Late Holocene Vegetation and Environmental Changes of Coastal Lowlands in Northern Iran: Possible Role of Climate, Human Impact and Caspian Sea Level Fluctuations

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Late Holocene vegetation and environmental changes of coastal lowlands in northern Iran: possible role of climate, human impact and Caspian Sea level fluctuations

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Abstract

Coastal forests and wetlands play an important role in supporting biological diversity, protecting the hinterlands and shorelines along the continental margins from erosion, as well as for contributing to carbon and freshwater storage. To reconstruct late Holocene vegetation and environmental dynamics in the coastal lowlands in northern Iran and detect the possible role of climate, human impact and Caspian Sea (CS) level fluctuation on coastal ecosystems, a multi-proxy analysis including pollen, spores, non-pollen palynomorphs, macro-charcoal and X-ray fluorescence analysis, have been applied on the radiocarbon dated sediment cores from the Eynak (EYK) lagoon further inland and Bibi Heybat (BBH) alder swamp near the coast. Open wetlands covered relatively large areas since the recorded period (1450 cal yr BP). At BBH larger areas of open vegetation occurred and alder forests covered only small areas that expanded during the late Little Ice Age (1650-1850 AD) and were most abundant during the last about 100 years. Further inland at EYK, areas of alder and mixed broad-leaved Hyrcanian forest were larger. Alder forest in general expanded since 600 cal yr BP. In the last 170 years, alder forest areas and wetlands declined strongly, due to deforestation and strong human activities. The intensity of human impact, climatic fluctuations and changes in CS level were the most important factors controlling the dynamics of the northern Iranian coastal vegetation.

Keywords Northern Iran, coastal wetlands, Hyrcanian forest, climate change, human impact, Caspian Sea level

Introduction

Coastal forests and wetlands play an important role in providing species-rich habitats for supporting biological diversity, as well as for contributing to carbon and freshwater storage (Barbier et al. 2011). Furthermore, coastal vegetation serves as “security guards” to protect the shorelines along the continental margins from erosion. Wetland ecosystems can also create a natural corridor to provide the pathway for their migration (Lindshield et al. 2016; Nasrollahzadeh et al. 2012).

Along the coastal region of the southern Caspian Sea (CS), the Hyrcanian forest has been recognized as a hotspot of biodiversity, important refugia, and last relicts of broad-leaved deciduous forests. This temperate forests covered the temperate zones of the northern hemisphere and survived from extreme climatic conditions during the Quaternary ice ages (Bertini 2003; Talebi et al. 2014). The current distribution of the Hyrcanian forest is along

the coast to the highland of the Alborz and Talysh Mountains. Despite the importance to understand the vegetation and environmental dynamics of the coastal lowlands in northern Iran, only a few studies are available. The coastal wetlands may have experienced marked changes following changes in the temperature, rainfall regime, and CS level changes through space and time (e.g. Shariatpanahi et al. 2013).

Two pollen records from Anzali and Amirkola lagoons (Fig. 1; Leroy et al. 2011) cover palaeoenvironmental changes during the last four centuries, indicating that brackish water has influenced the coastal plain of CS during the LIA, due to its high stands. Previous study also suggests that the CS level changed markedly in the past. It is noted that before 1500 cal yr BP, the CS level decreased and dropped to the lowest level of 42 m b.s.l. (Hoogendooren et al. 2005). While during the Little Ice Age (LIA), the sea level increased up to 21 m b.s.l. (Beni et al. 2013). The record Amirkola indicates that a dense alder forest (mainly by *Alnus glutinosa*) covered the lowland since ca. 1620 AD. The dense alder wetland forest has been temporarily disturbed by fire before it was converted by the expansion of rice fields from 1720 to 1800 AD. The vegetation was more stable in the Anzali record compared with the Amirkola record. From 1700 to 1830 AD, brackish water from the CS to the wetlands has been detected (Leroy et al. 2011).

An approximately 650-year old sediment core, recovered from the Langarud wetland (Fig. 1), located 10 km inland (Haghani et al. 2016), indicates that after the brackish water incursion at the early LIA (LIA is from 1350 to 1850 AD; Mann et al. 2009), the alder swamp, which is very sensitive to salt, became extensively damaged and the salty soils became unsuitable for agriculture activities.

Sedimentological studies also suggest that the CS plays a predominant role in the sediment deposition in the region of the Sefid Rud delta (Fig. 1) with sediments composed by both, marine CS and terrestrial origin (Kazancı et al. 2004). That coastal ecosystems have been influenced by the CS water level fluctuations has been recorded by modern satellite monitor technology in the southwestern CS of Gorgan bay and Gomishan lagoon (Jeihooni et al. 2019). However, the past CS water level fluctuations and the impact on the coastal region during the historical period still need to rely on the proxy-based reconstructions.

Nowadays, the increasing human activities, changing the coastal landscape by conversion to farmland, as well as constructions and pollution, the wetland ecosystems have been heavily disturbed, destroyed and threatened (Barbier et al. 2011; Lotze et al. 2006; Worm et al. 2006; Halpen et al. 2008; Gedan et al. 2009).

A multiproxy record from the wetlands near the slopes of Paen Zarbajar Mountain (Fig. 1), showed that the anthropogenic impact by constructions and fire became frequent during the last 100 years and played an important role in the decline of the Hyrcanian forest (Gu et al. 2021).

In order to reconstruct and to understand the development of the wetlands and coastal vegetation in the lowlands of northern Iran, including its changes, regarding the dynamics of the CS, climate change, as well as the human impact on wetlands and lagoons, a multi-proxy analysis, including pollen, spores, non-pollen palynomorphs (NPPs), loss on ignition (LOI), macro-charcoal and X-ray fluorescence (XRF) analysis has been conducted on sediment cores from two new locations.

