EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2025, 26(7), 126–138
https://doi.org/10.12912/27197050/204754
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Received: 2025.04.25
Accepted: 2025.05.28
Published: 2025.06.15

Assessing biodiversity across bioclimatic zones in northeastern Algeria using pollen rain analysis

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ABSTRACT

This study aims to explore the potential of pollen rain analysis as a method for assessing plant diversity across three bioclimatic zones in northeastern Algeria. The primary objective is to investigate how climate, vegetation structure, and biodiversity are interrelated, particularly how airborne pollen can be used to reveal the composition of plant communities and to evaluate the influence of climatic factors such as humidity and aridity, along with human activities. The research was carried out in three distinct bioclimatic regions of northeastern Algeria, each characterized by unique environmental conditions. The humid zone, located in the Edough Mountains near Annaba, features high rainfall and supports dense, diverse forest vegetation. The sub-humid zone, situated near Souk Ahras, represents a moderately moist forest environment with a mix of plant species. In contrast, the semi-arid zone, found south of Souk Ahras, is defined by low rainfall, higher temperatures, and sparse vegetation adapted to arid conditions. Pollen samples were collected from six strategically selected sites using pollen traps. After collection, the samples were examined under a microscope for identification and counting of pollen grains, allowing for the assessment of plant taxa diversity and relative abundance. Principal component analysis (PCA) was then used to identify patterns and relationships among pollen taxa, vegetation types, and environmental variables, with particular attention to indicator species that reflect specific climatic conditions and anthropogenic influence. The analysis revealed notable differences in pollen composition across the three bioclimatic zones, each exhibiting a distinct vegetation profile. Dominant tree and understory species varied between the regions. The PCA results demonstrated strong correlations between pollen assemblages, climatic gradients, and human impacts on vegetation distribution and structure. These findings underscore the reliability of pollen rain analysis as a valuable tool for monitoring plant biodiversity. By integrating climatic and environmental factors, the study highlights the effectiveness of airborne pollen analysis in enhancing our understanding of plant distribution, ecosystem dynamics, and the impacts of environmental change on biodiversity.

Keywords: airborne pollen, pollen traps, plant biodiversity, bioclimatic stages, principal component analysis.

INTRODUCTION

Northeastern Algeria, part of the Mediterranean Basin, hosts a rich and diverse ecosystem shaped by complex bioclimatic conditions. However, it faces significant environmental threats, notably climate change, aridification, and anthropogenic pressures such as deforestation and land-use changes (Pouget et al., 2016). Algeria's forests – covering approximately 4.1 million hectares or 1.7% of the national territory – are particularly vulnerable, with wildfires and land degradation posing major risks (FAO, 2020). These issues reflect broader Mediterranean trends, where climate change increasingly disrupts ecological balance.

Studies like Daoud and Kadik (2024) highlight how climate change is altering flora distribution in regions such as Djelfa. Mediterranean climate models predict rising temperatures, decreased precipitation, and more frequent extreme weather events (Lionello et al., 2012), which are expected to shift vegetation patterns and affect biodiversity and ecosystem services. In Algeria, forests dominated by cork oak (*Quercus suber* L., 1753), Aleppo pine (*Pinus halepensis* Mill., 1768), and cedar (*Cedrus atlantica* Endl. Manetti ex Carrière, 1855) are already experiencing changes in species composition due to increased drought stress and human disturbances (Benabderrahmane and Chenchouni, 2010).

While several field surveys have examined Algeria's floral diversity (Toubal et al., 2014; Hamel et al., 2019; Bellili et al., 2022; Daoud and Kadik, 2024), gaining deeper insight into how ecosystems respond to climatic and anthropogenic pressures calls for innovative approaches. This study introduces atmospheric pollen analysis as a method to evaluate plant biodiversity across various bioclimatic zones.

Palynology, the study of pollen and spores, offers insights into current and historical plant diversity. By capturing both local and distant pollen, it provides a broad view of vegetation responses to natural and anthropogenic changes (Lake et al., 2017). Pollen shifts serve as indicators of ecosystem resilience or vulnerability, especially in aridifying environments.

By comparing pollen data across multiple forest sites, this study investigates how vegetation patterns in northeastern Algeria are influenced by climate change and human activities. Additionally, it provides a regional perspective on the role of aridification in shaping biodiversity dynamics. Previous studies have estimated that around 80% of collected pollen is local, with the remainder being transported from more distant sources (Birks et al., 2016), using techniques such as moss cushions (Masier, 2006) and specialized pollen traps (Boughediri and Benslama, 2020).

This study addresses two main research questions: (1) How accurately do pollen records reflect the current vegetation across regions affected by varying climatic and anthropogenic pressures? (2) How can pollen data reveal the effects of climate change on plant populations and their reproductive strategies?

The research aims to analyze pollen rain across three bioclimatic stations in northeastern Algeria to assess the combined impact of climate change and anthropogenic factors on floristic diversity and species distribution.

MATERIALS AND METHODS

Study area and bioclimatic zones

This study was conducted across three regions in northeastern Algeria, each representing a distinct bioclimatic zone (Figure 1).

The first, the Edough Massif in Annaba Province, consists of low mountains reaching 1008 m above sea level. Its siliceous bedrock yields acidic soils that support forest vegetation. Proximity to the sea ensures high humidity (~80%), and the area is classified as humid temperate (Emberger, 1971). Two study sites (Site 1 and 2) are located here.

The second region, Souk Ahras near the Tunisian border, features a mountainous, forested landscape spanning two bioclimatic zones: subhumid in the north and semiarid in the south (Emberger, 1971). Four sites were studied, two in the subhumid north (Site 3 and 4) and two in the semiarid south (Site 5 and 6). Geographic, physical, and phytosociological details are presented in Table 1.

