ORIGINAL ARTICLE

Four millennia of vegetation and environmental history above the Hyrcanian forest, northern Iran

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Abstract

Past vegetation, fire, and climate dynamics, as well as human impact, have been reconstructed for the first time in the highlands of the Gilan province in the Alborz mountains (above the Hyrcanian forest) for the last 4,300 cal yrs BP. Multi-proxy analysis, including pollen, spores, non-pollen palynomorphs, charcoal, and geochemical analysis, has been applied to investigate the environmental changes at 2,280 m a.s.l., above the Hyrcanian forest. Dominant steppe vegetation occurred in the study area throughout the recorded period. The formation of the studied mire deposits, as well as vegetation composition, suggest a change to wetter climatic conditions after 4,300 until 1,700 cal yrs BP. Fires were frequent, which may imply long-lasting anthropogenic activities in the area. Less vegetation cover with a marked decrease of the Moisture Index (MI) suggests drier conditions between 1,700 and 1,000 cal yrs BP. A high proportion of Cichorioideae and Amaranthaceae, as well as the reduction of trees, in particular *Fagus* and *Quercus*, at lower elevations, indicate human activities such as intense livestock grazing and deforestation. Soil erosion as the result of less vegetation due to dry conditions and/or human activities can be reconstructed from a marked increase of *Glomus* spores and high values of K and Ti. Since 1,000 cal yrs BP, the increasing MI, as well as the rise of Poaceae and Cyperaceae together with forest recovery, suggest a change to wetter conditions. The occurrence of still frequent Cichorioideae and *Plantago lanceolata* along with *Sordaria* reflect continued intense grazing of livestock by humans.

Keywords Late Holocene · Northern Iran · Multi-proxy studies · Hyrcanian mountain vegetation · Climate change · Human impact

Introduction

Between the northern slopes of the Alborz Mountains and the southern coast of the Caspian Sea (CS) is a narrow belt, 20–70 km wide and ca. 800 km long, which is covered by broad-leaved deciduous Hyrcanian forest. It extends from the lowland up to > 2,000 m a.s.l. (Sabeti 1994; Sagheb-Talebi et al. 2014). However, above 2,000 m, the forests are mostly replaced by forest/steppe or steppe vegetation. The area covers approximately 1.9 million ha and consists of three provinces from west to east, namely Gilan, Mazandaran, and Golestan (Fig. 1 II). Some of the Arcto-Tertiary species occurred in the Hyrcanian forest. *Pterocarya fraxinifolia*, *Parrotia persica* and *Zelkova carpinifolia* grew in refugia from the Quaternary glaciations in the southern part of Europe (e.g. Zohary 1973; Leroy and Roiron 1996; Leroy and Arpe 2007; Ramezani et al. 2008; Leroy et al. 2013a, b). The history of the Hyrcanian region can provide important insights into past Quaternary vegetation history.

Palynological studies were begun in Iran by van Zeist and Wright (1963). Since then, a few palynological studies have still taken place throughout the country. Also, most of the studies have focused mainly on the Zagros Mountains (e.g. van Zeist and Bottema 1977; Wasylikowa 2005; Djamali et al. 2009b), and only a few have investigated the northern part of Iran. So far in these available studies, only Leroy et al. (2011) and Haghani et al. (2015) have investigated

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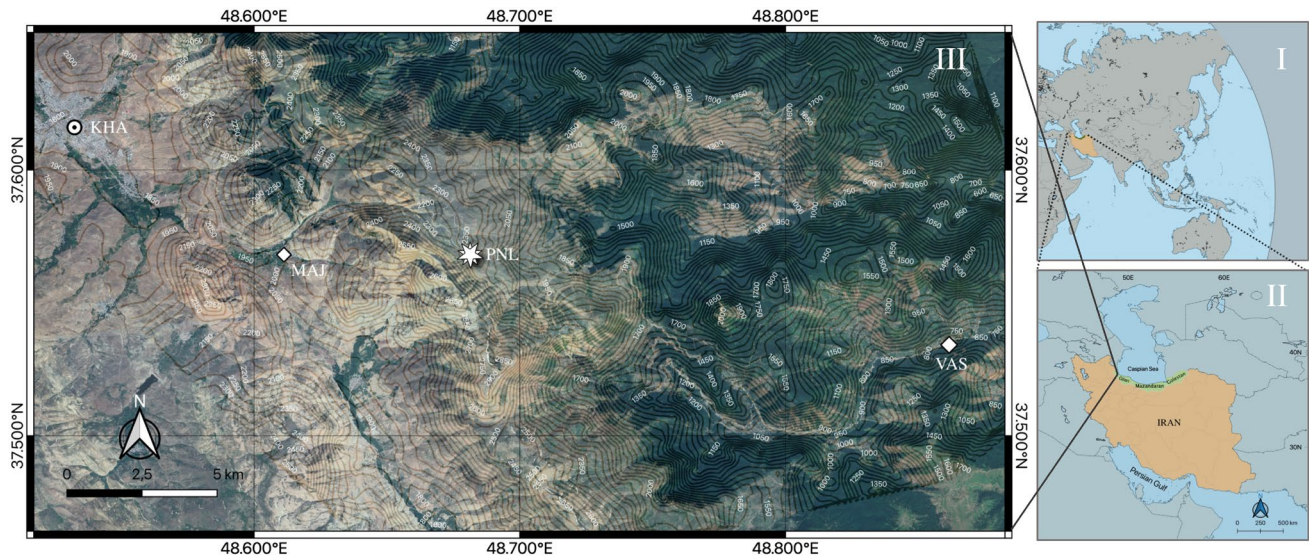
Fig. 1 Locations: **I** Geographical position of Iran; **II** Geographical distribution of the Hyrcanian forest in the northern part of Iran (in green); **III** location of the study area along with other places discussed in this study. The Pounel coring site (PNL) is marked with a white asterisk. Vaske village (VAS) and Majareh village (MAJ) are marked with white diamonds. The meteorological station of Khalkhal (KHA) is marked with a circled dot. The map was produced using natural earth data in a QGIS 3.14 environment

the palynological aspects of the southwestern part of the CS; while the other studies have mostly focused on the central and eastern part (e.g. Djamali et al. 2009a; Leroy et al. 2013a, b; Ramezani et al. 2008, 2013, 2016; Shumilovskikh et al. 2016; Leroy et al. 2019).