Study area

The two study sites are the Eynak lagoon in Rasht further inland (37°16'36.87"N, 49°32'17.66"E, 5 m a.s.l.), and Bibi Heybat alder swamp near the coast (37°21'10.83"N, 49°57'45.94"E, 15 m b.s.l.) in the Gilan province of northern Iran (Fig. 1). The topography of the study area is shaped by the mountain system of the Talesh Mountains

and western Alborz Mountains to the south, with steep slopes, and the lowland coastal plains adjacent to CS in the north. During the Holocene a set of coastal wetlands, alluvial fans, deltas, coastal lagoons have been formed. Several rivers and streams originate from the northern slopes of the Talesh Mountains and western Alborz Mountains. Among them, the largest is Sefidrud which is ca. 670 km long and formed a large delta in the coastal region (Krasnozhon et al. 1999). In 1962, the Manjil Dam was built to prevent flooding and to increase the rice production in the delta region.

Climate

The climate of the study area in the Gilan province has a generally humid climate with a Mediterranean climate with hot, dry summers and cool, wet winters (Köppen 1936). Due to the influence of the onshore winds from the Siberian High and the humid air mass, transported from the western Mediterranean Sea, Black Sea, and Atlantic Ocean (Heydarizad et al. 2019; Persoju et al. 2019), the maximum annual rainfall has been recorded in the southwestern coast with 1900 mm compared to the average annual rainfall of 1506 mm. The highest rainfall is between September and December, while between April and July less rainfall occurs. The average annual temperature in the Gilan province is 15.8 °C and ranges from the lowest average temperature of 4.1 °C in February to the highest of 27.8 °C in August (<https://www.worlddata.info/asia/iran/climate-gilan.php>; Ravanbakhs et al. 2013). Mountains above 1500 m can receive snow during the winter.

Vegetation and human impact

Due to the soil and the hydrological conditions, diverse vegetation occurs near the study area. The modern Hyrcanian forests in the lowland are mainly composed of alder swamps with the dominance of *Alnus glutinosa* spp. *barbata* at a lower elevation, while broad-leaved forests with *Parrotia persica*, *Pterocarya fraxinifolia*, *Carpinus betulus*, *Zelkova carpinifolia*, *Quercus castaneifolia* are distributed at higher elevated areas with relatively good drained soils (Djamali et al. 2009).

The observed local vegetation near the Eynak lagoon wetland in the western part of the city of Rasht includes species of *Ulmus carpinifolia* and *Zelkova carpinifolia*. *Phragmites australis* densely covers the wetlands and its margins. Also *Malva*, *Amaranthaceae* and different *Poaceae* species are distributed around the wetland. Recently, the exotic plant *Azolla* has seriously invaded the wetland and is becoming an environmental concern.

Based on the archaeological record from Yarshalman cave, early human settlements since the Pleistocene in Gilan was mainly located in high-elevated regions, (Biglari and Jahani 2011). Contrarily, the current human settlements are highly restricted to the coastal lowland, especially in the study area of the Eynak lagoon in Rasht.

Nowadays, due to the uncontrolled exploitation and agricultural developments, vast forest areas in the lowlands of northern Iran have been destroyed, converted to rice fields and cultivation land (e.g. olive trees, citrus, tangerine, lemon) in the coastal plains.

Methods

Coring and dating

The sediment core from the Eynak (EYK) lagoon is 300 cm long and was collected with a Livingstone corer. Four small one cm thick bulk samples (2 cm³) have been taken for the Accelerator Mass Spectrometry (AMS) radiocarbon dating. The sediment core from the Bibi Heybat (BBH) alder swamp is 116 cm long, taken with a

Russian peat corer. Three small bulk samples have been also taken for AMS dating. All dates have been calibrated with Clam package in the R-Studio platform (RStudio Team, 2015).

Palynological analysis

Pollen, spores, and non-pollen palynomorphs (NPPs) have been analyzed to reconstruct past vegetation, climatic, palaeoenvironmental changes as well as anthropogenic impacts on the ecosystems. In total 39 subsamples of 1 cm³ volume were taken along the EYK core and 23 subsamples along the BBH core, respectively. Before processing, one tablet with exotic *Lycopodium* (containing 9666 +/- 212 spores) was added for pollen concentration and influx calculations. The subsamples were sieved through 120 µm metal mesh to get rid of large particles. Standard analytical techniques (Faegri and Iversen, 1989) were applied for pollen analysis. HCl (~10%) was added to remove the calcareous and cold HF (~40%) treatment was applied to remove the siliceous content of the subsamples. Pollen, spores and NPPs were concentrated by sieving the concentrate through a 10 µm nylon mesh. The pollen identification was performed using published pollen morphological literature (Beug 2004; Tang et al. 2016), and the reference collection of the Department of Palynology and Climate Dynamics. Most of the samples were counted up to 300 pollen grains, while for the upper 56 cm section of the EYK core and whole BBH core, due to the low pollen content, at least up to 200 grains were counted. Fern spores and selected NPPs were counted and grouped as well. Pollen taxa were grouped as trees/shrubs, anthropogenic indicators (mostly cultivated plants), herbs, and wetland taxa. For percentage calculation, the pollen sum includes trees/shrubs, herbs and wetland (aquatic) taxa. Wetland taxa were included in the pollen sum as we want to illustrate the wetland dynamics in context of the other vegetation groups in space and time. Poaceae (>40 µm), *Juglans* and *Vitis* are selected as anthropogenic indicator taxa. *Plantago lanceolata* is frequently used to indicate human disturbance in the landscape (Stewart 1996), and is here included as well. Poaceae pollen grains larger than 40 µm with a large pore and thick annulus in this region are considered as *Oryza* type, which can be originated from the cereal cultivation in Southeast Asia (Liu et al. 2007; Qiu et al. 2014). The lowland of the study area is nowadays subject to rice cultivation (*Oryza sativa* L.) (e.g. Bahmaniar et al. 2007). The percentage of fern spores and NPPs were calculated on base of the pollen sum. Data are illustrated by TILIA and TILIAGRAPH; CONISS cluster analysis of the taxa which were included in the pollen sum was used for the zonation of the pollen diagram (Grimm 1987).

