Late Holocene paleoenvironmental changes inferred from multi-proxy studies of the Kholasht-Kouh Lake sediments in the Gilan mountains, northern Iran

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Abstract Past vegetation and environmental changes and the role of climate as well as human activities are of major interest. The Hyrcanian region with a high number of endemic species has a poorly known paleoenvironmental history, especially the western region of northern Iran. This study aims to investigate a radiocarbon-dated sediment core of the Kholasht-Kouh Lake (KHL) for the recorded between ca. 510 and 1180 cal yr BP. KHL is located at 2000 m elevation and surrounded with steppe vegetation above the present-day forest line. Multi-proxy analyses including pollen, non-pollen palynomorphs, charcoal, loss on ignition, and X-ray fluorescence were applied to reconstruct past environmental dynamics. The results indicate the dominance of herbaceous vegetation (mainly Poaceae, Artemisia, and Amaranthaceae) around the lake during the whole record, except for the period between 1010 and 740 cal yr BP. During this period of the Medieval Climatic Anomaly (1000–700 cal yr BP) mixed forest increased, consisting mainly of Quercus, Fagus, Carpinus, and Juniperus. The K, Ti and Si elements (as indicators for increased in detrital inputs) suggest relatively humid condition between 1180 and 1010 cal yr BP. Furthermore, higher lake levels may indicate from low values of the Mn/Ti, Ca/Ti and Sr/Ti ratios. After 1010 until 740 cal yr BP the highest value of the Si/Fe ratio, suggested warmest period of the record. While the lowest value of the Si/Fe ratio, in line with the reduction of other elements and ratios, between 740 till 510 cal yr BP represented cold and dry period. Humans were present around the study area at least since beginning of the record, but did not played an important role impacting the vegetation.

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

Introduction

In northern Iran along the coastal and mountain region of the southern Caspian Sea occur temperate forests, known as Hyrcanian forests. These forests, are designated as a biodiversity hotspot and consist of last relicts of the deciduous broadleaved species from the Arcto-Tertiary era (Zohary 1973; Leroy and Roiron 1996) like Gleditsia caspica, Parrotia persica, Pterocarya fraxinifolia and Zelkova carpinifolia. These relict species were growing extensively in the temperate regions of the Northern Hemisphere during the Pliocene. Though, they became extinct in Europe and northern Asia through the Quaternary (Zohary 1973).
The distribution of the Hyrcanian forest prior to the Last Glacial Maximum is not well known (Leroy et al. 2013), though its current distribution is from the coast of the Caspian Sea up to the highlands of the Alborz and Talysh Mountains (Sabeti 1994). Despite the importance of understanding past interactions between the climate and human activities in this region, the available studies are still insufficient and focused mainly on the coastal plains, especially the central and eastern plains (Naderi Beni et al. 2013; Khakpour Saej et al. 2013; Leroy et al. 2013, 2019). The western region’s (in Gilan province) have not been studied until last decade (Leroy et al. 2011; Haghani et al. 2015; Homami Totmaj et al. 2020; Gu et al. 2021). Although the mentioned studies did not cover the whole Holocene period, they shed some light on the vegetation of the western part of the Hyrcanian region.

Leroy et al. (2011) concluded that higher rainfall during the Little Ice Age (LIA) resulted in increase of the Caspian Sea level. They also indicated large-scale deforestation of the alder forest (*Alnus* sp.) between 300 and 220 cal yr BP (1700 to 1830 AD) due to more fire events, most probably related to the expansion of the rice paddies. Haghani et al. (2015) published the LIA effect on the settlements and environments around the Langaroud wetland (coast of Gilan). For this period, they evidenced water incursion 10 km, which increased soil salinity, and as the result agricultural activities reduced, the alder forest damaged, and the grassland vegetation expanded. The first investigation from the highlands of the Gilan reconstructed the anthropogenic and environmental changes for the entire late Holocene period on the Pounel mire at 2280 m a.s.l. (Homami Totmaj et al. 2020). The study showed that around the Pounel mire steppe was dominant at least for the past four millennia. Also, frequent fires during the Iron Age and later intensive grazing documented long-term human activities around the mire. Based on the newly published study (Homami Totmaj et al. 2021) at the mid-elevated Hyrcanian forest, humans influenced the area since the beginning of the record (ca. 1690 cal yr BP), though the strongest human impact dates back to ca. 65 cal yr BP by intensive deforestation. The study also documented changing from warm and humid conditions to cold and dry after 520 cal yr BP.