The multidisciplinary study of Leroy et al. (2019) in the south-east of the CS investigated the human responses to environmental alterations during the late Pleistocene and early Holocene. According to their palynological evidence, the cool and dry climatic conditions of the Younger Dryas period did not affect this area greatly. Also, their analyses of botanical, faunal and archaeological remains showed a gradual and low-cost adaptation to an early process of Neolithization in the southern Caspian basin.

Leroy et al. (2011) studied two lagoons, Anzali and Amirkola (also known as Amirkelaye). They indicated that during the Little Ice Age (LIA), the sea level increased as a result of more rainfall in the basin of the CS. Besides, due to anthropogenic activities, the dense alder forests were disturbed by fire and expansion of rice paddies between AD 1720 and 1800. Later Haghani et al. (2015) investigated the Langroud wetland. They showed that during the LIA, the high stand of CS caused brackish water incursion 10 km inland in Gilan province. As a result of this incursion, soil salinisation increased the abundance of steppe type vegetation, reduced agricultural activities, and damaged the alder swamp, which is very sensitive to saltwater.

There are only three studies from different elevations in the central part of the Hyrcanian Forest that permitted preparation of an altitudinal transect record in the Hyrcanian forest. These records from three peatlands at 550 m a.s.l. (Muzidarbon, Ramezani et al. 2008), 1,080 m a.s.l. (Tepe Kelar, Ramezani 2013) and 1,475 m a.s.l. (Veisar, Khakpour et al. 2013) reconstructed the vegetation history, climatic conditions and anthropogenic influence through the past 1,500 years. These studies show that (I) during the last 1,500 years, *Alnu*s, *Fagus*, *Carpinus* and *Quercus* have been present near the sites, (II) *Pterocarya fraxinifolia* became rare from 900 to 800 cal yrs BP, most probably due to the Medieval Climate Anomaly, (III) *Fagus*, *Quercus* and some other forest trees gradually declined more likely due to human impact and also climatic factors, (IV) pollen of cultivated plants like *Juglans*, *Corylus* and Cerealia, besides the pollen of the plants such as *Plantago, Sambucus* and *Polygonum*, indicate open landscapes especially for the last few centuries and (V) charcoal particles increased through the Veisar, a record that implies extensive human activities.

The current study is the first and longest palynological record for the highlands of Gilan province. We aim to investigate past vegetation and climate changes as well as fire and human impacts above the western part of the Hyrcanian forest, with the help of multi-proxy analysis. The main research questions are:

(1) How did vegetation and climate change during the last 4,300 years?
(2) What was the role of fire in the vegetation dynamics?
(3) How strongly did anthropogenic activities affect the western part of the Hyrcanian forest ecosystems?
(4) How natural is the modern vegetation?

Study area

Geographical setting

The Alborz Mountains, located in the south of the CS, is a barrier between the northern and the central parts of Iran (Fig. 1 II). The study area is located in the western part of the Alborz Mountains between Gilan and Ardabil provinces. The elevation ranges between − 26 m (in the coastal area) up to 2,872 m a.s.l. in Sonbol Kūh (Forest Rangelands and Watersheds Management Organization 2003). The sediment core was collected from a mire in a small basin located near the Pounel-Khalkhal road, in the so-called Pounel area (37° 34′ 3.80″ N, 48° 40′ 45.98″ E, 2,280 m a.s.l.). The site is 35 km distant from the CS. The nearest village is Majareh, located in Ardabil province, and is 5.7 km distant from the coring site (Fig. 1 III).

Climate

The climate in northern Iran is controlled by different components of regional atmospheric circulation patterns (Akhani et al. 2010). The mid-latitude westerlies transport a high amount of moisture from the North Atlantic Ocean, Black Sea and the Mediterranean Sea to the western part of Asia, contributing to the autumn–winter–spring precipitation of the southern Caspian region (Kendrew 1961; Alijani and Harman 1985). The Siberian Anticyclone, which flows over the north of Eurasia and extends into Central Asia, blocks the eastern penetration during the autumn and winter months and causes high rainfall during summer and autumn in coastal areas of the CS (Khalili 1973; Alijani and Harman 1985). According to spatial analysis of precipitation seasonality (cf. Domoers et al. 1998), the western and eastern parts of the Hyrcanian region are significantly different in terms of precipitation regime. The western part stands at the head of the north-easterly winds emanating from the Siberian Anticyclone or polar front. The winds sweep the CS surface and bring much of the moisture to the south of the Caspian region (Khalili 1973). The second most important rainfall mechanism in the Hyrcanian region is the precipitation from the CS (Alijani and Harman 1985), which minimises the length of the summer and suppresses dry conditions (Akhani et al. 2010).

Khalkhal station is the nearest meteorological station to the Pounel area (Fig. 1 III). The station is located at 1,797 m a.s.l., 13 km distant from the coring site. Based on the last 30 years of records from this site, there is a four-month dry period extending from June to September (Moradi et al. 2019). Also, the average annual temperature and precipitation is reported as 8.9 °C and 376 mm, respectively.