Macro-charcoal analysis

The macro-charcoal analysis was performed to examine past fire history in the study area. In total, 150 subsamples were taken from the EYK core at 2 cm intervals with a volume of 1 cm³. All samples were processed with 10% KOH and 6% hydrogen peroxide (H₂O₂) to digest and bleach organic material in the sediment samples (Stevenson and Haberle 2005). Macro-charred particles (>125 µm) were concentrated through wet sieving with low water pressure. Charred fragments were counted under a binocular dissecting microscope. Macro-charcoal particles are considered from local fires. Therefore, usually, the peaks of macro-charcoal are commonly used to track the local individual fire event (Higuera et al. 2011). Charcoal data were analyzed by the program CharAnalysis version 1.1 to detect past fire events in the study area (Higuera et al. 2009).

X-ray fluorescence analysis

To analyze the geochemical contents in the sediment core EYK, a high spatial resolution non-destructive X-ray fluorescence (XRF) of major elements with ITRAX XRF core scanner (Mo tube at 45kV, 25 mA, 5s exposer time)

was conducted at the Institute of Geography, University of Bremen (Croudace et al. 2006; Lutz and Pernicka 1996). Compositional variations were measured at a step size of 2 mm. In order to detect changes of the organic and carbonate content in the sediment, the ratios of inc/coh, Ca/Ti, and Ca/Fe have been selected (Davis et al. 2015).

Loss on ignition (LOI) analysis

To determine the carbonate and organic content in the EYK core, a standard LOI analysis procedure was applied (Bengtsson and Enell 1986; Dean 1974; Heiri et al. 2011). In total 40 subsamples with a volume of 1 cm³ sediment have been taken along the core. The wet weighted samples were dried up to 105 °C in a muffle furnace for 24 hours. After cooling down to room temperature, the weight of the dried material was measured. Then the dried samples were heated in the furnace up to 550 °C and then burned for 4 hours and after cooling measured again. In the end, the weight was measured again after furnace heating and burning up to 950 °C. The organic (550 °C) and carbonate (950 °C) content with LOI measurement was calculated using the following equation respectively: $LOI_{550\text{ }^{\circ}\text{C}} = ((DW_{105\text{ }^{\circ}\text{C}} - DW_{550\text{ }^{\circ}\text{C}})/DW_{105\text{ }^{\circ}\text{C}}) * 100$; $LOI_{950\text{ }^{\circ}\text{C}} = ((DW_{550\text{ }^{\circ}\text{C}} - DW_{950\text{ }^{\circ}\text{C}})/DW_{105\text{ }^{\circ}\text{C}}) * 100$. $LOI_{550/950\text{ }^{\circ}\text{C}}$ represents LOI at 550/950 °C (as a percentage), $DW_{105\text{ }^{\circ}\text{C}}$ represents the dry weight of the sample before combustion, and $DW_{550\text{ }^{\circ}\text{C}}$ the dry weight of the sample after heating to 550 °C.

Results from the Enayk lagoon sediment core

Stratigraphy and chronology

For the stratigraphy of the EYK sediment core (Fig. 4), four markedly different depositions can be visually identified. The bottom section of the sediment core from 300 to 110 cm core depth is formed by compact brownish clay. The middle section from 110 to 50 cm is characterized by dark/black organic layers with root remains. Between 50 and 38 cm the sediments are composed of a light brownish layer. The upper 38 cm is marked by dark greenish silt with dark undecomposed organic matter and plant remains. There are no sedimentary gaps that can be visibly identified in the sediment core. The age-depth model is based on four radiocarbon dates (Table 1, Fig. 2a), with an age at the core bottom at 300 cm with ca. 800 cal yr BP. Based on this age-depth model, the age of the EYK pollen zones have been calculated.

Pollen analytical and macro-charcoal results

According to the CONISS cluster analysis, three pollen zones (Zone EYK-I, EYK-II, EYK-III) and three subzones of Zone EYK-I (Ia, Ib, Ic) can be recognized (Fig. 4).

Zone EYK-I (300-132 cm, ca. 800-200 cal yr BP; ca. 1150 to 1750 AD with subzone EYK-Ia (300-228 cm, ca. 800-600 cal yr BP; ca. 1150 to 1350 AD), is characterized by a relatively stable pollen composition (Fig. 3). Tree and shrub pollen is represented by the dominance of *Alnus*, followed by lower values of *Carpinus betulus*, *Fagus*, *Zelkova/Ulmus*, *Buxus* and *Quercus* (Fig. 3). Anthropogenic indicators are mainly represented by *Juglans*, whereas *Vitis* were encountered only sporadically. Cultivated herbs are mainly represented by rather high values of Poaceae pollen larger than 40 µm, which was attributed to *Oryza sativa* (see methods). *Plantago lanceolata* pollen occur as well. Herb pollen, which is not so frequent, includes Poaceae (<40 µm), *Urtica*, and *Artemisia*. Wetland taxa are well represented, mainly by *Cyperus* and with lower values of other Cyperaceae, *Ludwigia*, *Typha latifolia* type, and *Myriophyllum* (Fig. 3). Fern spores have low percentages. Non-pollen palynomorphs (NPPs) are mainly represented by the green algae *Pediastrum* and a few single dinocysts (Fig. 4). At the beginning

