present at the base.
245–420 cm	Degraded peat: a lot of organic fibres; very moist; organic; spongy, soft, lamellar structure, wood debris present at 305 cm depth.

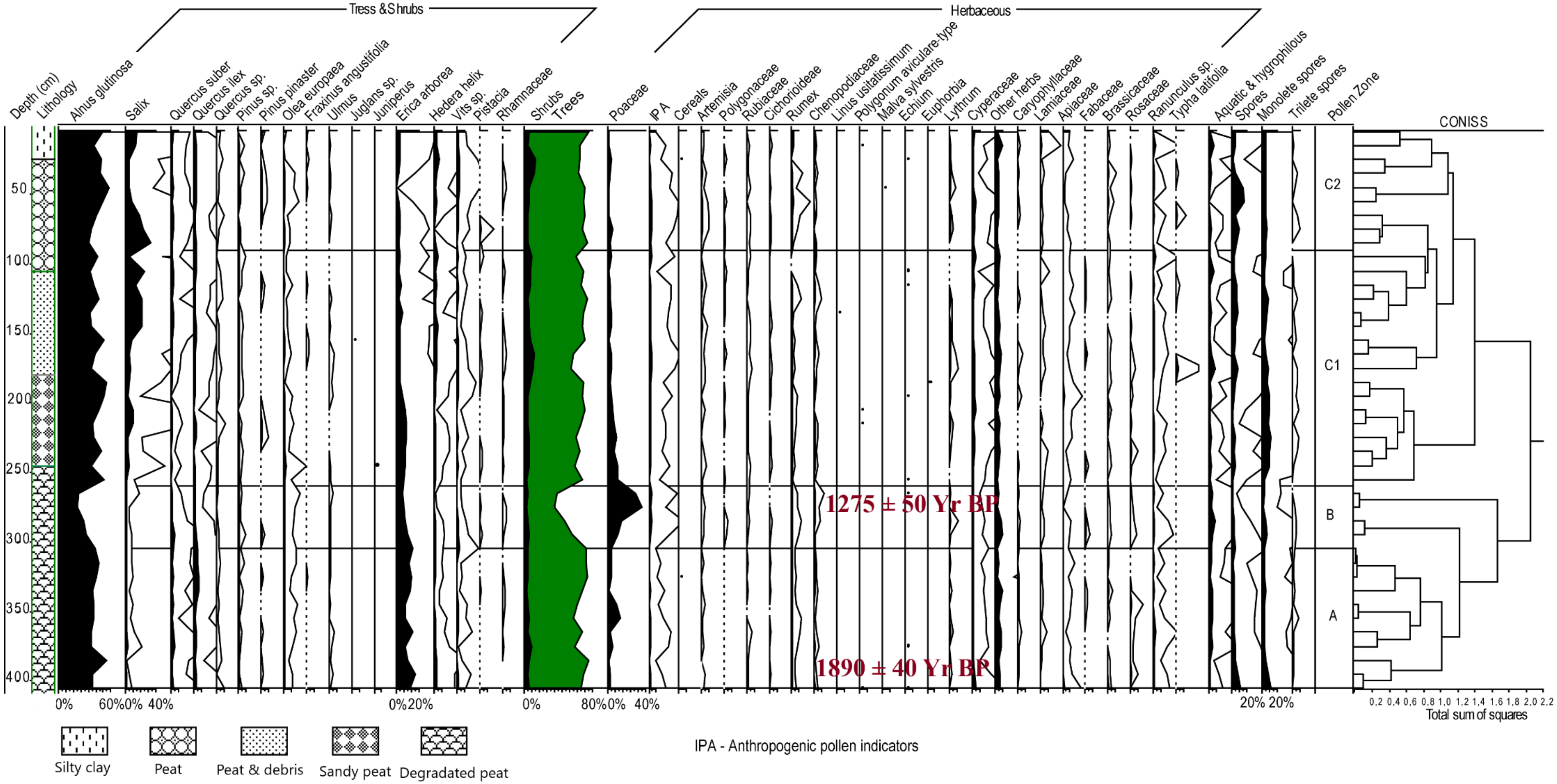

Figure 3. Simplified pollen diagram from Nechaa Righia.

coincides with a decline in *Erica arborea*, reflecting a noticeable change in vegetation dynamics. The presence of *Artemisia*, commonly associated with open vegetation influenced by human activity, is consistently observed from this point onward, reinforcing the idea that human intervention played a role in shaping the landscape during this period. This hypothesis is also confirmed by the presence of pollen grains from *Olea*, *Vitis* and *Pistacia*. The slight changes in the presence of *Salix* also deserve attention to understand the nuances of vegetation transition in this zone. The deforestation of higher and drier areas may have led to increased surface runoff towards the lower wetland regions. This is likely to have caused a rise in water levels and an increase in nutrient input within the wetland. These changes would have promoted the growth of *Salix*. Additionally, the shift to cooler and wetter climatic conditions may have further created favourable conditions for *Salix* while making the environment less suitable for *Erica*.