Documenting past environmental changes and the probable causes of the changes are crucial for the nature conservation and management as well as background information for the archeology. In the current study we want to reconstruct environmental dynamics for the late Holocene applying the multiproxy analysis and aim to answer the following questions: (1) How did vegetation and climate change during the recorded period in this high-elevated area? (2) How strongly was the vegetation affected by climate events such as the Medieval Climatic Anomaly (MCA) and LIA? (3) What were the human impacts, and how strong was the vegetation affected?

Study area

**Geographical setting and climate**

The Kholash-Kouh Lake (KHL), with the coordinates of 36°45′43.49″N, 49°53′42.79″E, located at the top of the mountain at 2000 m elevation above the tree line in the southeastern part of the Gilan province (Fig. 1). The lake is located on the old terraces and higher gravel fan formation, with the possibility of inputs from the thin-bedded limestone nummulite-bearing of Eocene and/or the conglomerate sandstone Triassic formations. The lake has an area of around 15 km², with a water depth of 3 m at the coring site. Klishom and Khoramkou or Kharehpu are the nearest villages located at 1900 and 1600 m a.s.l., respectively, with approximately 3.5 km distance to the Kholasht-Kouh Lake. Villagers live in the villages only during the summer, and cultivate mostly wheat, walnut and hazelnut.

The mid-latitude Westerlies and the Siberian Anticyclone are the two main climate systems that influence the whole Hyrcanian region in northern Iran (Djamali et al. 2010). Humidity gets blocked between the Caspian Sea (CS) and mountains, causing warm, humid summers with mild winters (Kendrew 1922). The precipitation decreases from the Caspian Sea’s coastal plain to the Alborz mountain’s highlands and from the western to the eastern region (Khalili 1973). The annual rainfall in Gilan, which is the highest through the whole country, is around 1400 mm per year (Rousta et al. 2017), but it decreases rapidly on the inland slopes of the coastal mountains. According to the nearest meteorological station (Jirandeh, at 11 km distance to the coring site at 1500 m elevation) the average annual temperature and rainfall is 11.5 °C
and 260 mm, respectively (Mohammadi Nia et al. 2015), representing semi-arid climate.

Vegetation

Based on the studies of Ramezani et al. (2013) on the central part of the Hyrcanian region, the forests can divide into three main zones. Lowland forests (<550 m elevation) mainly consist of *Carpinus betulus* L., *Parrotia persica* (DC.) C.A.Mey. and *Buxus hyrcana* L.. Mid-elevated forests (1300–550 m) include the main taxa such as *Fagus orientalis* Lipsky, *Alnus subcordata* C.A.Mey., *Acer velutinum* Boiss, *C. betulus*, *Diospyros lotus* L. and *Pterocarya fraxinifolia* (Lam.) Spach, and the high elevated forest (1300–2400 m) with the most dominant taxa of *F. orientalis*, *C. betulus* (lower than 1550 m), *C. orientalis*, *Sorbus torminalis* (L.) Crantz, *Pyrus*, *Acer campestre* L. and *Quercus macranthera* Fisch. & C.A.Mey. ex Hohen.. However, the current site is located above the forest line (in subalpine and alpine meadows according to the Akhani et al. (2010). The meadows consist mainly of grass species (*Poa, Festuca* and *Elmus*) together with hemicyryptophytes and geophytes like *Rumex, Primula, Anemone, Thalictrum, Potentilla*, and *Scilla* (Akhani et al. 2010). The Euxino-Hyrcanian species, *Quercus macranthera* typically grows in the high-altitude forests (1800–2300 m) of the Alborz mountain (Akhani et al. 2010). However, related to the topographic structure and further intensive anthropogenic activities, the subalpine oak forest is disjointed and receives much sunshine (Akhani et al. 2010). Oak trees are small, and their open intervals are covered by different montane steppe vegetation types of the Irano-Turanian zone (Akhani et al. 2010), such as *Astragalus, Artemisia, Acantholimon, Cousinia*.

The area of open vegetation with montane steppe around the lake is mostly covered with species of Poaceae and Asteraceae (e.g. *Artemisia* and...
Cousinia), Chamomile, Polygonatum and Echium. At the lower elevation, most of the region is rangeland or agricultural land. There are scattered regions covered with arboreal taxa at lower elevations on adjacent slopes (the nearest is the small Cypress forest in 1 km distance to the lake), mainly consisting of Cypress, Fagus, Carpinus, Quercus, Acer, Tilia, Juglans, and Crataegus.

Materials and methods

Coring, radiocarbon dating and age-depth modeling

A sediment core of 135 cm length, called Kholash-Kouh (KHL), was collected in September 2018, with a modified Livingstone corer (Livingstone 1955). The recovered sediments were sealed and taken to the Department of Palynology and Climate Dynamics of the Göttingen University and stored under dark and cold conditions.