Vegetation

Several studies have classified the modern vegetation of the Hyrcanian region into different zones (e.g. Heshmati 2007; Akhani et al. 2010; Ramezani et al. 2013; Dehshiri 2018). However, the Ramezani et al. (2013) investigation best suits the aim of this study, as the authors provided some information about pollen-vegetation relationships along an altitudinal transect in the central region of the Hyrcanian forest.

Based on this study, *Carpinus betulus*, *Parrotia persica* and *Buxus hyrcana* were the main forest taxa of the lowland forests (< 550 m elevation). In the lower mountains (1,300–550 m), *Fagus orientalis*, *Alnus subcordata*, *Acer velutinum*, *C. betulus*, *Diospyros lotus* and *Pterocarya fraxinifolia* were the most abundant trees. Also, in the upper mountains (1,300–2,400 m) the most dominant forest taxa were *F. orientalis*, *C. betulus* (lower than 1,550 m), *C. orientalis*, *Sorbus torminalis*, *Pyrus*, *Acer campestre* and *Quercus macranthera*. Ramezani et al. (2013) argued that for the wind-pollinated (anemophilous) taxa the ratio of the pollen abundance to the corresponding taxon abundance is relatively large (taxa like *Quercus*, *Fagus*, *Carpinus* and *Fraxinus*). However, for the insect-pollinated (entomophilous) taxa, the above ratio is relatively low (taxa like *Tilia*, *Acer*, *Parrotia*, *Diospyros* and *Ilex*).

Vegetation around the site: Herbaceous plants form the vegetation cover of the Pounel study site. The dominant species are Poaceae, Asteraceae, Amaranthaceae and *Artemisia* spp.. Other frequent taxa that are growing in the surrounding of the coring site include *Taraxacum*, *Ranunculus*, *Carex*, *Lythrum*, *Nasturtium officinalis* and *Veronica*. Furthermore, on the adjacent slopes at the same elevation as the coring site, such taxa as *Alchemilla*, *Geranium*, *Plantago lanceolata*, *Achillea* and *Trifolium* grow. The upper mountain forest occurs at around 2,000 m, less than 800 m below the coring site.

Human settlement

The most important six empires in Iran were: Elam (5,000–2,800 yrs BP), Medes (2,700–2,500 yrs BP), Achaemenids (2,550–2,280 yrs BP), Parthians (2,240–1,700 yrs BP), Sasanians (AD 224–651) and Safavids (AD 1501–1736). Arabs and Mongols conquered Iran at around 1,300 and 700 yrs BP, respectively (Daryaee 2011).

Archaeological evidence suggests that, at least for the last 4,000 years, humans have lived in the region of the Pounel site (Fallahian 2013). Vaske is an ancient village, 14 km distant from the study site (Fig. 1 III) at an altitude of around 1,000 m (Fallahian 2013). Several artefacts belonging to the Iron Age have been found in this village. Most of the inhabitants were engaged in farming and animal husbandry from at least since 1,700 yrs BP (Alizadeh 2014). Nowadays, human

activities (e.g. livestock grazing and road construction) have changed the vegetation of the Pounel region substantially.

Materials and methods

Sampling

A 128 cm-long sediment core of a mire area, called Pounel (PNL), was collected with a Russian corer (50 cm length, 5 cm diameter) in September 2016. The recovered three sections of the sediment core were wrapped in plastic film, placed in split PVC tubes, and stored in a cold room at $+4\ °C$.

Radiocarbon dating and age-depth modelling

Because of the lack of plant remains, four samples were taken from the bulk sediment for accelerator mass spectrometry (AMS) radiocarbon dating at Poznan Radiocarbon Laboratory in Poland. Based on the HCl test, which shows no reaction, and also the meagre amount of the Ca in the sediment core (see Fig. 5), the probable reservoir effect is very low or non-existent. The surface dating was assigned to the year of coring, which was in 2016 (-66 cal yrs BP). An age-depth model was constructed in R-studio (Fig. 2) with BACON version 2.2 (Blaauw and Christen 2011) with linear interpolation, using the Northern Hemisphere terrestrial calibration curve IntCal13 from Reimer et al. (2013).

Pollen analysis

For palynological analysis, 33 samples of 0.5 cm^3 were taken mostly at intervals of 4 cm along the entire core. Samples were processed by pollen analytical methods, including acetolysis (Faegri and Iversen 1989) and 40% HF treatment, and sieved with 120 μm mesh size. Each sample contained an exotic *Lycopodium* spore tablet in order to determine pollen concentration and influx. Beug (2004) and the reference collection of the Department of Palynology and Climate Dynamics in Göttingen were used as the references for pollen and spore identification. For each spectrum, a minimum of 300 pollen grains was counted. The pollen sum includes arboreal pollen (AP), non-arboreal pollen (NAP) and unknown pollen types. Pollen types attributable to aquatic plants, along with Cyperaceae (due to its local high frequencies), spores and non-pollen palynomorphs (NPPs), were excluded from the pollen sum.

Percentages of all the pollen taxa, as well as other taxa and NPPs, were calculated based on the pollen sum. The moisture index (MI), which is a ratio of (*Artemisia*+Poaceae)/Chenopodiaceae (Shumilovskikh et al. 2016), was calculated to identify changes in the climatic conditions.
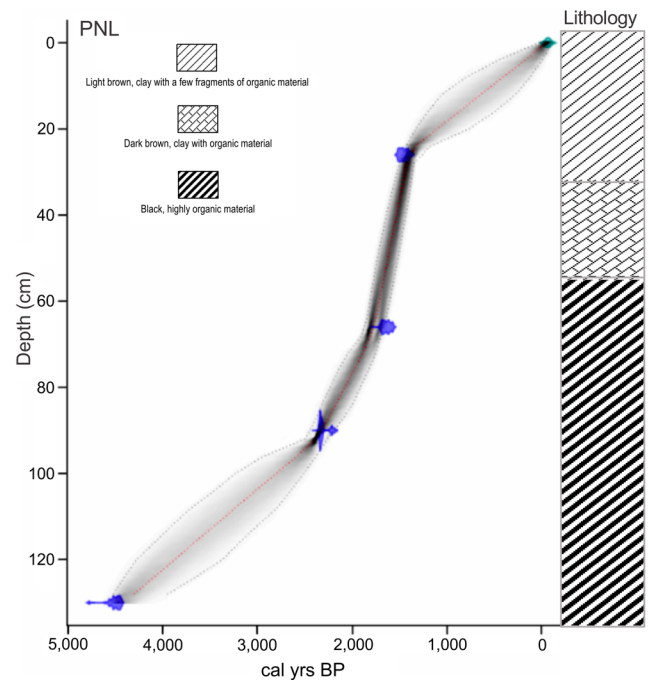

