J Paleolimnol (2015) 53:255–270
DOI 10.1007/s10933-014-9823-1

ORIGINAL PAPER

Ecosystem response to human- and climate-induced environmental stress on an anoxic coastal lagoon (Etoliko, Greece) since 1930 AD

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Received: 14 April 2014 / Accepted: 22 December 2014 / Published online: 7 January 2015

Abstract To better constrain the effects of anthropogenic impact on coastal wetlands with respect to natural variability, we here analyze annually laminated sediments from Etoliko lagoon (western Greece, Mediterranean Sea) spanning the last ~80 years. Subdecadal-scale palynomorph (pollen and dinoflagellate cyst) and seasonal-scale palynomorph (microfacies and μ-XRF) analyses were carried out to investigate the evolution of the aquatic environment and the surrounding terrestrial ecosystem. Based on a robust age model, which was developed using varve counting and ^{137}Cs dating, our results indicate that land-use changes have altered the vegetation dynamics and led to eutrophication of the aquatic environment particularly from the early 1980s onwards. In agreement with instrumental data and reports of fish mass mortality events, our varve composition and high-resolution element scanning data suggest that the ecosystem has been under unprecedented pressure since 1990 AD. In particular, the enhancement of anoxic conditions due to human-induced eutrophication is linked to high accumulation rates of organic matter, an increased presence of bacteria in sediment microfacies, and a decrease in the Fe/Mn ratio in the sediment. In addition, a change in varve type from calcite- to aragonite-dominated in 1983 and a higher Sr concentration during the 1990s indicate an increasingly saline aquatic environment. Comparison with meteorological data suggests that lower precipitation during a persistent positive North Atlantic Oscillation mode along with a gradual increase in mean summer temperature since the 1980s may have enhanced the saline conditions. These findings demonstrate that climate change can intensify the human impact on

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aquatic ecosystems. In conclusion, our analytical approach provides a valuable tool for evaluating the degree of degradation of Etoliko lagoon and the effectiveness of implemented management plans on the aquatic ecosystem, indicating that the efforts to restore its water circulation have only weakly contributed towards an environmental recovery.

Keywords Varve microfacies · Palynomorphs · μ-XRF scanning · Human impact · North Atlantic Oscillation · Eastern Mediterranean

Introduction

Coastal wetlands provide a wide range of ecological services to human society including food production, climate regulation (e.g., through carbon storage), and cultural and recreation activities (Keddy 2010). However, human manipulation of these ecosystems, which includes altering species composition and distribution as well as modifying ecosystem function, has led to an unprecedented degradation and loss of natural habitats over the last 150–300 years (Lotze et al. 2006; Barbier et al. 2011). This holds particularly true for coastal wetlands in the Mediterranean region, where human exploitation (e.g., overpopulation, tourism, agriculture, and aquaculture) and natural (e.g., climate) factors have severely undermined their ecological resilience (Brinson and Malvarez 2002; Lotze et al. 2006). In Greece, the spatial loss of lagoons, estuaries and coastal marshes caused by the expansion of agriculture, housing and tourism activities during the twentieth century was on the order of 45–60 % (Zalidis et al. 1997). The general lack of environmental monitoring studies and proxy records for natural variability for Greek wetlands over the last century (Zalidis et al. 1997; Zacharias et al. 2007) precludes an understanding of the interactions between natural ecosystem dynamics and anthropogenic forcing (Vitousek et al. 1997). This, in turn, renders it difficult to assess the level of environmental resilience, which is a crucial prerequisite for the implementation of successful conservation and management plans.

Circumventing the lack of monitoring data, annually laminated (i.e., varved) sediment records allow insights into natural and anthropogenic processes on seasonal timescales, yielding valuable archives of high-resolution environmental and climate information (O’ Sullivan 1983; Brauer 2004; Ojala et al. 2012; Kienel et al. 2013). Notably, varve-based studies for the Eastern Mediterranean region and particularly the Balkan Peninsula are generally missing (Ojala et al. 2012), and only sediments from two coastal lagoons have been investigated, i.e., Butrint (Albania; Ariztegui et al. 2010) and Etoliko (western Greece; Vött et al. 2007; Haenssler et al. 2013). Whereas the annually laminated character of the sediments from Butrint is firmly established (Ariztegui et al. 2010), uncertainties in absolute dating have raised concerns on whether the laminations at Etoliko represent true varves (Vött et al. 2007; Haenssler et al. 2013).