For the chronological framework, five organic sediment samples (1–2 cm³ each) were collected and sent to the Poznan Radiocarbon Laboratory in Poland for the Accelerator Mass Spectrometry (AMS) radiocarbon dating. An age-depth model and the calibrated ages have been done with the software R-Studio data platform, using CLAM package 2.4.0 (Blaauw 2010) (Fig. 2).

Palynological analysis

In total 34 pollen samples of 0.5 cm³ were collected in intervals of 4 cm along the core. Prior to processing the sediment samples, one tablet with 9.666 ± 212 exotic Lycopodium spores was added to each sample to calculate pollen concentration (grains cm⁻³) and pollen influx (grains cm⁻² yr⁻¹). The samples were processed by pollen analytical methods of Faegri and Iversen (1989), using the chemical treatment (10% HCl, 40% HF and acetolysis). Samples were sieved with a 120 μm mesh size to separate palynomorphs. Pollen and spore identification followed the literature (Beug 2004) and the reference collections from the Department of Palynology and Climate Dynamics.

A minimum count of 300 terrestrial pollen grains was counted for each sample. The percentages were calculated on the sum of arboreal (AP) (such as trees, shrubs, lianas) and non-arboreal pollen (NAP) (grasses and herbs) types, excluding pollen of aquatic plants and indeterminate taxa, spores, and non-pollen palynomorphs (NPPs).

Based on the pollen sum, the calculation and illustration of pollen, spores, and NPPs was done with

![Fig. 2 Lithology and age-depth model for the KHL sediment core plotted in CLAM](image-url)
TILIA and TILIAGRAPH program 2.1.1. (Grimm 1987). The pollen diagram zonation was done based on the cluster analysis of the percentages of the pollen included in the pollen sum, using CONISS (Grimm 1987).

Loss on ignition (LOI) analysis

For the determination of the organic and carbonate material, 34 samples were collected at 4 cm intervals along the core at the same depths as for pollen analysis. A P330 furnace was used at the Department of Palynology and Climate Dynamics of the Göttingen University for LOI (Heiri et al. 2001), while samples were dried for 24 h at 60 °C in advance. Then, 4 g of each dry sample were burnt at 550 °C for 4 h, to calculate the organic matter content (LOI 550) (Heiri et al. 2001). For calculation of the carbonate content, samples were burnt for a further 2 h at 950 °C.

Macro-charcoal analysis

In total 143 samples of 0.5 cm³ were collected in intervals of 1 cm along the entire KHL core, to track the role of fire in the study area. All samples were processed according to the method of Stevenson and Haberle (2005). All the samples remained for 12 h in 10% KOH, and then for 24 h in 6% H₂O₂ and sieved using the 125 μm mesh size. Charcoal concentrations and influx were calculated in TILIA software.

Geochemical analysis

Non-destructive X-ray fluorescence (XRF) analysis with the purpose of analyzing the geochemical content of the sediment core has been carried out at GEOPOLAR, University of Bremen (Germany). The ITRAX XRF-core scanner prepared the COX analytical systems (Croudace et al. 2006) for each 2 mm step using a Cr tube. Among the 40 detected elements, only those that show meaningful variations were chosen. The main chosen elements were K, Ca, Ti, Si, Mn, Fe, Sr. For better sight through the precipitation rate, climate changes, and erosional events different ratios (K/Ti, Si/Ti, Mn/Ti, Ca/Ti, Sr/Ti, Si/Fe, and inc/coh) was calculated.

Results

Lithology, chronology, LOI and sedimentology

Sediments are mainly composed of mud and muddy sand with alternating colors (Fig. 2). From 95 to 41 cm core depth the sediments consist of shells. A probable reservoir effect must be considered due to the frequent occurrence of aquatic plants such as *Potamogeton*.

Table 1 shows the five AMS radiocarbon dates. The uppermost sample at 7 cm were excluded from the age-depth model due to the older age than the lower sample at 15 cm. The Bayesian age-depth model is based on the polynomial regressions for the KHL core (Fig. 2). Based on the core chronology, the deposits accumulated in the late Holocene. The core base at 135 cm has an age of 1180 cal yr BP and the core top at 0 cm would be extrapolated 510 cal yr BP. The sedimentation rate with an average of 0.2 cm yr⁻¹ shows no significant changes through the whole core.