Fig. 2 Age-depth model for the PNL sediment core plotted by linear interpolation in BACON

The former family name Chenopodiaceae is replaced in this paper with its approved new name Amaranthaceae.

TILIA and TILIAGRAPH 2.1.1 (Grimm 1987) were used to illustrate the pollen, spore and NPP data. A cluster analysis was performed using CONISS (Grimm 1987) on the pollen sum to establish pollen zones (Fig. 5).

Macro-charcoal analysis

For charcoal analysis, 0.5 cm^3 samples were taken continuously along the PNL core at intervals of 1 cm down to 126 cm depth (126 samples). All samples were processed according to the method of Stevenson and Haberle (2005). Samples were placed in 10% KOH for 12 h, and then in 6% H_2O_2 for 24 h. Afterwards, the samples were sieved using a mesh size of 125 μm. Charcoal particles were counted with a binocular microscope.

Geochemistry

X-ray fluorescence (XRF), using an ITRAX XRF-core scanner COX analytical system (Croudace et al. 2006), was carried out at GEOPOLAR, University of Bremen (Germany). The XRF measurements were taken at 1 mm intervals down core by using a Cr tube. The main elements determined were Fe, Ti, Rb, K and Ca. Ti and K are detrital fraction indicators, while the Fe/Ti ratio mirrors redox conditions (Croudace and Rothwell 2015). Also, the Rb/K ratio and Ca were

analysed to track chemical weathering (Croudace and Rothwell 2015) and the occurrence of carbonate (Shumilovskikh et al. 2016), respectively (Fig. 5).

Results

Lithology

The PNL sediment core consists mainly of organic material (Fig. 2). Based on the colour and the material of the sediment, the core contains three different units. The first unit (128–58 cm) is composed of black and compact, highly decomposed organic material. The second unit (58–35 cm) consists of dark brown compact clay with organic material. Finally, the last unit (35–0 cm) contains light brown clay with a few organic materials.

Chronology and sedimentation rate

The age-depth model was prepared based on the four radiocarbon dates from the PNL core (Table 1, Fig. 2). The base of the PNL core dated to $4,303 \pm 35$ cal yrs BP. There is no indication of a possible hiatus in the core. For the core depth of 128–92 cm, the calculated sedimentation rate is low (0.02 cm/yr), and in the middle part between 92 and 68 cm, it increases slightly (0.04 cm/yr). A marked increase in sedimentation rate occurs from 68 to 28 cm (0.11 cm/yr). In the uppermost part from 28 to 0 cm, it decreases again to a low rate (0.02 cm/yr).

Description of the pollen, spores, and NPP data

The pollen diagram displays 44 pollen taxa (excluding aquatic taxa and indeterminate pollen types) and ten different NPP types (Figs. 3 and 4). The CONISS analysis applied to AP and NAP taxa suggests two pollen zones with five subzones.

Pollen concentration from the bottom to the top of the core shows a decreasing trend. The influx values are low in the first two subzones (PNL-Ia and Ib), while values increase markedly through PNL-IIa and IIb. Finally, during the last subzone (PNL-IIc), influx decreases to its lowest level.

Subzone PNL-Ia (128–90 cm; ca. 4,300–2,330 cal yrs BP)

The proportion of NAP (herbs) is higher than AP (shrubs and trees). NAP, in particular Poaceae (28–38%), Asteraceae subfamily Cichorioideae-type (6–14%), Apiaceae (4–13%) and *Artemisia* (2–8%), are the most frequent taxa. Amaranthaceae (3–8%) has its lowest values in this subzone, while *Ranunculus* (2–6%) and Campanulaceae (1–5%) have their highest values. The most frequent AP taxa are *Quercus*, *Fagus*, *Carpinus betulus* and *Pterocarya fraxinifolia*. In this subzone, *Carpinus betulus* (2–5%) has its highest percentages. Pollen grains of *Corylus* are also present. *Alnus* pollen grains are present from the beginning of the record. A few *Pinus* pollen grains occur in this subzone. *Lemna* pollen grains are rare. Fern spores are present. Spores of *Glomus* and coprophilous fungi are also present. The spores of various algae were also observed. The MI index shows some fluctuations and in comparison to the second zone (PNL-II) has relatively high values (Fig. 5).

Subzone PNL-Ib (90–62 cm; ca. 2,330–1,700 cal yrs BP)

In this subzone, Poaceae pollen (44–30%) decreases slightly, but in comparison to PNL-Ia, has higher proportions (average 37%). Other NAP keeps its previous trend or decreases slightly. Due to the increasing values of *Quercus*, *Fagus* and other trees and shrubs, the average amount of AP increases to some degree (15% in PNL-Ia to 24% in PNL-Ib). Cyperaceae reaches its highest proportions. Fern spores decrease to their lowest values. *Glomus* falls in comparison to the previous subzone. The MI index shows small fluctuations, but shows the highest value throughout the entire record.