Climatic and vegetation characteristics

Edough Massif (Annaba province)

Situated in the Mediterranean climate zone, the Edough Massif receives an average annual rainfall of 1115.49 mm, with dominant north-to-south winds averaging 2.96 m/s. Wind speeds are lowest in July (1.30 m/s) and highest in February (5.21 m/s) (Toubal et al., 2014). August is the hottest month, reaching 28.92 °C, while January is the coldest at 4.63 °C.

The region features dense, often stratified vegetation (BNEDER, 1980). Cork oak (*Quercus suber*) is the dominant species, accompanied by tree heath (*Erica arborea*), mastic tree (*Pistacia lentiscus*), myrtle (*Myrtus communis*), rockrose (*Cistus spp.*), strawberry tree (*Arbutus unedo*), and sweet chestnut (*Castanea sativa*). Higher altitudes and valleys host evergreen oak (*Quercus canariensis*), maritime pine (*Pinus pinaster*), and a transition to sub-Mediterranean vegetation above 800 m, including deciduous oak, holly (*Ilex aquifolium*), alder (*Alnus glutinosa*), laurustinus (*Viburnum tinus*), and hawthorn (*Crataegus monogyna*) (Toubal et al., 2014).

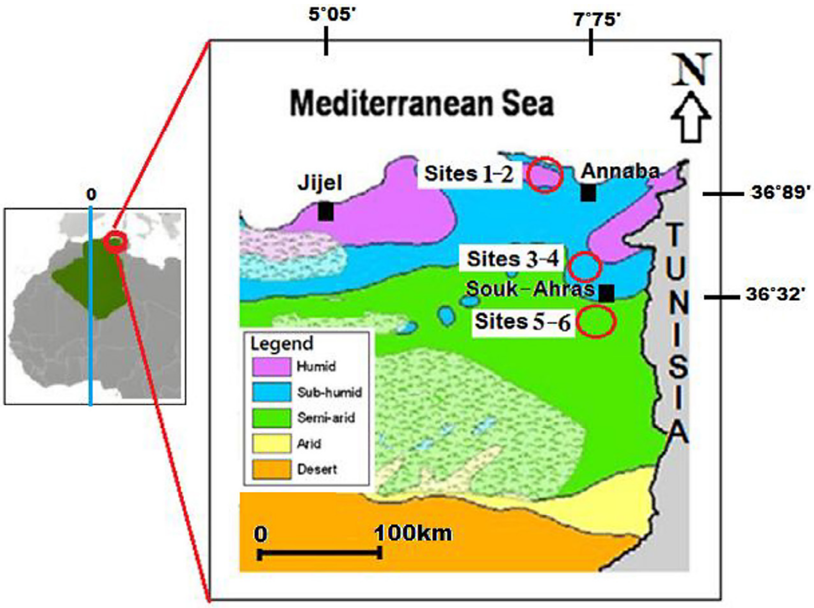

Figure 1. Map of the study area showing the six pollen sampling sites. Bioclimatic zones of northeastern Algeria are delineated based on Stewart's simplified bioclimatic classification (1974). N: North

Souk Ahras region

This region spans Mediterranean conditions in the north and desert influences in the south. January is the coldest month (7.48 °C), while July and August are the hottest, with maximum average temperatures of 26.42 °C and 25.91 °C, respectively (Samai, 2017).

According to BNEDER (1980), the province supports rich and economically important forest biodiversity. In the subhumid northern part, Aleppo pine (*Pinus halepensis*) dominates 43,625 hectares, while cork oak, evergreen oak (*Quercus canariensis*), and tree heath cover 16,448 hectares. Other species include cypress (*Cupressus spp.*), eucalyptus (*Eucalyptus camaldulensis*), and strawberry tree. In the southern semiarid zone, vegetation becomes sparser, with species adapted to aridity such as rosemary (*Rosmarinus officinalis*), rue (*Ruta graveolens*), Syrian rue (*Peganum harmala*), esparto grass (*Stipa tenacissima*), and juniper (*Juniperus oxycedrus*). However, detailed studies on floral biodiversity in this area remain limited.

Palynological sampling and analysis

Atmospheric pollen was collected monthly using pollen traps, each made from a 5-liter plastic container buried in open areas and filled with 10 cm² of water to capture airborne pollen (Karhglou et al., 2015). At each of the six study sites,

Table 1. Geographical location, coordinates and altitudes characteristics of the sites studied. The plant covers of the 3 bioclimatic stages

Stations / Bioclimatic stages	Sites	Geographical locations	Geographical coordinates	Altitudes m.	Plant cover
Station 1 Humid stage	1	Seraidi 1 (Annaba)	36°55,44 N; 7°42,33 E;	708	Cork oak forest
	2	Seraidi 2 (Annaba)	36°55,54 N; 7°42,34 E;	728	
Station 2 Subhumid stage	3	Ain Talha (Machrouha, Souk-Ahras)	36°20,73 N; 7°51,58 E;	864	Zean oak forest
	4	Oued Djedra (Ain Seynour, Souk-Ahras)	36°19,52 N; 7°52,79 E;	800	
Station 3 Semi-arid stage	5	El Gharra 1 (Zaarouria, Souk-Ahras)	36°11,84 N; 07°56,35 E;	955	Aleppo pine forest
	6	El Gharra 2 (Zaarouria, Souk-Ahras)	36°11,89 N; 7°56, 36 E;	962	

the total annual pollen count for each plant taxon was calculated and ranked in descending order. Pollen samples were examined under a ZEISS Axio Lab 1 microscope at 400x magnification in the Palynology Laboratory of the University of Annaba, Algeria. Entire slides were scanned to count a minimum of 300 pollen grains per slide, ensuring representative data. Taxa were identified based on morphological features such as shape, polarity, and aperture number, with additional reference to *Pollen and Spores of Europe and North Africa* (Reille, 1992) and the Palynological Database (PalDat) (https://www.paldat.org/) as needed.