of the record occurs a prominent peak of macro-charcoal, followed by relatively frequent macro-charcoal particles in this subzone compared to the following subzone (Fig. 5). In **subzone EYK-Ib (228-156 cm, ca. 600-300 cal yr BP; ca. 1350 to 1650 AD)**, *Alnus* pollen steadily increases and culminates close to the upper boundary of the subzone (Fig 3). *Quercus* shows a more or less similar trend; while other tree pollen remains relatively unchanged. The cultivated tree *Juglans* shows a low-value continuous curve. Individual grains of *Vitis* were also encountered. Pollen of cultivated herbs is mainly represented by Poaceae (>40 µm) and other herbs mainly by *Artemisia* and Poaceae (<40 µm). *Cyperus* is still the main constituent of the wetland group, however, percentages decrease in the upper part of the subzone. *Pediastrum* is the main NPP and *Desmodesmus* shows a small peak in the lower half of the subzone (Fig. 4). The main feature of **subzone EYK-Ic (156-132 cm; ca. 300-200 cal yr BP; ca. 1650 to 1750 AD)** is marked by the decrease of *Alnus* and a prominent maximum of *Cyperus*. Poaceae (<40 µm), *Urtica*, and *Artemisia* show low values. *Pediastrum* and *Desmodesmus* are absent in this section of the record (Fig. 4). Macro-charcoal particles increased.

Zone EYK-II (132-68 cm, ca. 200-100 cal yr BP; ca. 1750 to 1850 AD) is characterized by very high values (up to 86%) of tree and shrub pollen, with *Alnus* being the most important contributor, followed by *Carpinus betulus*, *Fagus*, *Zelkova/Ulmus*, *Quercus*, *Fraxinus*, and a small proportion of *Salix*. Pollen of *Pterocarya* is generally low throughout the record; however, values slightly increase in this zone. Among the pollen types attributable to cultivated taxa, Poaceae (>40 µm) and *Vitis* are the main constituents in the lower half of the zone and *Juglans* in the upper. NAP pollen types show negligible values. In the wetland group, *Cyperus* and other Cyperaceae have higher values at the end of the zone. Fern spores are almost absent. The NPP group is characterized by the dominance of *Pediastrum* and moderate values of *Botryococcus*, *Zygnemataceae*, and low values of dinocysts. Higher values of macro-charcoal particles occur at the beginning of the zone.

Zone EYK-III (68-0 cm, ca. 100-0 cal yr BP; ca. 1850 AD to present) is marked by a low pollen content, a strong decline of *Alnus* pollen (down to 17%), and a notable increase of Poaceae (>40 µm), which can be attributed to *Oryza sativa*. *Plantago lanceolata* type is highest represented in this zone of the whole record. Herbs increase to the highest proportion, which are mainly represented by Poaceae (<40 µm), Chenopodiaceae, *Artemisia*, *Urtica*, and *Galium*. The main constituent of the wetland group is now pollen of other Cyperaceae. Low values of *Ludwigia*, *Sparganium/Typha* type, and *Typha latifolia* type were also seen. Fern spores reach the highest values in the lower half of this zone. *Desmodesmus* shows two prominent peaks. Other NPPs of the zone include *Pediastrum* and *Zygnemataceae* with high abundance. *Dinocysts* form a continuous curve with relatively high values. *Podospora* rises in the top samples. Except for a small peak at the start of the zone, macro-charcoal particles are negligible.

X-ray fluorescence analysis

The XRF analysis provides geochemical elemental compositions in the EYK sediment core in high-resolution. The Ca/Ti and Ca/Fe ratio curves (Fig. 5), show low fluctuations between 300 and 68 cm core depth (pollen zone EYK I and II). Inc/coh shows a general increasing trend. Marked changes in the ratios of inc/coh, Ca/Ti, and Ca/Fe are found in the upper 68 cm core depth (pollen zone EYK III).

LOI results of EYK core

From 300 to 76 cm core depth, the LOI_{950 °C} record shows very low values (Fig. 5). From 76 to 30 cm, LOI_{950 °C} shows a continuously increasing trend and then an abrupt increase in the upper 30 cm of the core. LOI_{550 °C}, shows

more fluctuations. From 300 to 210 cm the LOI_{550 °C} has relatively low values. From 210 to 130 cm it shows an increasing trend to the highest level throughout the whole record. While from 130 to 74 cm the LOI_{550 °C} record shows an abrupt sharp decrease and then small fluctuations. From the upper 74 cm the LOI_{550 °C} record shows a strong increase.

Results from the Bibi Heybat alder swamp sediment core

Stratigraphy and chronology

The stratigraphy of the BBH sediment core is illustrated in Fig. 7. Four markedly different deposits can be visually identified. From 116 to 30 cm, the sediment is dominated by brownish clay; in between it is composed by several sandy layers, from 84 and 57 cm, 52 to 46 cm and from 41 to 38 cm, respectively. The upper 30 cm is composed by soft dark organic matter.

There are three radiocarbon dates for the BBH core (Table 1). The date from the middle section of the core at 70 cm is about 5000 cal yr BP, while the bottom date at 116 cm is ca. 1450 cal yr BP. Considering the marine transgression that occurred during the LIA in the lowland, the old age in the middle part of the core was most likely due to the marine sediment deposition of older material. Therefore, this old age was not considered in the age-depth model (Fig. 2b). Based on this age-depth model, the age of the BBH pollen zones have been calculated. However, these calculated ages have to be seen as a rough estimation of the pollen zones due to the difficulties to date the middle part of the core.

Pollen analytical results

According to the CONISS cluster analysis, three pollen zones (Zone BBH-I, BBH-II, BBH-III) can be recognized (Fig. 7).