Table 1 Results of radiocarbon dating and calibrated ages of the Pounel (PNL) core

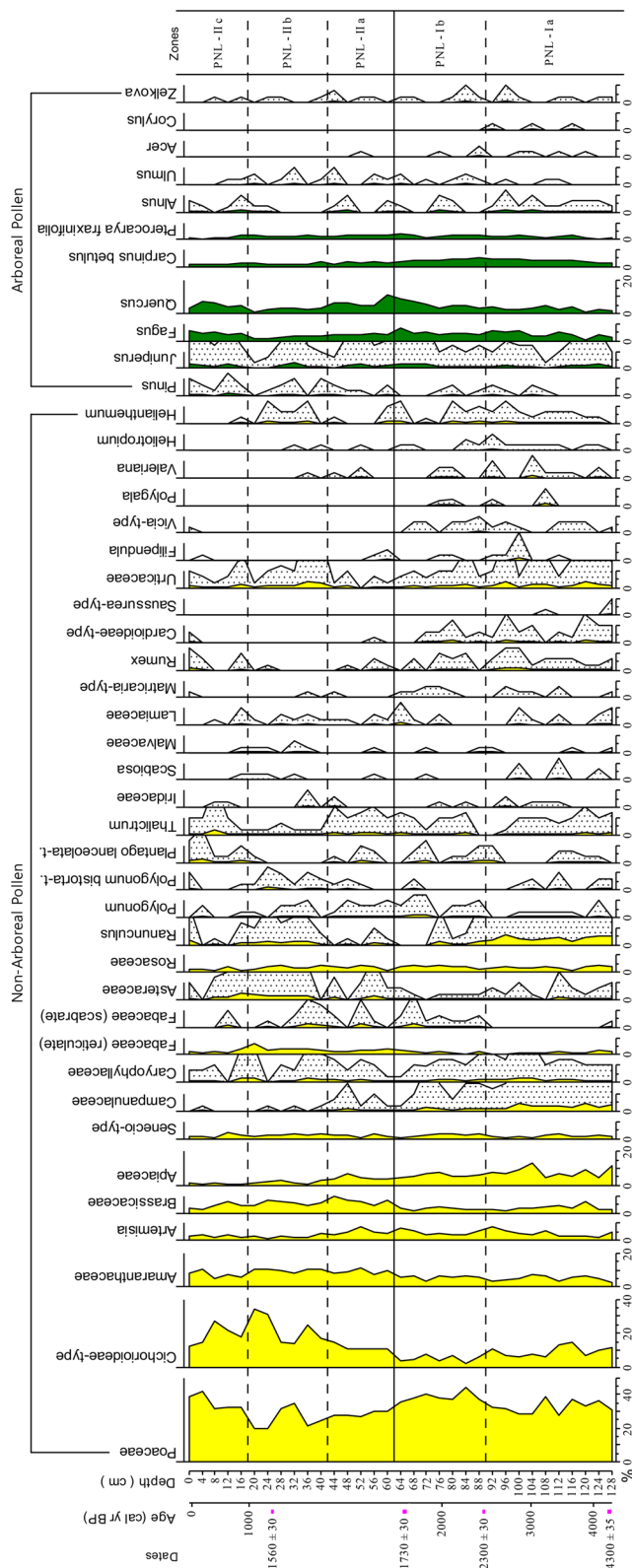| Lab.code	Core depth (cm)	Dated material	Age ^{14}C	Calibrated age (% probability)
Poz-107800	26	Bulk	1560 ± 30	AD 465–631 (93.7) AD 442–452 (1.7)
Poz-107801	66	Bulk	1730 ± 30	AD 322–417 (68.2) AD 250–305 (27.2)
Poz-107802	90	Bulk	2300 ± 30	321–211 BC (56.3) 399–346 BC (39.1)
Poz-85946	128	Bulk	4030 ± 30	2631–2471 BC (93.8) 2832–2821 BC (1.6)

Fig. 3 Percentage pollen diagram of the PNL core. Non-Arboreal Pollen (NAP) in yellow and Arboreal Pollen (AP) in green. Stippled curves are exaggerated 10×

Subzone PNL-IIa (62–42 cm; ca. 1,700–1,580 cal yrs BP) and PNL IIb (42–18 cm; ca. 1,580–1,000 cal yrs BP)

The most characteristic feature of these two subzones is the relatively low values of Poaceae pollen, but it remains the most frequent taxon (20–35%). Some of the pollen taxa, e.g. Cichorioideae-type, Amaranthaceae and Brassicaceae, increase and reach their highest values in the record. *Artemisia* pollen increases in subzone PNL-IIa but decreases in PNL-IIb. AP decreases, in particular *Quercus*, *Fagus* and *Carpinus betulus*. *Alnus*, *Acer*, *Corylus* and *Zelkova* become very rare from the end of PNL-IIa. *Lemna* pollen reaches its maximum amount throughout the whole core in PNL-IIb. Fern spores increase slightly. NPPs, which had constant values in the previous subzones, show some changes in these two subzones. *Glomus* reaches maximum values in PNL-IIb. Hdv-731 shows a peak in PNL-IIb. The MI index decreases to its lowest values in these two subzones.

Subzone PNL-IIc (18–0 cm; 1,000 to − 66 cal yrs BP)

Poaceae pollen increases to the previous values shown in PNL-Ib. *Thalictrum*, *Plantago lanceolata*-type and *Rumex* are higher than in the earlier subzones. However, other herbaceous taxa decrease. Amongst the AP, *Pterocarya fraxinifolia* presents lower values, while *Fagus* and *Quercus* show higher proportions. *Lemna* pollen is still present but falls in comparison to PNL-IIb. *Glomus* is also present but shows a decreasing trend. *Sordaria* and Hdv-1058A have become more abundant. The eggs of *Macrobiotus hufelandi* increase in the upper part of this subzone. The MI index increases in comparison to the previous two subzones (PNL-IIa and IIb), but it still shows lower values in comparison to the first zone (PNL-I).