From the bottom at 135 up to 102 cm core depth, the organic content has the highest value (mean: 0.35%), and the carbonate content represents medium values (mean: 0.41%). Later, between 102 and 46 cm, organic and carbonate contents reach their lowest and the highest value (0.22%, 0.58%), respectively. Finally, from 46 cm up to the core top, the organic content increases slightly to 0.32%, while the carbonate content reaches its lowest value of 0.18%.

![Table 1](image-url)
The pollen concentration and influx averages did not change markedly. Between 135 and 102 cm, the pollen concentration and influx are 15,123 grains cm\(^{-3}\) and 3287 grains cm\(^{-2}\) yr\(^{-1}\), respectively. While the values increase slightly between 102 and 46 cm (pollen concentration and influx respectively are 17,729 grains cm\(^{-3}\) and 3610 grains cm\(^{-2}\) yr\(^{-1}\)). From 46 cm to the surface, the average value of the pollen concentration and influx increase to the highest value (19,345 grains cm\(^{-3}\), 3938 grains cm\(^{-2}\) yr\(^{-1}\), respectively).

Description of the pollen, spores, NPPs, and macro-charcoal records

In total 63 pollen have been identified: 24 arboreal, 32 herb and 7 aquatic taxa. Also, two different types of fern spores and three NPPs (fungal spores and algae) have been recognized. The most frequent pollen taxa are illustrated in Fig. 3 (for the whole pollen diagram see the supplementary material). Pollen of the Juglans, Corylus, Prunus, Cerealia-type, Plantago lanceolata-type, P. major-media-type, Fabaceae (reticulate and psilate), Rumex, and Brassicaceae are grouped as primary and secondary indicators of human activity.

Based on our floristic knowledge the CONISS cluster analysis dendrogram suggest two major zones KHL-A, which is divided in two subzones KHL-AI and KHL-AII, and KHL-B (Figs. 3, 4).

Subzone KHL-AI (135–102 cm; 8 pollen samples; ca. 1180–1010 cal yr BP)

The AP (trees, shrubs and lianas) (51%) and NAP (herbs) (49%) are almost in balance with each other. Herbs are mainly represented by Artemisia (8–26%), Poaceae (7–14%), and Amaranthaceae (6–15%). Among AP Quercus (12–28%), Fagus (3–10%), Carpinus-type (5–14%), and Juniperus (4–13%) are the most frequent. Less frequent are Alnus (1–5%), Pterocarya fraxinifolia (1–4%) and Juglans (up to 2%), which show the highest value in this subzone. Aquatic pollen (except Cypereaceae and Lemna) have low frequencies. On the other hand, the human indicators pollen are well represented (5–12%), mainly by Plantago lanceolata-type (1–4%), Cerealia-type (1–4%), and Juglans (up to 2%) (Fig. 3). Fungal

![Fig. 3 Percentage diagram of the selected pollen taxa as well as fern spores and Non-arboreal pollen (NPPs) of the KHL core. Arboreal Pollen (AP) in green, Non-Arboreal Pollen (NAP) in yellow, Fern spores in pale green, Pediastrum (in black), NPPs in brown and ratios of aquatics to pollen sum in blue. The selected Human Indicators pollen is shown with a red outline with 10×, exaggeration.](image-url)
spores have the highest value (5–45%), mainly represented by the *Podospora* (coprophilous spores) (0–39%).

The charcoal concentration and influx (with averages of 197 particles cm\(^{-3}\) and 46 particles cm\(^{-2}\) yr\(^{-1}\), respectively) show their highest value only in the lowermost part of this subzone and then decrease continuously through the uppermost part of the core (Fig. 4).

**Subzone KHL-AII (102–46 cm; 14 pollen samples; ca. 1010–740 cal yr BP)**

This subzone is characterized by the high values of the AP and the low values of NAP. Arboreal pollen (50–81%) are represented mainly by *Quercus* (16–57%) and *Fagus* (3–28%). In comparison to other subzones, *Juglans* pollen decreases to the lowest value (0–1%), while *Salix* and *Fraxinus* increase (in particular in the uppermost part (0–2% and 0–3%, respectively). Herbaceous pollen representation is similar to the previous subzone by Poaceae (5–15%), *Artemisia* (1–12%), and Amaranthaceae (3–9%). The human indicator pollen decreases to the lowest values (1–9%). Aquatic pollen here is mainly represented by *Potamogeton*. *Pediastrum* has the lowest value (average: 3) among the other subzones and only shows a single peak in the uppermost part of this subzone. The fungal spores are well represented (2–16%) and consist mainly of *Glomus* (2–14%) rather than coprophilous spores (Fig. 3).