Data analysis

We applied PCA in R using the FactoMineR package (Lê et al., 2008) to investigate the relationships between plant species and bioclimatic zones. PCA simplifies complex datasets by transforming correlated variables into uncorrelated principal components (PCs) that account for the greatest variance. This allowed us to better understand how ecological factors influence species distribution.

The analysis incorporated species abundance along with key environmental variables, precipitation, temperature, and wind speed, across humid, subhumid, and semiarid zones. To ensure comparability, all data were standardized before calculating the covariance matrix and extracting the principal components representing the dominant environmental gradients.

RESULTS

Palynological data

Tables 2 to 7 present certain palynological characteristics of the collected pollen taxa, namely shape, symmetry, and the number of apertures. Figure 2 shows photos of some pollen taxa according to the database (PalDat). With the exception of the *Ericaceae*, which exhibit a tetrad shape, all other taxa have a monad shape. Regarding symmetry, with the exception of the *Poaceae*, *Ericaceae*, and *Cupressaceae*, which possess a heteropolar symmetry (Polarity), all other taxa

Table 2. Results of atmospheric pollen collection at Site 1 (Humid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Taxa	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Erica arborea*	*Ericaceae*	T	Tetrad, heteropolar tricolpate	1978.3	35.48
2	*Quercus suber*	*Fagaceae*	T	Monad, isopolar Tricolpate	1232.1	22.09
3	*Quercus coccefera*	*Fagaceae*	T	Monad, isopolar tricolpate	909.2	16.30
4	*Pinus pinaster*	*Pinaceae*	T	Monad, saccate monoporate	160.2	2.87
5	*Cytisus sp.*	*Fabaceae*	T	Monad, isopolar tricolpate	130.7	2.29
6	*Quercus canariensis*	*Fagaceae*	T	Monad, isopolar tricolpate	118.2	2.12
7	*Myrtus communis*	*Myrtaceae*	T	Monad, isopolar tricolpate	103	1.84
8	*Poaceae*	*Poaceae*	H	Monad, heteropolar monoporate	94.6	1.69
9	*Olea europaea*	*Oleaceae*	T	Monad, isopolar tricolpate	91.5	1.64
10	*Asteraceae*	*Asteraceae*	H	Monad, isopolar tricolpate	66.3	1.18
11	*Arbutus unedo*	*Ericaceae*	T	Tetrad, isopolar tricolpate	61.4	1.10
12	*Cyperaceae*	*Cyperaceae*	H	Considerable variation	59.3	1.06
13	*Smilax aspera*	*Smilacaceae*	T	Monad, isopolar inaperturate	44.3	0.79
14	*Junepirus oxycedrus*	*Cupressaceae*	T	Monad, heteropolar Irr. Num. aper.	33.5	0.60
15	*Pistacia lentiscus*	*Anacardiaceae*	T	Monad, irr. polarity tetracolpate	29.6	0.53

Table 3. Results of atmospheric pollen collection at Site 2 (Humid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Species	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Erica arborea*	*Ericacae*	T	Tetrad, heteropolar Tricolpate	1313.9	18.64
2	*Quercus suber*	*Fagaceae*	T	Monad, isopolar Tricolpate	1190.3	16.89
3	*Myrtus communis*	*Myrtaceae*	T	Monad, isopolar Tricolpate	1067.6	15.15
4	*Quercus coccifera*	*Fagaceae*	T	Monad, isopolar Tricolpate	600.3	8.51
5	*Quercus canariensis*	*Fagaceae*	T	Monad, isopolar Tricolpate	404.4	5.73
6	*Pinus pinaster*	*Pinaceae*	T	Monad, saccate Monoporate	334.9	4.75
7	*Ranunculus sp.*	*Ranunculaceae*	H	Monad, isopolar tricolpate	326.8	4.63
8	*Cytisus sp.*	*Fabaceae*	T	Monad, isopolar tricolpate	176.6	2.50
9	*Genista numidica*	*Fabaceae*	T	Monad, isopolar tricolpate	157.3	2.23
10	*Rumex conglomeratus*	*Polygonaceae*	H	Monad, isopolar tricolpate	135	1.91
11	*Euphorbia sp.*	*Euphorbiaceae*	H	Monad, isopolar tricolpate	129.1	1.83
12	*Veronica arvensis*	*Plantaginaceae*	H	Monad, Isopolar tricolpate	123.9	1.75
13	*Rosa sempervirens*	*Rosaceae*	T	Monad, isopolar tricolpate	119	1.68
14	*Lotus corniculatus*	*Fabaceae*	H	Monad, isopolar tricolpate	118	1.67
15	*Cistus sp.*	*Cistaceae*	T	Monad, isopolar tricolpate	110.3	1.56
16	*Olea europaea*	*Oleaceae*	T	Monad, isopolar tricolpate	108.7	1.54
17	*Poaceae*	*Poaceae*	H	Monad, heteropolar monoporate	71.6	1.01
18	*Cardamine hirsute*	*Brassicaceae*	H	Monad, isopolar tricolpate	59.1	0.83
19	*Plantago sp.*	*Plantaginaceae*	H	Monad, Irr. Polari. pantoporate	47.1	0.66
20	*Calicotome spinosa*	*Fabaceae*	T	Monad, isopolar tricolpate	43.6	0.61

display an isopolar symmetry. As for the number of apertures, there is a very great variability. A significant number of taxa exhibit a tricolpate aperture (three furrows). Exceptions include the *Cupressaceae* (inaperturate), *Poaceae* and *Pinaceae* (monoaperturate), *Amaranthaceae* and *Plantaginaceae* (pantoporate), *Rosmarinus officinalis* (hexaporate), and *Anacardiaceae* and *Asteraceae* (a variable number of apertures).