Charcoal data

Charcoal concentration and influx show their highest values in subzone PNL-Ia and decrease with some fluctuations from the beginning of PNL-Ib. Charcoal influx becomes very low from the end of the PNL-IIb up to the end of PNL-IIc.

XRF data

According to the geochemistry, main elements (K, Ca, Ti) and the ratio of Rb/K, as well as Fe/K, show relatively stable values in zone PNL-I. In zone PNL-II above 60 cm core depth up to the end of the zone, K and Ti increase while the Rb/K ratios decrease. Ca and the Fe/Ti ratio are almost
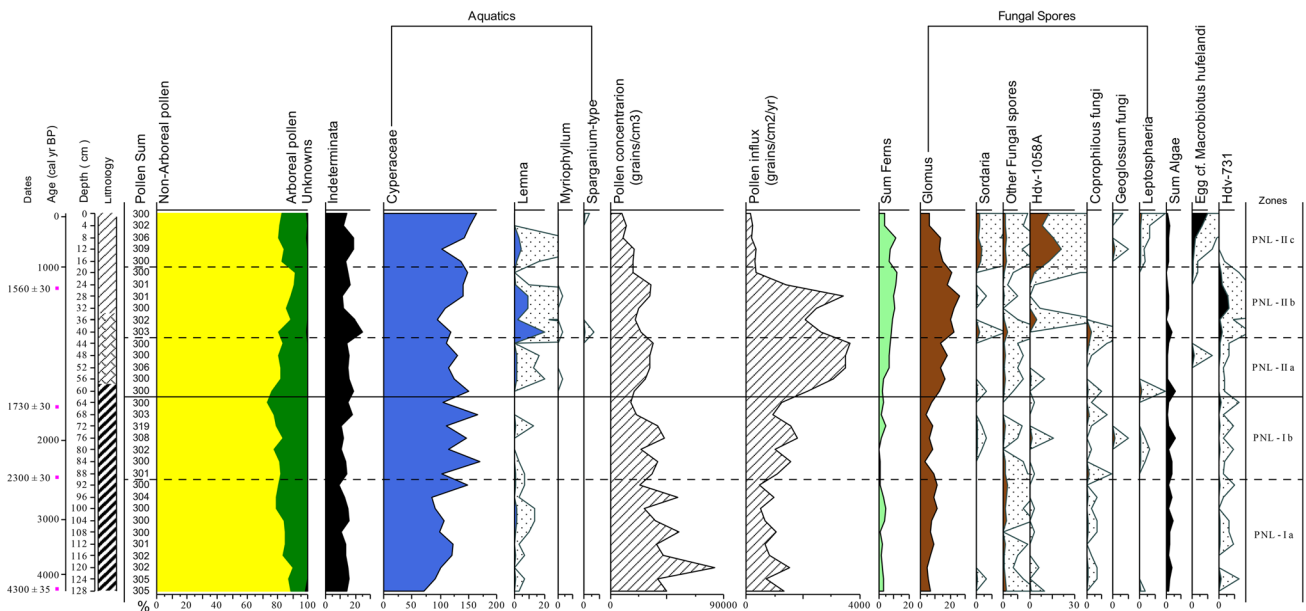
Fig. 4 Diagram with the results of the lithology, pollen summary diagram with the sum of NAP (in yellow), AP (in green) and Unknowns (in black), Aquatics (in blue), Pollen concentration and influx (hatched curves), sum of the Ferns (in pale green), Fungal spores (in brown) and other NPPs (in black). Stippled curves are exaggerated 10×

stable in PNL-IIa and IIb, but increase markedly in the upper part of PNL-IIc.

Interpretation and discussion

Local environment

The studied region is a mire that located in a small basin. It seems sediments started to accumulate in this area from at least 4,300 cal yrs BP. Multi-proxy analysis suggests wetter conditions prevailed for the small Pounel basin from 4,300 to 1,700 cal yrs BP. It also suggests drier conditions between 1,700 to 1,000 cal yrs BP, which later shift to wetter conditions for the last 1,000 years.

Cyperaceae frequency may suggest local changes in the moisture content of the mire area. Based on the current investigation, Cyperaceae, with some fluctuations, were the most frequent plant through the recorded periods. Their lowest frequency was from 4,300 to 2,330 cal yrs BP (PNL-Ia). However, the highest frequency was between 2,330 and 1,700 (PNL-Ib) and 1,000 cal yrs BP up to the present (PNL-IIc). *Lemna*, an aquatic plant, was frequent from 1,580 to ca. 1,200 cal yrs BP (upper and middle part of PNL-IIb), which may suggest shallow and more open water in the mire area.

Although the XRF results indicated stable sediment composition, higher proportions of Ti and K from 1,700 to 1,000 cal yrs BP (PNL-IIa and IIb) indicate an increase in erosion (Croudace and Rothwell 2015). *Glomus*, another

indicator of erosion (van Geel et al. 1989) had higher occurrence between 1,700 and 1,000 cal yrs BP. Also, a sharp shift in sedimentation rates occurred through 1,700–1,000 cal yrs BP (subzones PNL-IIa and IIb). Probably less vegetation cover led to an increase in the accumulation of aeolian inputs (Fig. 5). The lowest accumulation rate through the last 1,000 years may suggest vegetation recovery as the result of the wetter period.