Zone BBH-I (116-53 cm; ca. 1450 to 450 cal yr BP; ca. 500 to 1500 AD) is marked by low representation of tree and shrub pollen, which at the beginning of the record show slightly higher amounts of *Alnus*. *Quercus* and *Pterocarya* are represented with low values in the lowermost samples followed by higher values of *Pinus* thereafter. *Salix* shows the highest occurrence in this zone. Anthropogenic indicators are mainly represented by relatively frequent cultivated Poaceae (>40 µm) and *Pantago lanceolata* type. Herb pollen is dominant and mostly contributed by Chenopodiaceae, Poaceae (<40 µm), *Artemisia*, and Asteraceae. Wetland pollen is mainly represented by Cyperaceae. Fern spores are less represent at the lower part, while slightly increase to the upper part of the zone. Among the NPPs, *Glomus* is the most abundant type and has a prominent peak in the lower half of the zone. Dinocysts, foraminifera, and Zygnemataceae start to be continuously present in the upper part of the zone (Fig. 6).

Zone BBH II (53-16 cm; ca. 450 to 50 cal yr BP; ca. 1500 to 1900 AD) is characterized by a shift from herb pollen dominance in the lower half of the zone to higher values of *Alnus* in the upper part of the zone. While other tree and shrub pollen such as *Pterocarya*, *Quercus*, and *Salix* decrease towards the end of the zone. Anthropogenic indicators decrease. Herb pollen values are contributed by Chenopodiaceae, Poaceae (<40 µm), *Artemisia* and Asteraceae which shows a decreasing trend towards the upper part of this zone. Cyperaceae is still the main constituent of the wetland pollen group, in which individual grains of *Lemna minor*, *Potamogeton*, and *Typha latifolia* type were also encountered. The lower part of the zone is characterized by moderate values of trilete fern spores while the upper part shows substantial values of monolete spores. Several NPPs including *Diporotheca*,

Sordaria spp., Zygnemataceae, and *Glomus* show their highest values throughout the record. The dinocysts show an increasing trend in this zone.

Zone BBH III (16-0 cm; ca. 50 cal yr BP to present; ca. 1900 AD to present). The tree and shrub pollen group, now mainly composed of *Alnus*, shows an increasing trend and is mainly by an increase of *Alnus*, *Pterocarya*, and slightly *Juglans*. Anthropogenic indicators such as Poaceae (>40 µm) and *Plantago lanceolata* type are very rare. Herb pollen of Chenopodiaceae, Poaceae (<40 µm), *Artemisia*, and Asteraceae decrease to the lowest amount. The wetland pollen group with Cyperaceae is represented with the lowest values. Fern spores are almost not registered in this zone. Among the NPPs, *Diporotheca* decrease towards the upper part. *Sordaria* spp. and *Glomus* decline from the highest to lowest values. Zygnemataceae have relatively high values.

Interpretation and discussion of the EYK record

Phase I: ca. 1150 to 1750 AD (ca. 800-200 cal yr BP, Zone EYK-I)

For this period the pollen record indicate that the studied coastal plain of the southern CS further inland was dominated by alder forest and at higher elevated areas forests mixed temperate deciduous trees such as *Pterocarya*, *Carpinus betulus*, *Fagus*, *Zelkova/Ulmus*, *Buxus*, and *Quercus*. Ferns were not so frequent in the study area. Cultivated plants like *Juglans*, *Vitis* and *Oryza*, indicate human activities in the coastal plains. Human disturbances in the landscape is indicated by the occurrence of *Plantago lanceolata*. Small areas of open grassland occurred, documented by some Poaceae (<40 µm), *Urtica* and *Artemisia*. Large areas of wetlands were found already at that time, rich in *Cyperus* and with lower frequency of other Cyperaceae species. Shallow open water bodies are indicated by *Myriophyllum*. The development of wetlands in the study area is most likely due to the freshwater discharge of rivers, suggested by the high abundance of the freshwater algae *Pediastrum*.

LOI provides a reliable record for carbonate and organic content in the sediments of the EYK core. The low LOI_{950°C} values in this period suggest a low carbonate content in the sediment. Carbonate dissolution can occur in low water levels (Almendinger and Leete 1998), suggesting a low water level in the alder forest of the study area. A general low carbonate is also indicated by the low values of Ca/Ti and Ca/Fe ratios of the XRF data. The LOI_{550°C} record indicates a low organic content in the sediments with an increasing trend, which is supported by the increase of inc/coh record (Fig. 5). The increase of the organic content can be related to the increasing plant productivity (Bauer and Black, 1994).

More specific **from ca. 1150 to 1350 AD (ca. 800-600 cal yr BP, subzone EYK-Ia)**, the dominance of the wet alder forest and the high proportion of temperate mixed deciduous forest suggest optimal climatic conditions in northern Iran during this recorded period, which belongs to the second part of the MEWP. During the MEWP (between ca. 980 and 1210 AD), the CS level was low (Beni et al. 2013). The CS level is mainly influenced by the hydrological balance between the influx of water input (river discharge and precipitation) and output through evaporation over the CS and the watershed (Kroonenberg et al. 2000; Arpe et al. 2012). Studies suggest that the global temperature during the MEWP (900 to 1300 AD) was at least similar to the present-day (Easterbrook, 2016) and even 1 °C warmer in the Northern Hemisphere as recorded by the Greenland ice core (GISP2), (Stuiver and Grootes 2000). Such general higher temperatures likely caused higher evaporation in CS, which led to the lower CS level during the MEWP.

The green algae *Pediastrum* is frequent in freshwater bodies, such as shallow and eutrophic lakes (Jankovská and Komárek 2000). Abundant *Pediastrum* in the Eynak lagoon, suggest higher rainfall probably due to relatively wet

climatic conditions in the study area. As cultivated trees of *Juglans* as well as *Oryza* cultivation (Poaceae >40 µm) were relatively frequent, it is suggested that cultivation activities were relatively high during this period, maybe due to a warmer condition of the MEWP. The highest occurrence of fire at the beginning of the record might be due to human activities.