Floristic surveys

The results of the floristic surveys (Tables 2 to 7) present the composition of the vegetation at the study sites through pollen deposits. These tables highlight the diversity of forest types present in the different bioclimatic zones.

In the humid and subhumid regions, *Quercus suber* forests dominate, whereas the semiarid zone is characterized by mixed forests of *Pinus halepensis* and *Quercus ilex* (L, 1753). Each bioclimatic zone hosts a distinct set of dominant plant species that define its forest ecosystem.

In transitional areas between study sites, common species are present but contribute less significantly to the overall pollen count. Near the forested areas, herbaceous species dominate, and some taxa with minimal pollen counts suggest that they originate from distant regions. This aligns with the pollen spectra, which indicate that while local

Table 4. Results of atmospheric pollen collection at Site 3 (Subhumid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Species	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Quercus suber*	*Fagaceae*	T	Monad, isopolar tricolpate	363.9	17.60
2	*Quercus canariensis*	*Fagaceae*	T	Monad, isopolar tricolpate	276.1	12.35
3	*Galactites tomentosa*	*Asteraceae*	H	Monad, isopolar tricolpate	121.9	5.89
4	*Daucus sp.*	*Apiaceae*	H	Monad, isopolar tricolpate	111.1	5.37
5	*Clematis flammula*	*Ranunculaceae*	H	Monad, isopolar tricolpate	104.4	5.05
6	*Quercus coccifera*	*Fagaceae*	T	Monad, isopolar tricolpate	93.4	4.51
7	*Cytisus sp.*	*Fabaceae*	T	Monad tricolpate	90.5	4.37
8	*Eucalyptus camaldulensis*	*Myrtaceae*	T	Monad, isopolar tricolpate	86.7	4.19
9	*Marrubium sp.*	*Lamiaceae*	H	Monad, isopolar tricolpate	85.1	4.11
10	*Crataegus azarolus*	*Rosaceae*	T	Monad, isopolar tricolpate	58.1	2.81
11	*Pinus halepensis*	*Pinaceae*	T	Monad, saccate monoporate	57.3	2.77
12	*Asteraceae*	*Asteraceae*	H	Monad, isopolar tricolpate	55.3	2.67
13	*Olea europaea*	*Oleaceae*	T	Monad, isopolar tricolpate	44.2	2.13
14	*Plantago sp.*	*Plantaginaceae*	H	Monad, irr. polarity pantoporate	37.1	1.79
15	*Stellaria media*	*Caryophyllaceae*	H	Monad, isopolar pantoporate	33.6	1.62
16	*Sinapis arvensis*	*Brassicaceae*	H	Monad, isopolar tricolpate	24.4	1.18
17	*Pistacia lentiscus*	*Anacardiaceae*	T	Monad, Irr. Polarity tetracolpate	22.8	1.10

vegetation contributes the majority of the pollen, long-distance transport also plays a role in shaping the recorded assemblages.

Station 1

Tables 2 and 3 together list 26 plant species belonging to 18 families. There are 16 tree species and 10 herbaceous species. The most common species in this area are *Erica arborea* (35.48%), *Quercus suber* (22.09%), and *Quercus coccifera* (16.30%).

Together, these three species make up over 70% of the plant life at this station. Other species, such as *Pinus pinaster*, *Cytisus sp.* (Desf, 1798), *Arbutus unedo*, *Poaceae*, *Olea europaea* (L, 1753), *Asteraceae*, *Cyperaceae*, *Smilax aspera* (L, 1753), *Juniperus oxycedrus*, and *Pistacia lentiscus*, each contribute less than 5% to the overall pollen count.

Station 1 is largely composed of cork oak forest, with minor contributions from species like *Quercus canariensis*, *Pinus pinaster*, and *Juniperus oxycedrus*. The understory is dense and includes *Erica arborea*, *Myrtus communis*, *Cytisus sp.*, *Cistus sp.*(L, 1753), and *Pistacia lentiscus*. Herbaceous plants are less represented, with only two families showing very low frequencies: *Poaceae* (1.69%) and *Asteraceae* (1.18%). This is likely because many herbaceous plants are insect-pollinated and therefore produce less pollen, a trend that is also reflected in the pollen diagrams.

Station 2

Station 2 is mainly covered by a Zeen oak forest, which hosts a variety of species such as *Quercus coccifera*, *Quercus canariensis*, *Juniperus oxycedrus*, *Olea europaea*, and *Pinus halepensis*, though these species produce relatively low amounts of pollen. Recently, a *Eucalyptus*