The charcoal concentration and influx decrease markedly (with the averages of 17 particles cm\(^{-3}\) and 4 particles cm\(^{-2}\) yr\(^{-1}\), respectively).

**Zone KHL-B (46–0 cm; 12 pollen samples; ca. 740–510 cal yr BP)**

Herbaceous pollen (37–77%) prevailed to the AP (24–63%). *Quercus*, *Fagus*, and *Juniperus* values are
markedly lower compared with the previous subzone. *Carpinus*-type is the most frequent AP (4–15%). *Juglans* (0–1%) and *Corylus* (0–1%) increase. According to the NAP, Poaceae (8–29%), *Artemisia* (8–21%), and Amaranthaceae (7–10%) are the most frequent taxa. *Cerealia*-type (1–5%), *Plantago lanceolata*-type (2–7%), and *P. major-media*-type (0–4%) represent their highest value among the profile. The human indicators pollen increases to the highest average value (11%) with the range of 4–15%. Aquatic pollen show a decreasing trend except for the record uppermost part of the record, which show a single maximum due to an increase in *Myriophyllum* pollen. *Pediastrum* algae is representing continuously with an average of 3.5%.

The charcoal concentration and influx have the lowest value in this subzone (with the averages of 13 particles cm\(^{-3}\) and 3 particles cm\(^{-2}\) yr\(^{-1}\), respectively).

X-ray fluorescence analysis

From the elemental data set, the most reliable acquired elements were chosen. The elemental peak of K, Ca, Ti, Si, and ratios of K/Ti, Si/Ti, Mn/Ti, Ca/Ti, Sr/Ti, Si/Fe, and incoherent/coherent (inc/coh) are shown in Fig. 5. The zonation is based on the pollen cluster analysis (KHL-AI, AII, and B).

In order to be able to quantify the strength of dependence between pairs of elements correlation matrices were constructed for each subzone Table 2. The strong correlations (\(r \leq -0.70\) or \(\geq 0.70\)) are detectable with asterisks. Although the constructed matrices represent coupling and decoupling between elements through the KHL profile, the Fe correlates with K and Ti in all the units strongly and hence detrital inputs (Kylander et al. 2011). Silicate for the first two subzones (KHL-AI and AII) correlates strongly with K, Ti, and Fe while in the last zone (KHL-B) it has a moderate relationship which represents it is controlled mainly by the silicate sources (Kylander et al. 2011). Calcium strongly correlates with Sr in KHL-AI and KHL-B and suggests the importance of the carbonate precipitation (Kylander et al. 2011), while the KHL-AII shows minimal correlation. The Ca curve shows more distinct changes compared to other curves. At the base of the profile (KHL-AI), except for two peaks, it is not as high as the middle part (KHL-AII). The peak areas of Ca in the KHL-AII are high and more constant. The presence of the shells as the probable reason for this increment must be considered. From KHL-B the Ca profile shows a
slightly decreasing trend. Potassium, Ti and Si show the same broad pattern for all the subzones. The elemental peaks at the base part (KHL-AI) are the highest. Except for the middle part of the KHL-AII that shows several manifest increasing peaks, the rest of the profile represents a long-term decreasing trend that continues up to the surface of the core.

The depth profiles of all the ratios show almost the same pattern but different to the elemental profile. At the core base (KHL-AI), except for two small increases, they show a constant low amount. While during the middle part (KHL-AII) several increments and decreases are visible. The remaining portion of the core (KHL-B) is resumed the decreasing trend to the lowest amount.

The organic content profile (inc/coh ratio) at the lowest subzone (KHL-AI) with several changes shows a decreasing trend during the KHL-AII. However, it is constant but reaches the lowest amount. From the beginning of the upper zone (KHL-B), there is a gradual increase.

### Discussion

#### Chronological framework

The Kholash-Kouh lake is located near alluvial sediments. Possible inputs from the surrounding thin bedded limestone nummulite formation may influence the dating. The frequent occurrence of aquatic plants such as Potamogeton is likely to contribute to a reservoir effect in the dates that were obtained from bulk sediment samples (Marty and Myrbo 2014). Due to the lack of sufficient plant remains and charcoal particles, dating was done based on bulk organic matter. The chronology has uncertainties because of a potential reservoir effect and should be used with caution. Further studies may help for a better understanding of potential reservoir effects in the region.