From ca. 1350 to 1650 AD (ca. 600-300 cal yr BP, subzone EYK-Ib), the further expansion of the alder forest occurred during the early LIA, suggesting that the lowland of northern Iran was even wetter than in the previous period. This led to a retreat of the mixed forest in the higher elevated areas. Human activities, especially rice cultivation, were less frequent. *Cyperus* is still the dominant taxa around and in the shallow lagoon. The presence of green algae *Pediastrum* and *Desmodesmus*, suggest that the lagoon was dominated by freshwater. During this period, the CS level was still low. Beni et al. (2013) suggest that during early LIA, the CS water level dropped and reached a low stand at ca. 1600 AD. Afterward, the CS water level started to increase again. The less frequent fires in this period might be related to wetter and cooler conditions with less human activities.

From ca. 1650 to 1750 AD (ca. 300-200 cal yr BP, subzone EYK-Ic), the pollen record suggests that the forests, both in the lower and higher elevated areas, declined for a short period accompanied by a slight decrease in grassland and anthropogenic indicators. In the wetlands *Cyperus* was frequent. *Pediastrum* decrease to the lowest values, which suggests that during this period, the climate became drier. The palaeo-temperature reconstruction during the main LIA phase (ca. 1680 to 1800 AD) in the central Eastern Alps suggests that the temperature reached the lowest values (Ilyashuk et al. 2019). The relatively cold and dry climate can be the major factor causing the decline of forests. Fires became more frequent again, probably related to drier conditions and/or human activities. This can be related to the decrease of CS level from ca. 23 m b.s.l. to 26 m b.s.l. during this period (Beni et al. 2013).

Phase II: ca. 1750 to 1850 AD (ca. 200-100 cal yr BP, Zone EYK-II)

During this period, the pollen record indicates the largest expansion of the wet alder forest, while the mixed deciduous forest at elevated areas increased again at the end of this period. This is likely related to a wetter climate as the CS level was relatively high during this period (Beni et al. 2013). The proportions of cultivated plants reduced slightly and became unstable. The grassland which is dominated by Poaceae, Chenopodiaceae, *Urtica*, and *Artemisia*, retreated to their smallest areas. Compared to the previous Phase I, the wetland taxa markedly decreased, probably due to the expansion of the forest with a decrease at the end of the period.

The still low carbonate content, indicated by the low values of LOI_{950 °C} as well as low values of Ca/Fe and Ca/Ti ratios (Fig. 5), suggest that the water level of the alder forest was still low. The inc/coh ratio indicates that the organic matter input to the wetlands increased during this period. However, the declined values of LOI_{550 °C} record indicate a low organic content and suggesting low organic productivity. This might be related to the generally low temperature and unstable climate conditions during the coldest main LIA phase.

Phase III: ca. 1850 AD to present (ca. 100 cal yr BP to present, Zone EYK-III)

In the last ca. 170 years, the pollen record indicates the strongest change in the vegetation. The coastal alder forest showed the strongest decline throughout the whole record. Also *Pterocarya* became rare in the forest. The grassland area, frequent in Poaceae, Chenopodiaceae, *Artemisia*, *Urtica*, and *Galium*, increased markedly. Rice cultivation also markedly expanded during this period. Also, the increase of the *Plantago lanceolata* suggests that strong human disturbance occurred. These changes indicate that large areas of the alder forest have been replaced by human activities. Nowadays, in the lowland of the study area alder forests are almost entirely converted to

urban and agricultural land. Changes in the wetland vegetation were indicated by the more frequent occurrence of Cyperaceae, *Ludwigia*, *Sparganium* and *Typha*, while *Cyperus* was absent. The reduction can be related as well to the marked increase in human activities.

The LOI and XRF data also indicate marked changes in the environment for the last about 170 years. The abrupt increase in the LOI_{950 °C} record reflects a strong increase in carbonate content of the sediments, which is also reflected by the high ratios of Ca/Fe and Ca/Ti. The high carbonate content was likely due to the increase of water level in the wetlands, which also mark the formation of the EYK lagoon. The stable high values of Ca/Fe, Ca/Ti, and LOI_{950 °C} record suggests that the modern Eynak lagoon was established about 50 years ago. The hydrological changes in the Eynak lagoon were very likely due to human activities.

Abrupt strong changes in the geochemical composition of the wetland deposits have been also detected in the ZBR record for the same period (Gu et al. 2021). The increased water level of the lagoon can be related to the dam reconstruction in the study area. A previous study also documents that dams and dikes were frequently constructed around the wetlands in northern Iran for water storage, maintenance of irrigation systems to increase rice production and to improve the cultivation (Kardavani 1991). The very rare occurrence of fires might be related to the decrease of burning activities, increasing of the water table as well as the wet condition surrounding the lagoon. Meanwhile, the increased LOI_{950 °C} record suggests that the continuous increase of organic content deposits which also suggests the improvement of organic productivity can be related to human activities.

Interpretation and discussion of the BBH core

Phase I: ca. 500 to 1500 AD (ca. 1450 to 450 cal yr BP; Zone BBH-I)

The BBH pollen record suggests that in the lower elevated coastal areas close to the CS of northern Iran, the landscape was dominated by open grassland vegetation with Chenopodiaceae, Poaceae, *Artemisia*, and Asteraceae. Alder forest occurred only in small areas at the beginning of the record and declined during this period. Later, since around 1050 AD, the alder forest started to re-expand slightly. Anthropogenic indicators such as Poaceae (>40 µm) and *Plantago lanceolata* type are relatively frequent, indicating rice cultivation and other human disturbances in the study area. Wetlands, mainly shown by the Cyperaceae, were also first relatively small and increased in the second half of the period. Also from 1050 AD onwards, marine dinocysts and foraminifera were found in the deposits, indicating that the coring area of BBH was under the influence of brackish water from the CS, maybe via the Sefied Rud River (Fig. 1). This is further confirmed by the presence of sandy layers in the sediment core (84 to 57 cm depth). *Glomus* is a good indicator of active soil erosion, referring to limited soil moisture (Medeanic and Silva 2010; van Geel 2002). During this period, the high abundance of *Glomus*, which indicates low soil moisture hence active soil erosion under relatively dry conditions with heavy rainfalls.