Table 5. Results of atmospheric pollen collection at Site 4 (Subhumid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Species	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Fraxinus angustifolia*	*Fraxinaceae*	T	Monad, isopolar tricolpate	1054.8	27.05
2	*Quercus suber*	*Fagaceae*	T	Monad, isopolar tricolpate	344.8	8.84
3	*Quercus coccifera*	*Fagaceae*	T	Monad, isopolar tricolpate	277.4	7.11
4	*Asteraceae*	*Asteraceae*	H	Monad, isopolar tricolpate	229.7	5.88
5	*Brassicaceae*	*Brassicaceae*	H	Monad, isopolar tricolpate	221.6	5.68
6	*Senecio leucanthemifolius*	*Asteraceae*	H	Monad, isopolar tricolpate	153.6	3.93
7	*Poaceae*	*Poaceae*	H	Monad, heteropolar Monoporate	146.2	3.74
8	*Hypochaeris radicata*	*Asteraceae*	H	Monad, isopolar Tricolpate	127.8	3.27
9	*Junepirus oxycedrus*	*Cupressaceae*	T	Monad, heteropolar Irr. Num. aper.	121.4	3.11
10	*Plantago sp.*	*Plantaginaceae*	H	Monad, irr. polari pantoporate	118.1	3.02
11	*Erica arborea*	*Ericaceae*	T	Tetrad, heteropolar tricolpate	103	2.64
12	*Galactites tomentosa*	*Asteraceae*	H	Monad, isopolar tricolpate	100.7	2.58
13	*Rumex conglomeratus*	*Polugonaceae*	H	Monad, isopolar tricolpate	98.9	2.53
14	*Biscutella didyma*	*Brassicaceae*	H	Monad, isopolar tricolpate	92.4	2.36
15	*Pinus halepensis*	*Pinaceae*	T	Monad, saccate, monoporate	77.7	1.99
16	*Olea europaea*	*Oleaceae*	T	Monad, isopolar tricolpate	70.2	1.80
17	*Cynara cardunculus*	*Asteraceae*	H	Monad, isopolar tricolpate	50.4	1.29
18	*Paronychia argentea*	*Caryophillaceae*	H	Monad, pantoporate	50.2	1.28
19	*Ranunculus sp.*	*Ranunculaceae*	H	Monad, isopolar tetracolpate	37	0.94
20	*Quercus canariensis*	*Fagaceae*	T	Monad, isopolar tricolpate	32.8	0.84

camaldulensis forest has been planted nearby. The understory of the cork oak forest here is dense, including species such as *Erica arborea*, *Cytisus sp.*, *Pistacia lentiscus*, and *Salix sp.*(L, 1753). Dominant herbaceous species include members of the *Asteraceae*, *Brassicaceae*, *Poaceae*, *Daucus sp.* (L, 1753), and *Senecio leucanthemifolius* (Poir, 1789) families.

Tables 4 and 5 together list 29 species belonging to 20 families. There are 17 tree species and 12 herbaceous species. The species with the highest pollen production are *Fraxinus angustifolia* (Vahl, 1804) (27.05%), *Quercus suber* (17.60%), *Quercus canariensis* (12.35%), *Asteraceae* (5.88%), and *Brassicaceae* (5.68%). Species with lower pollen production include, *Eucalyptus camaldulensis* (4.19%)*, Erica arborea* (2.64%), *Pinus halepensis* (2.77%), and *Pistacia lentiscus* (1.10%). The presence of pollen from tree species such as *Fraxinus angustifolia* and *Quercus suber* aligns with the pollen spectra, further supporting the bioclimatic distinctions reflected in the diagrams.

Station 3

Tables 6 and 7 together list 25 plant species belonging to 20 families. There are 14 tree species and 11 herbaceous species.

The most common species are *Cistus sp.* (38.62%), *Pinus halepensis* (10.52%), *Quercus*

Table 6. Results of atmospheric pollen collection at Site 5 (Semiarid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Species	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Cistus sp.*	*Cistaceae*	T	Monad, isopolar tricolpate	1440.9	38.62
2	*Quercus ilex*	Fagaceae	T	Monad, isopolar tricolpate	343.6	9.20
3	*Pinus halepensis*	*Pinaceae*	T	Monad, saccate, monoporate	280.5	7.51
4	*Pistacia lentiscus*	*Anacardiaceae*	T	Monad, Variable aper. number	209.0	5.59
5	*Poaceae*	*Poaceae*	H	Monad, heteropol Monoporate	196.7	5.25
6	*Asteraceae*	*Asteraceae*	H	Monad, isopolar Tricolpate	148.0	3.96
7	*Cupressaceae*	*Cupressaceae*	T	Monad, isopolar Inaperturate	66.1	1.77
8	*Juniperus oxycedrus*	*Cupressaceae*	T	Monad, heteropolar Irr. Num. aper.	60.1	1.60
9	*Globularia alypum*	*Plantaginaceae*	T	Monad, isopolar tricolpate	58.8	1.57
10	*Plantago sp.*	*Plantaginaceae*	H	Monad, Irr. Polarity pantoporate	55.7	1.49
11	*Urtica sp.*	*Urticaceae*	H	Monad, isopolar triporate	54.0	1.44
12	*Spartium junceum*	*Fabaceae*	T	Monad, isopolar tricolpate	50.2	1.34
13	*Ranunculus sp.*	*Ranunculaceae*	H	Monad, isopolar tetracolpate	41.3	1.10
14	*Amaranthaceae*	*Amaranthaceae*	H	Monad, isopolar pantoporate	39.8	1.14
15	*Phillyrea latifolea*	*Oleaceae*	T	Monad, isopolar tricolpate	34.3	0.91
16	*Betulaceae*	*Betulaceae*	T	Monad, isopolar triporate	31.3	0.83
17	*Rubus ulmoflius*	*Rosaceae*	T	Monad, isopolar tricolpate	27.1	0.72
18	*Rosmarinus officinalis*	*Lamiaceae*	H	Monad, isopolar hexacolpate	26.3	0.70
19	*Brassicaceae*	*Brassicaceae*	H	Monad, isopolar tricolpate	20.2	0.54
20	*Artemisia sp.*	*Asteraceae*	H	Monad, isopolar tricolpate	16.0	0.42

ilex (9.84%), and members of the *Poaceae* family (5.25%). *Quercus ilex* is the only oak species present at this station, reflecting its adaptation to the semiarid zone, where it thrives in drought conditions and on poor limestone soils typical of North Africa. The *Pinaceae* family is wind-pollinated, with its pollen well suited for long-distance dispersal (Tables 6 and 7). The increasing dominance of *Pinus halepensis* and *Cistus sp.* in Station 3 corresponds with the shift towards a drier climate, as seen in the pollen diagrams. The high presence of *Cistus sp.*, a species characteristic of degraded forests and shrublands, highlights the ongoing aridification process and possible anthropogenic pressures affecting the semiarid region.