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**Table 2** Correlations matrices (r values) for the Kholasht-Kouh sequence in each defined zones and subzones

| Depth (cm) | Si   | K    | Ca   | Ti   | Mn   | Fe   | Sr   | Al   |
|-----------|------|------|------|------|------|------|------|------|
| 0–46      |      |      |      |      |      |      |      |      |
| Si        | 1.00 |      |      |      |      |      |      |      |
| K         | 0.66 | 1.00 |      |      |      |      |      |      |
| Ca        | 0.19 | 0.17 | 1.00 |      |      |      |      |      |
| Ti        | 0.62 | 0.89*| −0.12| 1.00 |      |      |      |      |
| Mn        | 0.30 | 0.31 | 0.26 | 0.25 | 1.00 |      |      |      |
| Fe        | 0.64 | 0.86*| −0.16| 0.94*| 0.30 | 1.00 |      |      |
| Sr        | 0.28 | 0.33 | 0.95*| 0.06 | 0.32 | 0.02 | 1.00 |      |
| Al        | 0.17 | 0.08 | 0.10 | 0.08 | 0.04 | 0.10 | 0.11 | 1.00 |
| 46–102    |      |      |      |      |      |      |      |      |
| Si        | 1.00 |      |      |      |      |      |      |      |
| K         | 0.81*| 1.00 |      |      |      |      |      |      |
| Ca        | −0.32| −0.43| 1.00 |      |      |      |      |      |
| Ti        | 0.79*| 0.97*| −0.48| 1.00 |      |      |      |      |
| Mn        | 0.20 | 0.28 | 0.20 | 0.25 | 1.00 |      |      |      |
| Fe        | 0.75*| 0.96*| −0.48| 0.97*| 0.31 | 1.00 |      |      |
| Sr        | 0.05 | 0.08 | 0.20 | 0.07 | 0.12 | 0.04 | 1.00 |      |
| Al        | 0.19 | 0.17 | −0.05| 0.15 | 0.06 | 0.16 | −0.03| 1.00 |
| 102–135   |      |      |      |      |      |      |      |      |
| Si        | 1.00 |      |      |      |      |      |      |      |
| K         | 0.96*| 1.00 |      |      |      |      |      |      |
| Ca        | −0.05| −0.08| 1.00 |      |      |      |      |      |
| Ti        | 0.94*| 0.96*| −0.27| 1.00 |      |      |      |      |
| Mn        | 0.53 | 0.52 | 0.53 | 0.42 | 1.00 |      |      |      |
| Fe        | 0.91*| 0.94*| −0.32| 0.98*| 0.37 | 1.00 |      |      |
| Sr        | 0.18 | 0.15 | 0.95*| −0.04| 0.68 | −0.10| 1.00 |      |
| Al        | 0.28 | 0.25 | 0.16 | 0.20 | 0.20 | 0.20 | 0.20 | 1.00 |
Local environment of Kholash-Kouh Lake

**Period 1180–1010 cal yr BP (778–940 AD, subzone KHL-AI)**

The high occurrence of Cyperaceae, but rare aquatic plants such as *Potamogeton* and *Myriophyllum* and some algae of *Pediastrum* suggest shallow water at the initiation of the lake. Later during this period, *Lemna* and later *Potamogeton* as well as *Pediastrum* increased, while Cyperaceae decreased, except a short phase in the middle of the period, which suggests an increasing and fluctuating lake levels, probably due to higher rainfall rates. The two phases with a high frequency of *Lemna* reflect a nutrient-rich environment (Wolverton and McDonald 1981), which is in line with the highest amount of the organic content during this period.

During this period accumulated in the lake detritus mud and muddy sand. The selected XRF-data of elements such as K, Ti and Si indicate relatively humid condition. At around 1120–1040 cal yr BP (124–108 cm), the high amounts of K, Ti and Si show also high correlation in-between, and may indicate an increase in detrital inputs (Davies et al. 2015). High values of K/Ti ratio is an indicator for more physical weathering due to drier condition (Davies et al. 2015). In this case, the low value of K/Ti ratio (except the two peaks) may indicate humid condition for this period. Manganese as an insoluble oxide element can represent changes in the lake level or biological activity in the lake (Davison 1993; Kylander et al. 2011). Lower lake level and/or photosynthesis, both can increase the Mn/Ti ratio. The low Mn/Ti ratio, besides the Ca/Ti and Sr/Ti ratios (indicator for lower lake level (Haberzettl et al. 2009; Kylander et al. 2011, 2013)), and rare presence of *Potamogeton* which grows in shallow lakes (Xu et al. 2020), can point to the higher lake level. The Si/Fe ratio, which can be used as temperature indicator (Erbs-Hansen et al. 2013), showed an increasing trend.