This dual influence of human activity and environmental change makes the interpretation of vegetation dynamics in this area more challenging.

Pollen Zone C (0 cm–260 cm)

This zone is marked by a significant increase in the presence of *Alnus* and *Salix*, indicating notable environmental changes in the local area. Concurrently, a decrease in *Erica arborea* is observed, which may suggest competition between these taxa for available resources. *Alnus* and *Salix* typically thrive in marshy and humid environments, whereas *Erica arborea* is better adapted to drier conditions. As these species do not coexist in the same habitat, this shift in their abundance reinforces the idea that environmental changes favoured the growth of *Alnus* and *Salix* at the expense of *Erica arborea*. Additionally, the recording of anthropogenic pollen indicators (e.g. pollen from *Juglans*, *Pistacia*, *Olea*, *Vitis*, *Cerealia*, *Polygonaceae*, *Polygonum aviculare*-type, *Chenopodiaceae*, *Cichoroideae*, *Artemisia*, *Rumex*, *Rubiaceae*, *Hypericum*, *Lythrum*, *Malva*, *Linum usitatissimum*, *Euphorbia*, *Bistorta*, *Carlina*, *Echium*) raises questions about anthropogenic effects on the local vegetation, highlighting the importance of considering human factors in the interpretation of palaeobotanical data in this region (Behre 1981). At a depth of 85 cm, an inversion in the trend is observed between *Alnus* and *Salix*, with a decrease in *Alnus* and an increase in *Salix*. At a depth of 45 cm, the opposite phenomenon occurs, likely due to competition for nutrients and water. It can be observed that this sequence reflects the current vegetation of the region quite accurately and does not differ from the landscape. On a long-term timescale such as over the whole of the Quaternary, successive extinctions can be considered to have occurred mainly in the glacial-interglacial episodes of the Pleistocene according to latitude and secondarily according to longitude, while certain refuge zones were established and have persisted until today (Hewitt 1999, Vogel *et al*. 1999, Médail & Diadema 2006, Médail & Diadema 2009).

DISCUSSION

Our findings reveal a correspondence between the sequence of vegetation changes recorded at the Nechaa Righia study site and other palynological sequences documented in previous regional studies. This correspondence highlights that the timing of significant shifts in vegetation dynamics at Nechaa Righia closely matches timelines established in earlier research (Ben Tiba & Reille 1982, Benslama *et al.* 2010, Youbi & Benslama 2015, Kahit *et al.* 2017, Kahit *et al.* 2018). This alignment suggests that

Table 3. Interpretation pollen zones defined from Nechaa Righia core.

Pollen zone	Sub-zones	Depth	Significant taxa / short interpetation
C	C2	0–90 cm	IPA, Poaceae, *Salix*, *Alnus*, *Erica*, *Myrtus*, hygrophilous taxa, spores
	C1	90–260 cm	*Alnus*, *Erica*, Poaceae
B		260–305 cm	Decline of *Alnus*, increase of Poaceae, decrease of *Erica arborea*
A		305–405 cm	Dominance of *Alnus* and *Erica*, low presence of *Quercus* and *Salix*

the ecological processes observed at Nechaa Righia are part of broader environmental and climatic trends across the region. Paleoclimatically, several scientific studies have agreed that the climate in the Northern Hemisphere has oscillated between warm and cold periods over the last millennium (Reille *et al*. 1997, Mann 2005, Julià *et al*. 2007, Vennetier *et al*. 2010). However, these changes have not yet been proven on a global scale. The current vegetation primarily results from climatic changes during the Pliocene and Pleistocene periods (Suc 1984, de Beaulieu *et al*. 2005).