Statistical analysis

The results of the ACP are represented by Figure 3 which highlights the separation between the taxa.

Axis 1 explains 34.4% of the variance and reflects a bioclimatic gradient from humid to semiarid conditions, relating to moisture availability and climatic conditions in the regions studied. The results of the floristic surveys (Tables 2–7) confirm this trend; reveal distinct shifts in species composition across bioclimatic zones. Taxa such

Table 7. Results of atmospheric pollen collection at Site 6 (Semiarid stage). List of taxa that make up the plant cover, ranked in descending order of total annual pollen count. Some plant and pollen characteristics

N°	Species	Family	Tree (T) or Herbaceous (H)	Pollen description	Total annual pollen count	% of the total number
1	*Cistus sp.*	*Cistaceae*	T	Monad, isopolar tricolpate	1561.8	35.18
2	*Pinus halepensis*	*Pinaceae*	T	Monad, saccate, monoporate	467.2	10.52
3	*Asteraceae*	*Asteraceae*	H	Monad, isopolar tricolpate	453.0	10.20
4	*Quercus ilex*	*Fagaceae*	T	Monad, isopolar tricolpate	436.9	9.84
5	*Phillyrea latifolea*	*Oleaceae*	T	Monad, isopolar tricolpate	308.3	6.94
6	*Poaceae*	*Poaceae*	H	Monad, heteropol Monoporate	166.4	3.74
7	*Olea europaea*	*Oleaceae*	T	Monad, isopolar Tricolpate	164.1	3.69
8	*Rosmarinus officinalis*	*Lamiaceae*	H	Monad, isopolar Hexacolpate	90.8	2.40
9	*Apiaceae*	*Apiaceae*	H	Monad, isopolar Tricolpate	89.9	2.02
10	*Brassicaceae*	*Brassicaceae*	H	Monad, isopolar Tricolpate	78.4	1.76
11	*Ranunculus sp.*	*Ranunculaceae*	H	Monad, isopolar tetracolpate	76.2	1.71
12	*Plantago sp.*	*Plantaginaceae*	H	Monad, Irr. polarity pantoporate	61.8	1.39
13	*Globularia alypum*	*Plantaginaceae*	T	Monad, isopolar tricolpate	55.1	1.24
14	*Spartium junceum*	*Fabaceae*	T	Monad, isopolar tricolpate	47.7	1.07
15	*Amaranthaceae*	*Amaranthaceae*	H	Monad, isopolar pantoporate	47.6	1.07
16	*Myrtus communis*	*Myrtaceae*	T	Monad, isopolar tricolpate	46.6	1.04
17	*Junepirus oxycedrus*	*Cupressaveae*	T	Monad, heteropolar Irr. Num. aper.	45.3	1.02
18	*Pistacia lentiscus*	*Anacardiaceae*	T	Monad, irr. Polarity tetracolpate	42.3	0.95
19	*Centaurea napifolia*	*Asteraceae*	H	Monad, isopolar Tricolpate	30.3	0.62
20	*Erica arborea*	*Ericaceae*	T	Tetrad, heteropolar Tricolpate	19.6	0.44
21	*Artemisia sp.*	*Asteraceae*	H	Monad, isopolar Tricolpate	16.7	0.37

as *Eucalyptus*, *Fraxinus*, *Myrtus communis*, and *Quercus canariensis* are correlated with humid to subhumid stages, indicating their preference for more humid environments. Sites on the positive side of Axis 1 (1, 2, 3, and 4) are characterized by higher rainfall, cooler temperatures, and denser vegetation, promoting the growth of these species. In contrast, sites on the negative side (5 and 6) represent more arid conditions with vegetation adapted to drier climates, consistent with pollen evidence showing an increase in *Pinus halepensis* and *Cistus sp.* taxa in semiarid areas.

Axis 2, explaining 26.6% of the variance, differentiates shrub and herbaceous taxa (*Pistacia lentiscus*, *Phillyrea latifolia*, L, 1753) from tree taxa (*Erica arborea*, *Quercus coccifera*). The negative side reflects vegetation adapted to semiarid or Mediterranean conditions, while the positive side indicates species suited to open, wind-exposed, wetter landscapes. The pollen data further corroborate these ecological patterns, as pollen assemblages from sites dominated by *Pinus halepensis* and *Cistus sp*. exhibit high representation in the semiarid stages. Conversely, sites associated with *Fraxinus* and *Myrtus* contain pollen spectra indicative of moist environments.

The statistical results align closely with floristic surveys, which reveal that taxa near the