At the end of this period Cyperaceae decreased markedly, and *Potamogeton* became abundant. At the same time, values of K, Ti, and Si together with the ratios of the K/Ti and Si/Fe decreased markedly, suggesting relatively cold temperatures with a short drought event.

**Period 1010–740 cal yr BP (940–1214 AD, subzone KHL-AII)**

The low occurrence of Cyperaceae at the lake shore vegetation and frequent *Potamogeton*, probably covering large parts of the lake surface, likely reduced strongly the occurrence of *Lemna*, suggesting a relatively low lake level. *Potamogeton* is common in water depths between 60 and 120 cm depth, and their distribution is limited to water depths deeper than 200 cm (Zhou et al. 2017). *Pediastrum* is frequent in eutrophic lake conditions (Sá et al. 2019), therefore its low occurrence for most of the time in this period is in line with low amounts of organic matter.

During this period deposits in the lake are mostly muddy sand material. The Mn/Ti, Ca/Ti, and Sr/Ti ratios are in line with the abundance of the *Potamogeton*, and verified the lower lake level for this period. Mn/Ti, Ca/Ti, and Sr/Ti ratios were high except for short periods between ca. 984 to 965 and ca. 807 to 748 cal yr BP (96–92 cm and 60–48 cm, respectively). In both mentioned periods the rainfall probably was more frequent (due to the lowest K/Ti ratio). Besides reducing the temperature (referring to the reduction of the Si/Fe ratio) it may also reduce the lake water evaporation and result in higher water levels. The increased K, Ti, and Si (indicators for detrital inputs) around 807 to 748 cal yr BP suggest that the deposit was fed mostly by the surface water. Potassium can confirm the dense vegetation covers (Davies et al. 2015) in close distance to the Kholash-Kouh lake, the denser vegetation increased the K leaching through chemical weathering and resulted in lower K values. Referring to the high Si/Fe ratio values, this period (ca. 1010–740 cal yr BP) was the warmest throughout the whole recorded late Holocene. This warm period occurred during the MCA, ca. 950–1250 AD or 1000–700 cal yr BP (Ruddiman 2001). Several records document this period as the warmest of the late Holocene (Ramezani 2013; Haghani et al. 2015; Homami Totmaj et al. 2021).

**Period 740–510 cal yr BP (1214–1436 AD, zone KHL-B)**

The lower occurrence of Cyperaceae decreased markedly, and *Potamogeton* became abundant. At the same time, values of K, Ti, and Si together with the ratios of the K/Ti and Si/Fe decreased markedly, suggesting relatively cold temperatures with a short drought event.
had the lowest value, and represented the coldest climate in the record during the LIA, ca. 1350–1850 AD or 600–100 cal yr BP (Mann et al. 2009). Also, the comprehensive study at Neor Lake (180 km northwest to the study site), documented the occurrence of the strongest Siberian High during the last 5000 years (Sharifi et al. 2015). Potassium, Ti, and Si also indicate lower detrital inputs for this period. The ratios of Ca/Ti, Sr/Ti, and Mn/Ti represented the lowest values in the record. Carbonate and silicate weathering affected the amount of Ca and Sr elements in the catchment (Kylander et al. 2013). The lowest value of carbonate matter content verified low inputs of carbonate for this period. The possible reason for the Mn/Ti ratio reduction has been sedimentation during anoxic conditions in the lake. Ice cover and high organic matter content are the two important drivers for methanogenesis in lakes (Wetzel 2001; Kylander et al. 2013), which formed anoxic conditions. Also, the incoherent/coherent (inc/coh) ratio, commonly used as parameter for evaluating the organic content in the lake sediments (Burnett et al. 2011), verified the highest organic matter of the core during this period.

Vegetation changes (forest vs. open vegetation), and anthropogenic activities

Period 1180–1010 cal yr BP (778–940 AD, subzone KHL-AI)

The pollen record (Figs. 3, 4) indicate that the study area was covered by relatively high proportion of non-arboreal vegetation. The open vegetation surrounding the lake was composed mainly of Artemisia, Amaranthaceae and Poaceae.

Forest areas at lower elevations, were mainly composed of Quercus, Fagus, Carpinus and Juniperus. After ca. 1100 cal yr BP (120 cm core depth) Quercus decreased, while Fagus and Carpinus species increased in the forest. This reduction of Quercus occurred with the increase of the human pollen indicator. The highest frequency of coprophilous spores and macro-charcoal particles at the beginning of this record indicate human settlements engaged in animal husbandry at lower elevations. A few Cerealia pollen, as well as Plantago and other indicators suggest anthropogenic activities in the region of the lake at lower elevations. The archaeological site of Ghale Kouti (16 km distance to Kholash-Kouh) at 1600 m a.s.l., consists of cemeteries from the Iron Age (Fallahian 2013) and verifies presence of humans at the lake’s lower elevations since ancient times.