Etoliko lagoon is part of a mosaic of ecologically sensitive ecosystems (widely known as Messolonghi lagoons) that comprises freshwater wetlands, coastal marshes, dunes, and riparian forests hosting numerous endemic, partially endangered floral and faunal elements (Dafis et al. 1997). At present, these ecosystems are under human-induced pressure mainly because of agriculture, salt production, farming and fishing practices (Dafis et al. 1997). The degradation of the Etoliko lagoon is well reflected by several fish mass mortality events that occurred since 1990 AD. These events have been caused by H_2S release and oxygen deficit in the water column due to human-driven eutrophication (Leonardos and Sinis 1997; Dimitriou 2007; Gianni and Zacharias 2011). Despite the severe impact of these fish kills on the local economy (Leonardos and Sinis 1997), no continuous environmental monitoring was established after their outbreak in 1990s, thus precluding a deeper understanding of the Etoliko ecosystem response to the human-induced stress.

In light of the above, we here apply an integrated sedimentological, geochemical and palynological approach to a new sediment core from Etoliko lagoon (western Greece) spanning the last ~80 years, from 1929 to 2011. In particular, we (1) establish a robust core chronology based on varve counting and radionuclide dating; (2) reconstruct ecosystem changes in the water body and catchment area using pollen, dinoflagellate cyst (dinocyst), micro-X-ray fluorescence (μ-XRF) scanning, and varve microfacies data, and; (3) integrate these results with available meteorological and historical records to obtain a high-resolution paleoenvironmental record of human- and climate-induced changes in the Balkans since the early twentieth century.

Study site

The Etoliko lagoon (also spelled Aitoliko or Aetoliko in the literature) is part of an extensive complex of wetlands and coastal habitats on the Ionian coast of western Greece, which are protected by international laws such as the Ramsar Convention and the European Habitats Directive 92/43/EEC (*Natura* 2000" biotope: GR2310001; Dafis et al. 1997; Fig. 1). The lagoon is about 7 km long and 2–3 km wide, and up to 30 m deep. A small island located in the southern part of the lagoon separates Etoliko from the shallow (<2 m deep) Messolonghi lagoon (Fig. 1). The two lagoons are connected through two narrow openings (total length 170 m, mean depth 1.2 m) with a total cross sectional area of ∼200 m^2 (Gianni et al. 2011). The Messolonghi lagoon, in turn, is directly connected to the open sea (i.e., the Gulf of Patras, ∼12 km south of Etoliko). This geography allows the circulation of seawater in both the Messolonghi and Etoliko lagoons. Owing to its depth, its orientation with regard to the coastline and the lack of a direct front to the open sea, Etoliko represents a rather atypical lagoonal setting. This present-day morphology has resulted from the landscape evolution of the region since the late Pleistocene. During the Last Glacial, a lake predecessing the present-day lagoon formed in a subsiding tectonic basin that was generated by NW/SE-trending fault activity since the late Pliocene (Vött et al. 2007). As a consequence of the sea-level rise and the erosion of sand barriers during the Holocene, this lake was connected to the sea from ∼3200 years BP onwards, ultimately forming Etoliko lagoon (Vött et al. 2007).

The catchment area of the Etoliko lagoon currently comprises ∼71 km^2; it is drained by few, seasonally dry creeks that account for the natural flow of freshwater into the lagoon. The Etoliko lagoon is surrounded by hills that are composed of Cenozoic limestones to the east (∼700 m max altitude) and Triassic evaporites and Plio-Pleistocene sediments to the west (∼180 m max altitude). The vegetation in the catchment area is dominated by Mediterranean sclerophylls (including evergreen *Quercus*, *Juniperus* and *Pistacia*) and cultivated olive trees; in addition,