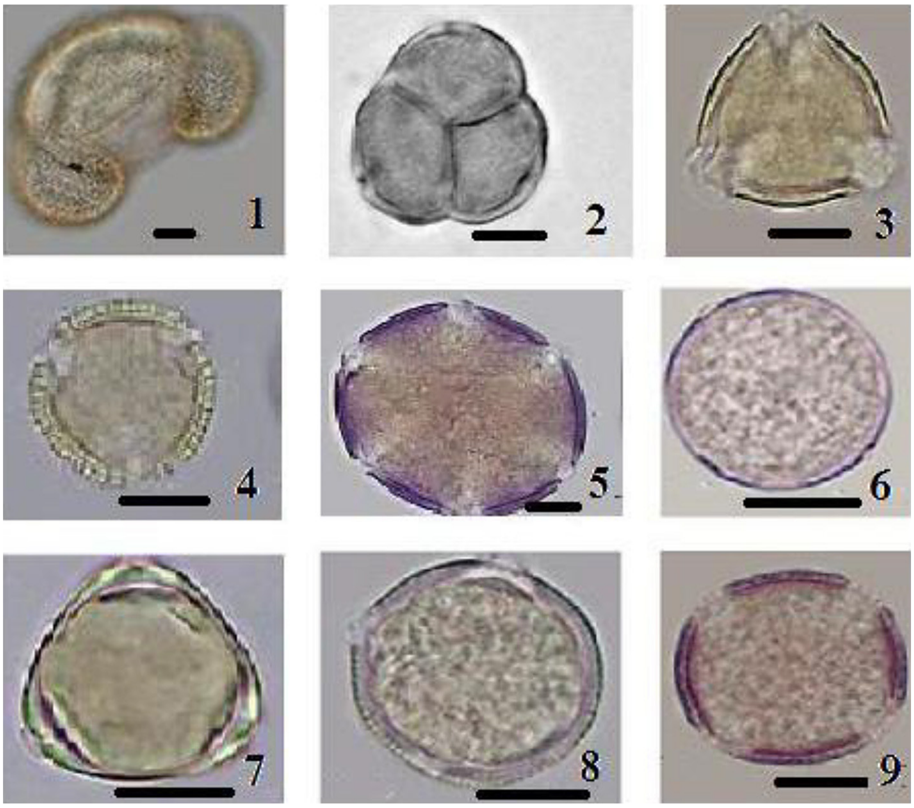

Figure 2. Photographs of *Pollen* taxa from the Palynological Database (PalDat). Scale bar: Black lines represent 10 µm. Photograph 1 – *Pollen of Pinus halepensis*: Monad, saccate, monoporate. Photograph 2 – *Pollen of Erica arborea*: Tetrad, heteropolar, tricolpate Photograph 3 – *Pollen of Quercus coccifera*: Monad, isopolar, tricolpate. Photograph 4 – *Pollen of Olea europaea*: Monad, isopolar, tricolpate. Photograph 5 – *Pollen of Rosmarinus officinalis*: Monad, isopolar, hexacolpate. Photograph 6 – *Pollen of Plantago sp.*: Monad, irregular polarity, pantoporate. Photograph 7 – *Pollen of Eucalyptus camaldulensis*: Monad, isopolar, tricolpate. Photograph 8 – *Pollen of Pistacia lentiscus*: Monad, irregular polarity, tetracolpate. Photograph 9 – *Pollen of Ranunculus sp.*: Monad, isopolar, tetracolpate

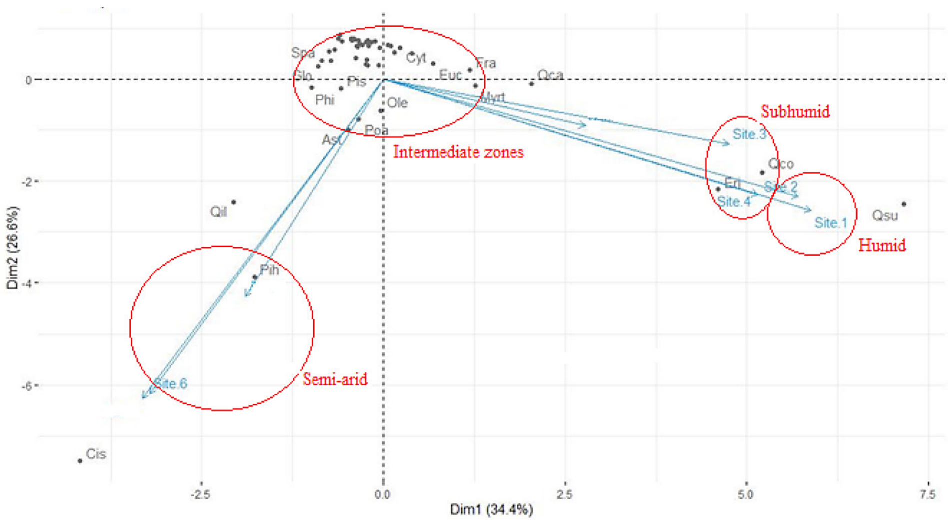

Figure 3. Principal component analysis (PCA) of pollen taxa across the six study sites. (Dim1 and Dim2 represent the first and second principal components (axes 1 and 2), respectively). Abbreviations of plant taxa: *Spa* = *Spartium junceum*, *Glo* = *Globularia alypum*, *Phi* = *Phillyrea latifolia*, *Pis* = *Pistacia lentiscus*, *Cyt* = *Cytisus* sp., *Euc* = *Eucalyptus camaldulensis*, *Fra* = *Fraxinus angustifolia*, *Ole* = *Olea europaea*, *Myrt* = *Myrtus communis*, *Qca* = *Quercus canariensis*, *Ast* = Asteraceae, *Poa* = Poaceae, *Qil* = *Quercus ilex*, *Pih* = *Pinus halepensis*, *Cis* = *Cistus* sp., *Eri* = *Erica arborea*, *Qco* = *Quercus coccifera*, *Qsu* = *Quercus suber*

humid side of Axis 1 (*Quercus suber*, *Erica arborea*) thrive in closed forests with stable moisture levels, whereas species such as *Cistus sp.* and *Pistacia lentiscus* are more frequent in seasonally dry environments, highlighting their role as indicators of aridity.

Additionally, transition species such as *Spartium junceum* (L, 1753) and *Globularia alypum* (L, 1753), which occupy intermediate positions in the PCA serve as important ecological markers of shifting climatic conditions.