Vegetation and other environmental changes in the study area

According to the pollen record (Fig. 3), the studied site was above the forest line for at least during the past 4,300 cal yrs BP. The dominant diverse herbaceous vegetation covered the study area, and the most frequent species were Poaceae, Cichorioideae (Asteraceae), Amaranthaceae, *Artemisia* and Apiaceae. At some distance from the coring site, *Quercus* (cf. *macranthera*), *Fagus orientalis*, *Carpinus* and *Juniperus* spp. were probably the most frequent trees. However, less frequent trees consisted of *Zelkova*, *Ulmus*, *Acer* and *Corylus*. The occurrence of *Pterocarya* and *Alnus* pollen in our record suggests their relatively long-distance pollen dispersal, as they grow at lower elevations. Winds that blow from the CS lowlands might transport their pollen to the upper mountain area. As *Pinus* was not introduced to Iran before the last century (Ramezani et al. 2016), its pollen occurrence
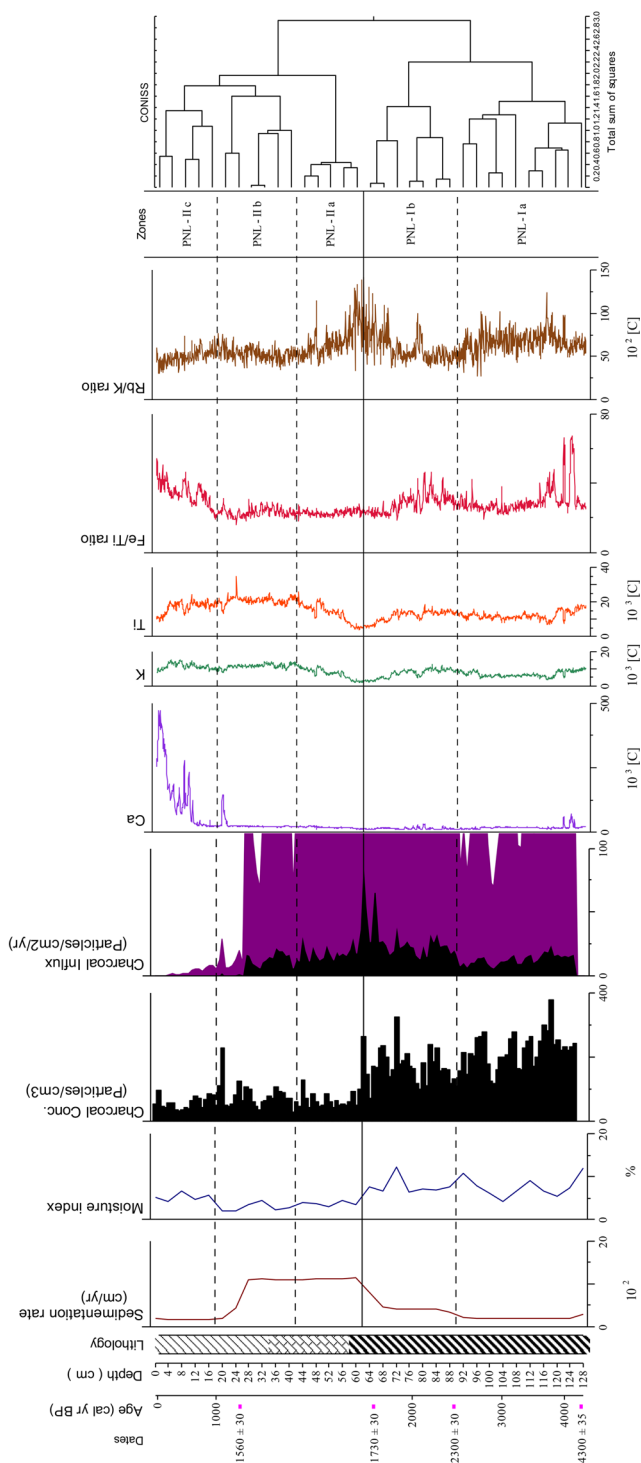
Fig. 5 Diagram with the results of the lithology, sedimentation rate, Moisture Index, charcoal concentration and influx, selected geochemical elements (based on counts per second), and CONISS of the pollen data (excluding Aquatics). 10× exaggerated charcoal influx curve shown in purple

in the studied core is due to long-distant transport from the Caucasus or Turkey.

Period 4,300 to 1,700 cal yrs BP (zone PNL-I)

The record started with a wide variety of herbaceous plants with the dominance of Poaceae. Stable vegetational and environmental features were indicated by high values of pollen concentration, low sedimentation rate, and the steady presence of mineral elements (Figs. 4 and 5). Arboreal plants increased slightly (from 16% in PNL-Ia to 22% in PNL-Ib), and suggest the occupation of larger areas in comparison to the beginning of the record. Increasing Cyperaceae, along with the highest values of MI (Fig. 5) suggest wet conditions. Also, Ryabogina et al. (2019) indicated moisture increasing for the eastern part of the Caucasus between 2,400 and 1,700 cal yrs BP.

Period 1,700 cal yrs BP to present (zone PNL-II)

The results revealed more substantial changes in vegetation for this period. Poaceae decreased while Cichorioideae, Amaranthaceae and Brassicaceae increased until 1,000 cal yrs BP. Cichorioideae reached its highest values between 1,700 and 1,000 cal yrs BP. It can be an indicator of drier conditions, an open landscape (Leroy et al. 2013a) and/or grazing activity (Florenzano et al. 2015). The high sedimentation rate, an increasing trend of K and Ti, a marked increase in Cichorioideae and Brassicaceae, together with *Glomus,* indicate that the area was sparsely vegetated (especially between 1,700 and 1,000 cal yrs BP). Although the forest showed an increasing trend between 4,300 and 1,700 cal yrs BP, it decreased from 1,700 to 1,000 cal yrs BP (PNL-IIa and IIb). *Quercus* and *Fagus* were markedly less frequent ca. 1,580 to 1,000 cal yrs BP. Ferns were present from the beginning of the record, but they increased in this period. It seems that with the reduction of arboreal plants ferns increased. Kooch et al. (2011) verified that ferns like *Dryopteris filixmas* and *Pteridium aquilinum* grew more in disturbed forests, especially in the disturbed *Fagus* forests.