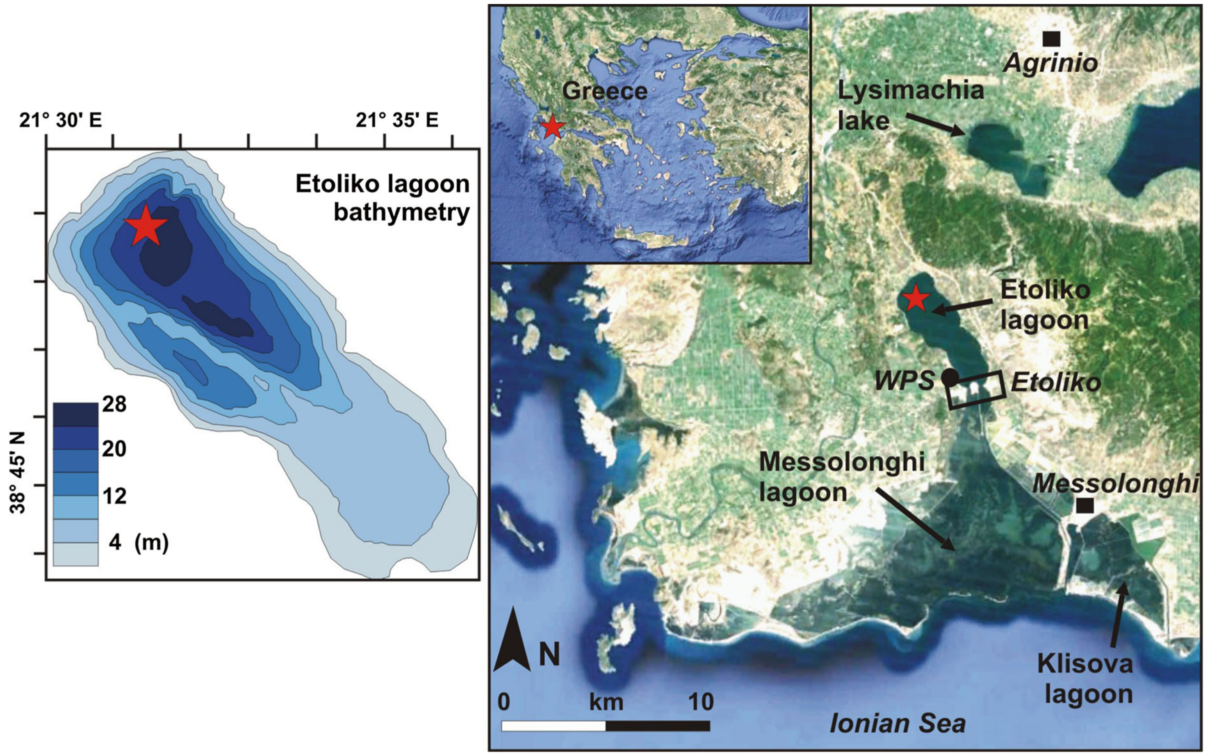


Fig. 1 Map of the study area and coring location indicated with a *star*. Background map adapted from 'Google Earth'. Bathymetry of the Etoliko lagoon adapted from Avramidis et al. (2014). *WPS* water pumping station

riparian and mountainous forests, coastal marsh and dune plant communities and crops are found within the limits of the Messolonghi–Etoliko lagoon complex (Dafis et al. 1997).

Climatically, the area is characterized by typical Mediterranean conditions, with dry summers and wet winters. Based on available meteorological data from the towns of Etoliko and Agrinio (20 km north of Etoliko), the mean annual temperature since 1952 is 17.3 °C (mean winter 9.0 °C; mean summer 26.4 °C) and the mean annual precipitation since 1947 is 915 mm, with ~65 % of the rain falling between November and March.