DISCUSSION

Palynological analysis provides valuable insights into ecological environments. At Station 1, the dominance of tree taxa over herbaceous taxa suggests a closed forest structure. In contrast, Stations 2 and 3 exhibit a more balanced representation, indicating more open forest ecosystems. Significant vegetation changes observed at Station 1, such as the increasing presence of *Erica arborea* alongside a decline in *Quercus suber*, and the disappearance of *Castanea sativa* and *Ilex aquifolium*, point to ecological transitions likely driven by climate change and anthropogenic pressures. The PCA results reinforce the role of *Erica arborea* as a key indicator of forest regression, consistent with previous findings attributing vegetation degradation to overexploitation, overgrazing, and wildfires (Oularbi and Zeghiche, 2009).

Pollen rain analysis effectively identifies dominant anemophilous (wind-pollinated) taxa, but tends to underrepresent entomophilous species such as *Myrtus communis* and *Phillyrea latifolia* (Boutahar et al., 2023). This limitation highlights the need for refined sampling methods to enhance the accuracy of biodiversity assessments. At Station 2, floristic diversity remains relatively high despite anthropogenic pressures, with *Fraxinus angustifolia* and *Quercus suber* identified as key forest components (Samai, 2017). PCA results associate *Fraxinus angustifolia* with humid environments, while the presence of understory species such as *Pistacia lentiscus* and *Salix* sp. underscores the importance of local microclimatic conditions in maintaining species richness.

In the semiarid conditions of Station 3, *Cistus* species are dominant, reflecting their adaptation to xeric, nutrient-poor, and fire-prone environments. The PCA places *Cistus* sp. and *Pinus halepensis* along the aridity gradient, underscoring their ecological resilience. The concurrent decline of mesophilous taxa and expansion of xerophytes illustrates vegetation shifts driven by climate change. Across all study sites, statistical analysis identifies key taxa associated with each bioclimatic zone, revealing how dispersal mechanisms influence pollen representation. Furthermore, the increasing dominance of herbaceous over woody species, partly attributed to overgrazing (Hamel et al., 2019), highlights significant anthropogenic pressures. This is further supported by the presence of ruderal species such as *Galactites tomentosa* (Moench, 1794) and *Plantago* sp. (L, 1753), which serve as indicators of ecological disturbance (Etienne, 2010).

These findings are consistent with those of Daoud and Kadik (2024), who reported climate-driven vegetation shifts in the Djelfa region, further reinforcing the role of climate variability as a major driver of ecological change in northeastern Algeria. The increasing prevalence of stress-tolerant species indicates an ongoing process of ecosystem adaptation.

This study highlights the combined influence of climate change and anthropogenic pressure on the structure and composition of vegetation communities. The integration of floristic surveys with multivariate statistical analyses provides a robust framework for interpreting bioclimatic transitions and ecological gradients. These findings emphasize the importance of long-term ecological monitoring and improved pollen sampling techniques to enhance biodiversity assessments in vulnerable regions. Conservation strategies should prioritize adaptive management approaches to mitigate human-induced degradation, promote species resilience, and preserve ecological functionality.

Moreover, the methodology employed, pollen rain analysis, proves to be an effective tool for reconstructing vegetation dynamics and may serve as a valuable reference for future ecological studies across Mediterranean ecosystems.

CONCLUSION

This study highlights the vital importance of plant biodiversity in northeastern Algeria, a region increasingly exposed to anthropogenic pressure, wildfires, and climate change. Through a palynological approach, we have shown how these factors influence floristic composition across three bioclimatic zones; humid, subhumid, and semiarid. The pollen record reveals distinct species assemblages, marked bioclimatic transitions, and vegetation responses to ongoing climatic shifts.

Our results confirm that pollen data are reliable proxies for reconstructing vegetation history and tracking ecological trends, although the representation of current flora is shaped by both climate variability and human influence. Dominant taxa are well reflected, while species with low pollen production or limited dispersal tend to be underrepresented. Notably, the increasing dominance of *Erica arborea* over *Quercus suber* in recent pollen assemblages reflects intensifying aridity, consistent with rising temperatures and reduced precipitation. Land-use changes and fire regimes further exacerbate these transformations.

By identifying indicator taxa for each bioclimatic stage, we illustrate how climate variability affects species distribution and pollen deposition. Transitional zones, particularly sensitive to environmental fluctuations, show the most pronounced compositional shifts. The decline of drought-intolerant species such as *Castanea sativa*, *Ilex aquifolium*, and *Viburnum tinus* suggests a growing mismatch between their ecological requirements and prevailing conditions.

Our PCA results support the link between climate trends, especially increasing aridity, and changes in vegetation structure. Semiarid and transitional areas emerge as particularly vulnerable, facing compounded impacts from natural and anthropogenic disturbances. In this context, pollen analysis proves to be a valuable tool for assessing ecosystem resilience and identifying species at risk under future climate scenarios.

In sum, integrating ecological and climatic data enhances our understanding of biodiversity dynamics in Mediterranean regions. Monitoring changes in pollen assemblages offers key insights into long-term pressures affecting vegetation and species adaptability. Moving forward, interdisciplinary approaches, combining climate modeling, ecological monitoring, and aeropalynology, will be crucial for predicting vegetation shifts, informing conservation strategies, and mitigating the impacts of climate change. Conservation efforts should focus on protecting and restoring key species, especially in transitional zones, to strengthen ecosystem resilience in the face of increasing aridity.

Acknowledgments

The authors sincerely thank Vincent Lebreton and Nathalie Combourieu-Nebout for warmly welcoming Ms. Boughediri Soumaia to their laboratory at the National Museum of Natural History in Paris (France), and for their valuable guidance and support throughout her internship.

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