Additionally, the long history of human influence has profoundly impacted the organisation of landscapes and Mediterranean ecosystem diversity (Allen 2001). Suc (1984) revealed that Mediterranean sclerophyllous plants increased as mega mesothermic plants gradually became rare and subsequently disappeared. Long-term changes in Mediterranean ecosystems are often attributed to gradual climatic shifts and evolutionary processes, while recent changes are characterised by rapid modifications driven by anthropogenic actions and climatic variability. Despite the climatic changes that occurred during the glacial–interglacial periods of the Pleistocene, this area acted as a refuge where plant life persisted (Hewitt 1999, Vogel *et al.* 1999). Recent studies underscore the significance of these refuge areas in explaining the structure, uniqueness and sustainability of contemporary Mediterranean biodiversity. Numerous studies highlight the importance of such research (Tzedakis *et al.* 2002, Petit *et al*. 2003, Médail & Diadema 2009), demonstrating how these refuges have shaped the biodiversity and ecological resilience observed nowadays. The Medieval Warm Period may have been characterised by increased precipitation in certain regions, potentially supporting more robust vegetation and wetland expansion, while the Little Ice Age might have brought shifts in hydrological regimes, with some areas experiencing heightened aridity and others increased wetness due to regional climatic variability. These hydrological changes are particularly relevant for understanding the vegetation dynamics and sedimentary processes in our study site. Incorporating proxies for precipitation and evaporation, such as pollen from hygrophilous plants or sedimentary records indicating water level fluctuations, could provide a more comprehensive perspective on the environmental impacts of these climatic periods in our area of focus. Scientists discuss a warm period between 900 and 1300 AD, corresponding to the Medieval Warm Period, and a cold period between 1400 and 1850 AD, known as the Little Ice Age (LIA). These significant climatic fluctuations have been evaluated by several researchers including Jones & Mann (2004), Moberg *et al*. (2005) and Guiot (2012). For example, according to Moberg *et al.* (2005), temperatures comparable to those recorded in the 20th century prior to 1990 were observed between 1000 and 1100 AD. In contrast, the lowest temperatures, approximately 0.7 K below the 1961–1990 average, occurred around 1600 AD. This significant natural variability in the past highlights the influential role of multi-centennial climate fluctuations, which are likely to continue in the future. Changes in temperature also drive variations in water availability and humidity, which in turn profoundly affect habitat conditions and vegetation growth.

Distinguishing between climate change and human impact on vegetation is challenging due to their often simultaneous occurrence and overlapping effects. Climate-induced changes typically manifest as gradual and broad alterations in vegetation over time, reflecting shifts in environmental conditions such as moisture levels or temperature. For instance, variations in the dominance of species like *Alnus*, *Salix* or *Erica arborea* can indicate natural responses to climatic fluctuations. In contrast, human influence is often marked by abrupt and localised changes. A sudden increase in pollen from anthropogenic taxa, such as *Olea* (olive), *Vitis* (vine), *Pistacia* or Cerealia, serves as a clear indicator of human activities like agriculture, deforestation or landscape modification.

The Medieval Warm Period

At low altitudes in the Righia alder forest, the largest in North Africa according to Belouahem-Abed *et al*. (2011), the association of *Alnus* and Cyperaceae reflects a very dominant presence of wet meadows due to the climatic warming characteristic of this period (Mann 2005). Remarkably, their persistence throughout the period, despite the warming, is supported by several similar studies (Stambouli-Essassi 2003, Benslama 2007). In northern Algeria, alder forests with *Alnus glutinosa* represent an original and unique ecosystem, despite their presence in northern Morocco and north-western Tunisia, according to the works of Damblon (1991) and El-Hamouti *et al*. (1991). Ben Tiba & Reille (1982) confirmed the regional presence of *Alnus* in Kroumiria from 50,000 to 30,000 years before present. Aquatic taxa and spores mark their presence with a low but persistent percentage due to the flooding of the Nechaa Righia site, which is an alluvial contact zone (Benslama 2007). It can be observed that there is resistance of the cork oak forest with slight fluctuations towards the end of the

Medieval Warm Period, alongside the development of willow forests, which is also supported by Kahit *et al*. (2017, 2018). Regarding the anthropogenic pollen indicators, *Olea* has been present since the beginning of the pollen spectrum, dating to around 28 AD up to the present day, according to the study of several archaeological sites in the El Kala region (Bouchareb 2006). Northern Algeria was a zone of oil production for the Romans since their arrival in the region, dated on our diagram to around 28 AD, up to the present day (Attoui & de Vos Raaijmakers 2003, Ghit *et al*. 2018). The Romans occupied northern Algeria starting from 26 AD (Martín-Puertas *et al*. 2010, Calò *et al*. 2013, Kahit *et al*. 2017). This period is also marked by the arrival of the Yemenites, known for their cultivation of cereals and olives, after the Byzantines and Romans (Brun 1992). However, Cerealia-type pollen is only slightly present in the diagram. This can be explained by low pollination or pollination occurring during the dry season, which prevents the sedimentation of pollen in the peat, and may also be due to the low resistance of pollen. Additionally, it is possible that cleistogamic cereals, which produce pollen that does not disperse effectively, were cultivated during this time. Furthermore, the agricultural fields may not have been situated in the immediate vicinity of the wetland area, further limiting the presence of Cerealia-type pollen in the sedimentary record. Evidence of human activity in North Africa during this period has been well-documented by multiple studies (Ben Tiba 1982, Ballouche 1986, Ballouche & Damblon 1988, Stambouli 1997).