Regarding its physicochemical parameters, the water column of the Etoliko lagoon is permanently stratified and can be generally divided into two main layers (Table 1): a surface layer with seasonally varying temperature (~11–30 °C), salinity (~12.5–22.4 ‰) and dissolved oxygen content (5.4–16 mg L^{-1}), and an anoxic bottom layer with rather stable temperature (~13–16 °C), higher salinity (~22.5–32.5 ‰) and high H_2S content (up to 1632 µmol L^{-1}) (Hatzikakidis 1952; Danielidis 1991; Albanakis et al. 1995; Gianni et al. 2011, 2013; Friedrich et al. 2014; Avramidis et al. 2014). Available measurements of the dissolved oxygen concentration in the water column show that the oxic/anoxic interface has gradually migrated upwards in the water column, reaching as high as ~4 m below the water surface in 2004 (Table 1). The latest data (from 2011) place this interface at ~10 m from the water surface. Finally, the Etoliko lagoon can be classified as meso- to eutrophic, based on chlorophyll-*a* (between 1984 and 1985: 0–6.2 µg L^{-1}; between 2006 and 2007: 3.2–14.9 µg L^{-1}) and total phosphorus (1984/1985: 12–39 ppb; 2006/2007: 13.3–36.3 µg L^{-1}) concentrations at the water surface (Table 1).

Materials and methods

Coring at Etoliko was carried out in October 2012 using a UWITEC free-fall corer from a small catamaran platform. A 2-m-long core (ETO12-2) was recovered from 28 m water depth in the northern part of the lagoon (38° 28′ 52″ N / 21° 18′ 56″ E; Fig. 1). The topmost 72 cm of the cored sediments are continuously laminated, whereas slump depositions have disturbed the laminations further downcore. This study focuses on the topmost 35 cm of core ETO12-2 (Fig. 2).

To determine radionuclide activities, about 10–36 g of freeze-dried, continuous (every 2–5 cm) sediment samples were measured. The activity concentration of artificial ^{137}Cs (half-live 30.1 years) was determined gamma spectrometrically using Canberra-Eurisys Broad Energy Germanium detectors (BEGe-5030). The spectra were analyzed using single photopeak efficiencies generated by the LabSOCS

Table 1 Physicochemical parameters of the Etoliko lagoon between 1951 and 2011

	1951 Hatzikakidis (1952)	1984–1985 Danielidis (1991)	1994 Albanakis et al. (1995)	2004 Chalkias (2006)	2006–2008 Gianni et al. (2011, 2012, 2013)	2010–2011 Friedrich et al. (2014); Avramidis et al. (2014)
Temperature (°C)						
Surface	13.0–27.0	11.6–30.2	14.0–28.0	16.2–23.0	11.0–29.4	12.0–29.0
Bottom	15.0–16.0	15.5–15.6	14.6	14.0–14.8	13.0–13.7	14.0–15.0
Salinity (‰)						
Surface	14.5–19.9	12.5–13.2	17.0–18.0	–	18.8–22.4	18.5–21.5
Bottom	31.0–32.5	27.5–28.5	26.5–27.0	–	25.9–27.5	22.5–25.5
Dissolved oxygen (mg L^{-1})						
Surface	7.8–10.4	7.4–12	8.0–16.0	5.4–11.3	7.3–14.1	7.0–8.2
Bottom	0	0	0	0.2–0.4	0–1.3	0
H_2S (μmol L^{-1}) at bottom	847	–	–	–	882–1632	176
Chlorophyll-*a* (µg L^{-1})	–	0–6.2	–	–	3.2–14.9	–
Total phosphorus	–	12–39 (ppb)	–	–	13.3–36.3 (µg L^{-1})	–
Oxic/anoxic interface [min–max depth (m)]	14–19	10–13	7–10	4	17– lake bottom	10–14