Period 1010–740 cal yr BP (940–1214 AD, subzone KHL-AII)

During this period, the dominant herbs decreased markedly, while trees increased in density and/or expanded from lower to upper elevations. The warm condition during this period, may provided favorable conditions for forest expansion. This forest expansion is also documented in our previous studies from Annal Lake (700 m elevation) and Pounel mire (2200 m elevation) for the same time period (Homami Totmaj et al. 2020, 2021), about 125 km and 145 km distance to the site, respectively. However, in the KHL record Quercus is the most abundant forest taxon, while in the Annal Lake Carpinus betulus and Alnus (characteristic tree for lower than 1000 m elevations) were the most abundant ones. After ca. 860 cal yr BP (72 cm core depth), Fagus trees became more frequent indicating more closed canopy compared to previous phase, Fagus sapling, as the shade tolerant taxa out compete the light-demanding Quercus sapling (Ligot et al. 2013). Alinezhad et al. (2021) showed also in their study on Neor Lake that over the last 1800 years, Quercus had the strongest occurrence at ca. 1000 cal yr BP, followed by a reduction after ca. 600 cal yr BP. The human activities showed a reduction during this period, documented with lowest frequency of Cerealia and other human indicator taxa, rarity of the coprophilous spores and macro-charcoal particles. Though, this reduction is opposite to our previous studies at Annal Lake and Pounel mire (Homami Totmaj et al. 2020, 2021), which showed increased anthropogenic activities. Based on the current settlements (there is a small summer use village in 3.5 km distance to the lake) we may argue that people were always present at several distances to the lake, nevertheless expansion of the forest, resulted in higher arboreal pollen deposition, while reduced presence of the human pollen indicators specially the Cerealia.
Period 740–510 cal yr BP (1214–1436 AD, subzone KHL-B)

Since this period, herbs, specially Poaceae, Artemisia, and Amaranthaceae increased markedly probably due to deforestation. The strong reduction of arboreal plants, especially Quercus and Fagus, is the most characteristic between 740 and ca. 510 cal yr BP, most probably due to selective logging as the wood is better. However, Carpinus increased which may refer to the growth of Carpinus orientalis, characteristic tree for the 2300 to 2400 elevation (Ramezani et al. 2013). A probable reason for the forest reduction may have resulted from the construction activities by humans and/or the need of wood for fire, as this period remained during the Little Ice Age with prevailed cold climatic conditions. However, fires were rare during this period, indicating that the possible practice of frequent burning of the steppe vegetation at the beginning of the record changed.

The highest values of Cerealia and Plantago is in line with reduction of the trees indicate intensified of anthropogenic activities lead to extensive deforestation and expansion of steppe vegetation.

Conclusions

Our multi-proxy analysis of the Kholash-Kouh lake core, located above the modern forest line, allowed us to reconstruct the vegetation and climate changes, local fire history and anthropogenic activities since 1180 cal yr BP. Referring to the palynological reconstruction, three distinct periods have been identified. The surrounding of the lake was covered mainly by herbaceous vegetation with species of Poaceae, Artemisia, and Amaranthaceae, for the whole recorded period. The only exceptional period between 1010 and 740 cal yr BP, documented the dominance of the forest mainly with Quercus, Fagus, Carpinus and Juniperus, rather than steppe vegetation.

The geochemical elements such as K, Ti and Si represented relatively humid condition between 1180 and 1010 cal yr BP. Furthermore, low values of the Mn/Ti, Ca/Ti and Sr/Ti ratios suggested higher lake level. After 1010 up to 740 cal yr BP the highest value of the Si/Fe ratio, represented warmest period throughout the record. While its lowest value, in line with the reduction of other elements and ratios, after 740 cal yr BP represented cold and dry period. In conclusion, according to the XRF results, this study is in line with the past surveys, verified the warmest and coldest conditions, due to the Medieval Climatic Anomaly (1000–700 cal yr BP) and Little Ice Age (600–100 cal yr BP), respectively.

Finally, the human impacts on the lake and surroundings were investigated, indicating the strongest environmental disturbance resulted from the marked deforestation and expansion of steppe vegetation. The higher occurrences of Cerealia and Plantago reflect intensified agro-pastoral activities at lower elevations between ca.740 and 510 cal yr BP. With regard to anthropogenic activities, it seems that humans were present only at several distances to the lake and seem to have not played an important role in the lake’s environmental changes.

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