Phase II: ca. 1500 to 1900 AD (ca. 450 to 50 cal yr BP; Zone BBH-II)

This is a transitional period, the dominant open grassland changed to an alder swamp forest with relatively frequent occurrence of *Pterocarya*. Ferns increased markedly in the second part of this period and might have played a role in the successional development of the alder swamp. The decrease of Poaceae pollen (> 40 µm) suggests that the rice cultivation reduced slightly in the study area. Wetland plants increased slightly and were dominated by Cyperaceae. The higher occurrence of dinocysts and foraminifera suggests that during this period, the BBH coring site was still influenced by the brackish water of the CS. Soil erosion still occurred, as suggested by the continuous high presence of *Glomus*. In the second part of this period (ca. 1800 to 1900 AD), the abundance

of *Sordaria* spp. and *Diporothea* is high. *Diporothea* can either indicate soil disturbance and extensive soil erosion or suggest a wet and eutrophic habitat (Hillbrand et al. 2012) while *Sordaria* spp. is a good indicator for the large herbivores' animals (Baker et al. 2016). Therefore, the high abundance of *Sordaria* spp. and *Diporothea*, suggest that the wetland was disturbed by anthropogenic activities, which was likely due to grazing activities.

Phase III: ca. 1900 AD to present (ca. 50 cal yr BP to present; Zone BBH III)

The highest dominance of *Alnus* indicates that the largest expansion of alder forest occurred only during this relatively recent period. In this phase, the abundant Zygnemataceae which is commonly associated with shallow water habitats (Worobiec 2014), accompanied by the dominance of *Alnus*, probably refers to the final formation of the wet alder swamp. At the study site, the area of open vegetation retreated markedly as well as the cultivated area. The decreasing trend of *Sordaria* spp., *Diporothea*, and *Glomus* from the highest values to the lowest in the upper record, suggest less anthropogenic disturbance (cattle grazing) in the area. The open wetland areas became very small as indicated by the decrease of Cyperaceae.

Comparison between the two new sites and other sites in the lowlands of northern Iran

This study indicates a marked difference in the vegetation composition in the lowland of the EYK study area further inland and the BBH area near the coast of the CS (Fig. 1). The BBH record (15 m b.s.l.) shows that the studied coastal area was mainly dominated by open grassland vegetation from 500 to 1850 AD. The wet alder forest area was the lowest between 750 and 1050 AD. The EIG record at ca. 550 m elevation from the northern slope of the central Alborz Mountains also indicates little presence of alder forest before 1050 AD (Ramezani et al. 2008). Stronger soil erosion was recorded in the BBH core, which can be related to the strong erosive environmental condition during MEWP (900 to 1300 AD). Such MEWP related soil erosion is also recorded by the EIG record (Ramezani et al. 2008). The BBH pollen record shows that a slight increase of alder forest occurred after 1050 AD and between 1450 and 1650 AD, while a stronger expansion occurred from 1850 to 1950 AD. The largest expansion that occurred was recently after 1950 AD.

The EYK site (5 m a.s.l.), located further inland and 20 m higher than the BBH coring site, showed an increasing trend of alder forest expansion between 1150 and 1850 AD, except the strong decline between 1650 to 1750 AD. This stronger reduction is also shown in the pollen record of the BBH core. After the LIA at 1850 AD, with the increase of open vegetation and cultivated areas, the alder forest declined strongly at the EKY site.

The study by Beni *et al.* (2013) indicates that during the MEWP, the water level of the CS was relatively low (ranging from ca. 23.5 m to 25.5 m b.s.l.), while during the second part of the LIA, the level of the CS was as high as ca. 21 m b.s.l. (compared with 27 m b.s.l. in 2014). Between MEWP and LIA (1250 and 1350 AD) the CS level reached as high as 19 m b.s.l. Therefore, it is supposed that large lowland regions were influenced by the invasion of brackish water from the CS during the high water level stands of the CS level between MEWP and LIA and in the second part of the LIA.

However, the frequent presence of dinocysts and foraminifera in the BBH record (15 m b.s.l.), suggests that the BBH site was already influenced by brackish water since 1050 AD. Due to the location of the EYK core further inland at a higher elevation, the ecosystem was not directly under the brackish water influence from the CS, but with the Sefid Rud River connection is possible. However, the increasing trend of alder forest and other broadleaved forest expansion in the EYK study area, suggest that the moisture increase can be linked to the increased CS level.

The record from the coastal lagoon Amirkola (Fig. 1), located at 23 m b.s.l., indicates that the vegetation was dominated by dense alder forest since the beginning of the record at ca. 1620 AD, and then the lagoon was continuously influenced by the CS until ca. 1800 AD (Leroy *et al.* 2011). Unfortunately, due to the younger age of the Amirkola record, the CS influence of the coastal area could not be reconstructed. However, the BBH core suggests that the CS water influence in the lowland of the BBH area occurred at least since 1050 AD as indicated by the continuous occurrence of dinocysts and foraminifera in the record.