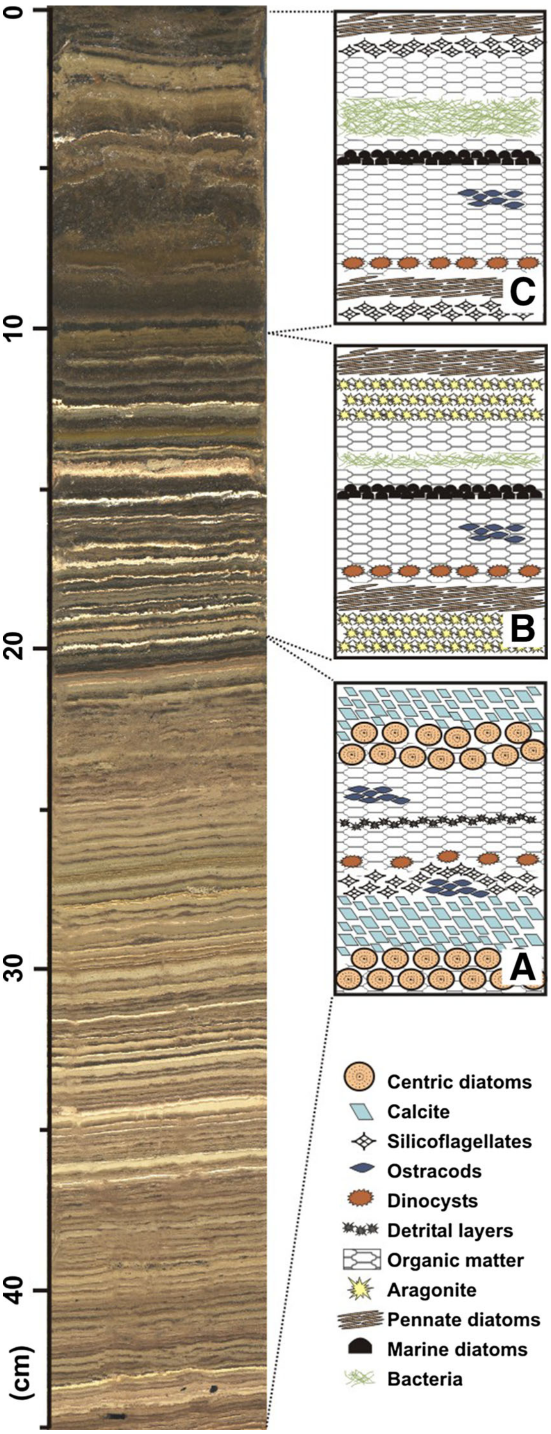


Fig. 2 Photograph of the uppermost 45 cm of core ETO12-2. **a**–**c** Schematic description of the three Etoliko varve types

(Canberra-Eurisys) calibration software, which takes into account the self-absorption of γ-rays both in samples and beakers. The samples were measured in cylindrical transparent polystyrene beakers (Karl Bock GmbH & Co. KG, 27 × 73 mm). The measuring time varied between 24 and 48 h until counting uncertainties of less than 5 % for ^{137}Cs were achieved. All ^{137}Cs activity concentrations were decay-corrected to the date of sampling (10.10.2012).

Thin-sections (size: 120 x 35 mm) for varve counting were prepared following standard techniques, comprising freeze-drying, impregnation with Araldite 2020 epoxy resin under vacuum, sawing, and grinding of the sediment. To warrant continuity of observation, successive thin sections with an overlap of 2 cm were analysed. Varve microfacies analysis was carried out using a petrographic microscope at 100-400x magnification allowing the precise description and measurement of the seasonal sub-layer thicknesses (Brauer et al. 2008; Koutsodendris et al. 2011). The varve types were used to establish the core zonation.

For palynological (pollen and dinocyst) analyses, ~4 cm^3 of sediment were continuously sampled every 1.8 cm. Based on the chronology of core ETO12-2, the palynological data exhibit a sub-decadal resolution ranging between 1 and 8 years (mean 4 years). The palynological preparation followed standard techniques including sediment freeze-drying, weighing (sample dry weight range 0.13–1.56 g), treatment with HCl (>30 %) and HF (40 %), sieving (10 μm), and mounting on glass slides. All samples were spiked with *Lycopodium* spores to facilitate the calculation of palynomorph accumulation rates. In total, 20 samples were analysed using a Zeiss Axioskop light microscope at 400x magnification. An average of 324 pollen grains excluding pollen from aquatics and spores (with a minimum always above 300 pollen grains) and 90 dinocysts (range 16–176 dinocysts) were counted per sample.

Element geochemical measurements were carried out on the sediment blocks that had been impregnated with Araldite 2020 epoxy resin using a μ-XRF EAGLE III XL spectrometer (200 μm step size, 10 s count time, 30 kV tube voltage, and 30 mA tube current).