Little Ice Age (LIA)

At the beginning of this age, the climate became milder and more humid as indicated by various studies (Jalut *et al*. 2000, Jiménez Sánchez & Farias Arquer 2002, Mann 2005, Styllas *et al*. 2018). Archibald (2007) notes that the Little Ice Age (LIA) was characterised by an average temperature decrease of 0.5 to 1.5 °C below 20th-century averages. However, the timing and duration of the LIA are debated, with some researchers placing its onset between the 13th and 15th centuries. This early stage was marked by a gradual cooling trend, which was later followed by a more intense cold period between 1570 and 1730 (Nicolussi *et al*. 2022). Therefore, it can be concluded that the initial phase of the LIA was less cold than the period from 1570 to 1730. An expansion of hygrophilous taxa (*Alnus*, Juncaceae, Cyperaceae, and Nymphaeaceae) and the development of willow forests were observed. This proliferation was accompanied by a regression of deciduous oaks.

From the late 19th century to the present

Since the late 19th century, the deciduous oak forest has seen a resurgence following a brief decline, a trend also noted by Kahit *et al*. (2018). *Erica* has persisted throughout the Holocene despite the climatic changes known in the region. The alder forest has also persisted in the region from the Holocene to the present day, despite a slight decline at the beginning of the Little Ice Age (LIA). According to Médail & Diadema (2009), the Mediterranean is considered a refuge, which may explain the resilience of characteristic taxa in the north-eastern Algerian landscape, such as the alder forest, considered to be of local origin (Belouahem-Abed *et al*. 2011). The interplay between climate change and human activity presents challenges in interpreting vegetation dynamics, particularly for species like *Alnus* and *Poaceae*. Gradual changes in the dominance of *Alnus* often reflect natural climatic fluctuations, such as shifts in moisture levels that favour its growth in wetter conditions. Conversely, the rise in *Poaceae* can indicate drier conditions or localised human activities such as deforestation, which create environments suitable for grasses to thrive. While climate-induced changes tend to occur gradually over broader regions, abrupt increases in anthropogenic pollen including taxa such as *Olea*, *Vitis* or Cerealia signal direct human intervention in the landscape. Differentiating these influences requires careful analysis of both environmental proxies and anthropogenic indicators to better understand the combined impacts on vegetation over time.

Concluding remarks

The results of this study highlight the link between the chronological dynamics of vegetation in the region and the study site of Nechaa Righia. A significant correlation is evident when comparing these results with previous studies at the local and regional levels. The significant climatic variations of the last millennium, such as the Medieval Warm Period and the Little Ice Age, have had a substantial impact on low-altitude vegetation in the Righia alder forest, the largest in North Africa. Despite these changes, the alder forests with *Alnus glutinosa* in north-eastern Algeria remain a unique ecosystem, also present in northern Morocco and north-western Tunisia.

The Medieval Warm Period and the Little Ice Age are likely to have brought contrasting hydrological changes that significantly influenced vegetation and sedimentary processes. Increased precipitation during the Medieval Warm Period may have supported robust vegetation and wetland expansion, while the Little Ice Age introduced shifts in water availability, with some areas becoming drier and others wetter. Understanding these effects requires incorporating proxies such as pollen from moisture-dependent plants and sedimentary evidence of water level changes to provide a clearer picture of how these climatic periods shaped the local environment.

From the Roman era to the present day, taxa indicating anthropisation, such as *Olea*, confirm continuous human activity in the region. These human activities probably negatively influenced the growth of *Erica arborea* in drier areas. Grassland expanded during the Medieval warm period. Changes in vegetation on the higher and drier ground may have influenced nutrient richness and water levels in the wetland area due to increase surface runoff. Hygrophilous species such as *Salix* expanded significantly at Nechaa Righia after 658–876 AD, probably because of increased wetness. These vegetation changes may have been associated with climatic conditions such as increased precipitation or decreased evapotranspiration due to cooler conditions during the Little Ice Age, while deciduous oaks have experienced a resurgence in growth since the late 19th century.

In summary, even though the climatic conditions have varied greatly, the typical flora of north-eastern Algeria, such as the alder forests and *Erica*, has managed to survive due to its adaptation as a Mediterranean refuge. This resilience highlights the importance of preserving and sustainably managing these ecosystems in the face of current environmental challenges.

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AUTHOR CONTRIBUTIONS

Conceptualisation: MD, AR; methodology: AR, MD, MB; software: AR, MD; validation: MD, AR, MB; formal analysis: AR, MD, IM, MB; investigation: AR, MD, IM, MB; resources: AR, MD; data curation: MD, AR, IM; writing—original draft preparation: AR, MD; writing—review and editing: MD, AR, IM, MB; visualisation: MD, AR, MB; supervision: MD, MB. All authors have read and agreed to the published version of the manuscript.

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