After the LIA at AD 1850, as the CS rapidly regressed, the BBH core showed that the alder forest developed in the coastal region and continued to expand in the study area. While in the slightly elevated area further inland, where human activities were pronounced, the EYK record shows a marked reduction of alder forest and an increase of grassland and cultivated plants. Haghani *et al.* (2016) indicated that after the brackish water incursion during LIA, the environment was unsuitable for agriculture. Moreover, the abundance of water algae Zygnemataceae from the BBH record suggests that the ecosystem changed to alder swamp ecosystem with shallow water. Therefore, due to the increase of water tables and the formation of the swamp ecosystem, the BBH area was probably not favored for agriculture and grazing. The BBH area was then abandoned as humans, which is likely moved to more favorable areas. This might explain less human activities and disturbance in the BBH record during the last 100 years. The development of dense alder forests in the BBH area was likely related to less anthropogenic activities. However, as the EYK record shows a strong reduction of the alder forest, deforestation became intense during the last 170 years. The increase of the anthropogenic impact has been also recorded in ZBR wetlands during the last 100 years (Gu *et al.* 2020).

Summary and Conclusion

The two new multi-proxy records, including pollen, spores, NPPs, charcoal, LOI and geochemical elements, from the coastal plain of northern Iran, provide new insights into vegetation and environmental changes during the late Holocene. The results of the archives from the coastal Bibi Heybat (BBH) alder swamp and the Eynak (EYK) lagoon further inland indicate that since the beginning of recorded time (BBH since 500 AD, EYK since 1150 AD) the areas of alder forest were smaller in particular at BBH. Here only smaller areas were covered by alder forest. For the recorded MEWP (900 to 1300 AD) with relatively small areas of alder swamp, it is suggesting that the climate was warmer and drier. The dry condition is especially indicated by the soil erosion in the BBH record and the high fire frequency of the EYK macro-charcoal record. During the cold phase in the LIA period with the CS high stands between 1600 and 1850 AD, both records indicate an expansion of alder forest, which might be related to humid air mass from the CS that could potentially contribute to the forest expansion. The inland EYK record indicates that since the last 170 years, a strong reduction in alder forest occurred, while the coastal BBH record shows the opposite for the last about 100 years. This indicates little anthropogenic impact in the coastal area of the BBH alder swamp, but intensified human impact in the Eynak wetland area, might be related to changes of the coastal environment, and with the influence of the brackish water of CS, the BBH alder swamp was not so suitable for agriculture anymore. These new records show that relatively large and little disturbed open wetlands occurred in the EYK study area which changed by the strong human impacts over the last 170 years, while in the BBH study area, open wetlands were mostly replaced by the alder forest extension since the last about 100 years. These two new environmental records suggest that late Holocene climatic fluctuations, changes in CS level, but

in particular the intensity of human activities are the most important factors controlling the dynamics of the northern Iranian coastal vegetation and wetlands.

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Declarations

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Conflicts of interest/Competing interests (not applicable)

Ethics approval (not applicable)

Consent to participate (not applicable)

Consent for publication (not applicable)

Availability of data and material (The datasets used and/or analysed during the current study are available from the corresponding author on request.)

Code availability (not applicable)

Authors' contributions (All of the co-authors contributed to the study conception and design. Data analysis and the draft of the manuscript were performed by Dr. Fang Gu. Dr. Kamaledin Alizadeh and Prof. Dr. Hermann Behling commented on the manuscript. All authors read and approved the final manuscript)

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Figure and Table captions

Figure 1. Map showing the location of sediment cores (red triangles) from the Eynak (EYK) lagoon in Rasht and the Bibi Heybat (BBH) alder swamp.

Figure 2. Age-depth model of the sediment core EYK (a) and BBH (b).

Figure 3. Pollen percentage diagram, showing the most frequent taxa of the EYK core, grouped into trees/shrubs, anthropogenic indicators, herbs, wetlands, and the pollen zones.

Figure 4. Summary diagram showing the stratigraphy of the sediment core, vegetation groups, ferns, NPPs, pollen sum, concentration and influx, pollen zones, the CONISS dendrogram and pollen zones of the EYK core.

Figure 5. Diagram showing the $LOI_{550\text{ }^{\circ}\text{C}}$, $LOI_{950\text{ }^{\circ}\text{C}}$, ratios of Inc/coh, Ca/Ti, Ca/Fe of the XRF data and macro-charcoal particles of the EYK core.

Figure 6 Pollen, spore, and NPP percentage diagram, showing the most frequent taxa of the BBH core, grouped into trees/shrubs, anthropogenic indicators, herbs, wetlands, as well as ferns and the pollen zones.

Figure 7. Summary diagram showing the stratigraphy of the sediment core, vegetation groups, pollen count, concentration and influx, the CONISS dendrogram and pollen zones of the BBH core.

Table 1. Radiocarbon dates from sediment core EYK and BBH with the calibrated ages reported for 2σ range and with highest probabilities shown in parentheses.

Figures

Figure 1

Map showing the location of sediment cores (red triangles) from the Eynak (EYK) lagoon in Rasht and the Bibi Heybat (BBH) alder swamp. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square

concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Age-depth model of the sediment core EYK (a) and BBH (b).

Figure 3

Pollen percentage diagram, showing the most frequent taxa of the EYK core, grouped into trees/shrubs, anthropogenic indicators, herbs, wetlands, and the pollen zones.

Figure 4

Summary diagram showing the stratigraphy of the sediment core, vegetation groups, ferns, NPPs, pollen sum, concentration and influx, pollen zones, the CONISS dendrogram and pollen zones of the EYK core.

Figure 5

Diagram showing the LOI550 °C, LOI950 °C, ratios of Inc/coh, Ca/Ti, Ca/Fe of the XRF data and macro-charcoal particles of the EYK core.

Figure 6

Pollen, spore, and NPP percentage diagram, showing the most frequent taxa of the BBH core, grouped into trees/shrubs, anthropogenic indicators, herbs, wetlands, as well as ferns and the pollen zones.

Figure 7

Summary diagram showing the stratigraphy of the sediment core, vegetation groups, pollen count, concentration and influx, the CONISS dendrogram and pollen zones of the BBH core.

Supplementary Files

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- [Table1.jpg](#)