Instrumental climate data were obtained from the closest station (Agrinio town) for the periods 1956–2004 (temperature) and 1947–2004 (precipitation); additional temperature and precipitation data from 2004 onwards were obtained from a new meteorological station in the town of Etoliko. Gaps in the mean monthly meteorological measurements were filled in using the spectral statistical-interpolation (SSI) analysis (Parish

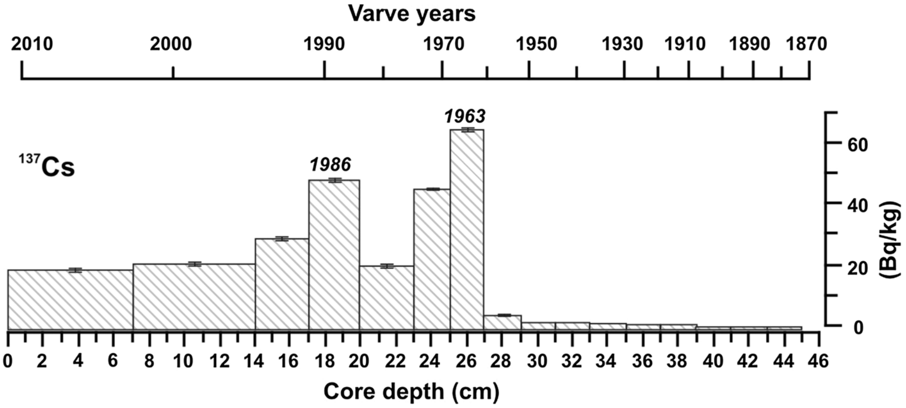


Fig. 3 ^{137}Cs activity concentration (in Bq kg^{-1} decay-corrected to the date of sampling 10.10.2012) ±1σ (*error bars*) plotted against core depth (cm) and varve chronology (years)

and Derber 1992). In total, 23 randomly distributed gaps of precipitation values (~3 % of total measurements) and one missing temperature value were statistical filled (95 % confidence level).

Results

Age model

The ^{137}Cs activity was measured on continuous sediment samples that integrate about five light and dark layer couplets. The vertical distribution of ^{137}Cs in core ETO12-2 shows two distinct peaks at 25.5 and 18 cm (Fig. 3). In particular, the younger ^{137}Cs maximum (48.4 ± 0.7 Bq kg^{-1}) can be assigned to the radioactive fallout connected to the Chernobyl accident in 1986. The radioactive substances of the accident spread over Greece, with the total deposition of ^{137}Cs around Etoliko being >5 kBq m^{-2} (deposition values calculated for August–November 1986; Petropoulos et al. 2001). The older peak (64.8 ± 0.6 Bq kg^{-1}) can be assigned to nuclear weapon testing, which reached maxima in 1959 and 1963 (Bachhuber et al. 1982; Appleby 2001). The two ^{137}Cs maxima are in full agreement with the varve counting, which indicates that the uppermost 35 cm of core ETO12-2 span 82 years, from 1929 to 2011 AD (Fig. 3).

Microfacies analysis

The finely laminated sediments from Etoliko lagoon as documented in core ETO12-2 comprise couplets of discrete light and dark layers (Fig. 2). Based on the microfacies analysis, three types of light and dark layer couplets are identified (Fig. 2a–c). The first type consists of alternating calcite (light) and organic-rich (dark) layers (Figs. 2a, 4a) and is found at core depths from 35 to 21 cm spanning the time period between 1929 and 1982 (Fig. 3). More specifically, the calcite layers are often associated with the presence of large (>100 µm) centric diatoms frustules (mainly *Coscinodiscus granii*), which often form distinct sub-layers directly below the calcite layers (Fig. 4b). In a few cases, the light layers are characterized by the formation of centric diatom sub-layers without calcite deposition. The calcite layers are followed by a sub-layer that is rich in silicoflagellate skeletons (*Dictyocha fibula*; Fig. 4c–d). The subsequent dark layer is predominantly composed of amorphous organic matter and diatoms frustules as well as plant remains, dinocysts and thin detrital layers. In addition, lenses of ostracod and gastropod shells are also observed, often at the transition between the calcite- and the organic-rich layers and within the latter (Fig. 2a). The mean thickness of the calcite/organic-rich layer couplets is 2.70 mm (Stdev 0.94), with the organic-rich layers being generally thicker (mean 2.35 mm; Stdev 0.83) than the calcite layers (mean 0.35 mm; Stdev 0.28).