After 1,000 cal yrs BP (PNL-IIc), Poaceae species became more frequent while Cichorioideae decreased in the mire vegetation of Pounel. Furthermore, forest re-expanded, and trees like *Quercus*, *Fagus* and *Carpinus betulus* became more frequent in the forest. Ferns were still abundant during the last 1,000 years, but they decreased whenever the forest recovered.

According to the calculated MI and the vegetational changes, it seems that since ca. 1,700 until 1,000 cal yrs BP, drier conditions prevailed. While, in the last 1,000 cal yrs BP, increasing MI as well as forest recovery indicates the change to a wetter state. Other studies also support the transition from drier to wetter conditions for the last

1,700 cal yrs ʙᴘ. Ryabogina et al. (2019) suggested a dry and warm period during 1,700–550 cal yrs ʙᴘ in the eastern part of the Caucasus. Sharifi et al. (2015) indicated that during 1,800–1,500 cal yrs ʙᴘ, dry conditions prevailed in the whole country of Iran and led to the occurrence of famine. Hoogendooren et al. (2005) showed the Caspian Sea level began to decrease before 1,500 cal yrs ʙᴘ and reached its minimum depth (− 42 m) around 1,500 cal yrs ʙᴘ. Naderi Beni et al. (2013) indicated that the CS level rose to − 21 m during the Little Ice Age.

Human impact

Besides climatic changes, the role of human activities in changing the vegetation since early times needs to be considered. Pastoralism and grazing occurred on the high elevation of the Talysh (Talesh) Mountain, ca. 40 km to the west of the PNL site, from at least 6,500 cal yrs ʙᴘ (Ponel et al. 2013). The occurrence of Cichorioideae, Brassicaceae and *Plantago lanceolata* as well as coprophilous fungi and *Sordaria* spores suggests livestock grazing in the study area at least for the past 4,300 years.

At the beginning of the Iron Age (around 4,000–3,500 ʙᴘ (Ramezani et al. 2008)), the need for charcoal increased for the purpose of metal smelting. Therefore, one possible reason for frequent charcoal before 2,330 cal yrs ʙᴘ (PNL-Ia) may be an increase in metal usage in human life.

The iron mine of Masoule, along with Vaske village, is good evidence of human metal-working practices. Archaeologists suggested that the Masoule iron mine (ca. 50 km from PNL) was mined during the fourth millennium ʙᴘ (Ghorbani 2013). Also, Vaske village is famous for its discovered graves with handicrafts dating from the Iron Age (Fallahian 2013) (Fig. 1 III).

Setting fires for the hunting of animals is another probable reason for frequent fires. The marked decrease in frequent fires after 2,330 cal yrs ʙᴘ may indicate changes in land use due to the growing human population. Alizadeh (2014) published a study that showed people during the Sasanian Empire (between ᴀᴅ 224 and 651) constructed sophisticated irrigation systems, known as Qanat, thus allowing them to be more farmers than hunters. Also, the high occurrence of Cichorioideae between 1,700 and 1,000 cal yrs ʙᴘ, may reflect an increase in livestock grazing activity (Florenzano et al. 2015).

Wood has long been a primary source for different human needs, especially from trees like *Fagus*, *Quercus*, *Carpinus* and *Pterocarya*. Therefore, besides the dry conditions that could have led to a reduction in the number of arboreal plants, anthropogenic activities could also have caused a reduction in trees, mainly *Fagus* and *Quercus*, around 1,580–1,000 cal yrs ʙᴘ.

A more substantial increase of *Sordaria* spores, as well as *Plantago lanceolata*, suggests an increase of grazing for the last 1,000 years (PNL-IIc). Also, Ca (an indicator of $CaCO_3$ and suggesting more livestock around the area (cf. Shahack-Gross et al. 2003)) showed a marked increase for the last 1,000 years.

Summary and conclusions

The multi-proxy study of the PNL sediment core from an elevation of 2,284 m reflects dominant steppe vegetation above the Hyrcanian forest, at least for the last 4,300 years. Vegetation composition in the study area was relatively stable, but several changes could be detected. Climate change, as well as anthropogenic activities, affected the Pounel area throughout the period. Results of the different proxies indicated changing from a wetter (ca. 4,300–1,700 cal yrs ʙᴘ) to a drier period (ca. 1,700–1,000 cal yrs ʙᴘ) and then back to wetter conditions (for ca. last 1,000 years) in the Pounel mire.

Smelting metals like iron, and/or setting fires for the hunting of animals are the most probable reasons for the high frequency of fire between 4,300 to 2,330 cal yrs ʙᴘ. However, changing land use is the possible reason for the reduction of fire since 1,700 cal yrs ʙᴘ.

Through the whole record, steppe vegetation was dominant in the Pounel area. *Quercus*, *Fagus* and *Carpinus* were the most prevalent trees in the Hyrcanian upper mountain forest. Their reduction may be due to the results of both human activities and prevailing drier conditions between 1,580 and 1,000 cal yrs ʙᴘ.

The MI, as well as the marked increase in Cichorioideae, Amaranthaceae and Brassicaceae species and decrease in Poaceae together with arboreal plants on one hand, and increased K and Ti values on the other, reflects changes from wetter to drier conditions. However, intensified grazing, with the assumption of increasing human population remains valid between 1,700 and 1,000 cal yrs ʙᴘ.

Forest recovery since 1,000 cal yrs ʙᴘ suggests a change to wetter conditions. However, the increased presence of Poaceae and *Plantago lanceolata*, as well as *Sordaria* spores and increased Ca values, would suggest continuously intensive pastoralism. For investigating the role of humans in changing the landscape of Gilan through time, more paleoecological and archaeological research is needed.

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