The second type of light and dark couplets consists of alternating aragonite and organic-rich layers (Fig. 2b). This type is found between 21 and 10 cm, which corresponds to the time period from 1983 to 2001 in core ETO12-2. In contrast to the first type, the aragonite layers are not associated with the deposition of large centric diatoms and are never overlain by

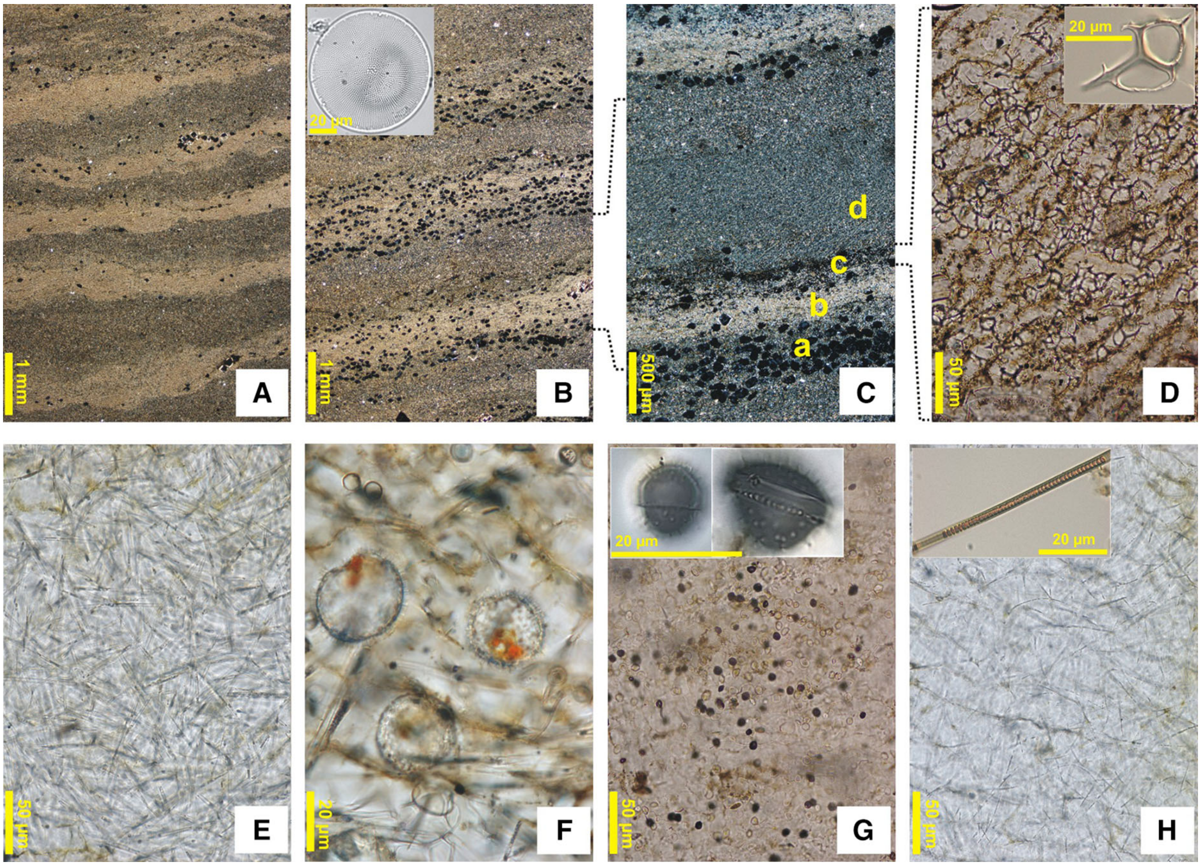


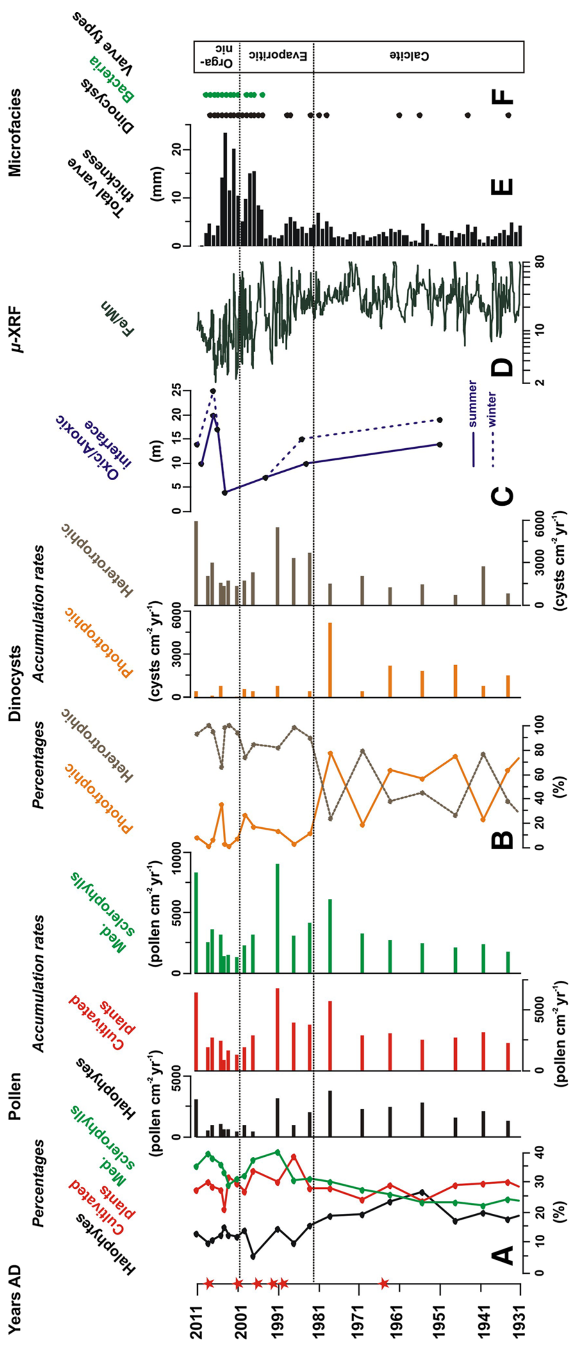
Fig. 4 Photographs of the Etoliko varves: **a**, **b** typical calcite varves with and without presence of centric diatoms photographed under cross-polarized light; close-up photograph of *Coscinodiscus granii*; **c** close-up photograph of calcite varves under cross-polarized light: *a* centric diatom sub-layer, *b* calcite, *c* silicoflagellate sub-layer, *d* organic-rich sub-layer; **d** silicoflagellate sub-layer and close-up photograph of *Dictyocha fibula*; **e** pennate diatom sub-layer; **f** cysts of the calcareous dinoflagellate *Scrippsiella trochoidea*; **g** sub-layer of marine diatoms and close up photographs of *Chaetoceros* sp.; **h** bacteria sub-layer

silicoflagellate skeleton sub-layers; instead, almost monospecific sub-layers of pennate diatoms (*Nitzschia* sp.) occur directly above the aragonite (Fig. 4e). The organic-rich layers are dominated by amorphous organic matter, dinocysts (Fig. 4f), and lenses of bivalves, ostracod and gastropod shells. Diatom remains are also abundant, with marine diatom frustules (e.g., *Chaetoceros* sp.) often forming distinct sub-layers (Fig. 4g). Finally, mm-thick sub-layers of bacteria may also be present within the organic-rich layers (Fig. 4h). The mean thickness of the aragonite/organic-rich couplets is 7.60 mm (Stdev 5.60). In general, the organic-rich layers are thicker than in the calcite/organic-rich couplets (mean 6.60 mm; Stdev 5.40).

The third type of light and dark couplets consists of alternating organic layers with different composition (Fig. 2c). It occurs in the uppermost 10 cm (2002–2011) of core ETO12-2. A typical couplet of this type comprises a layer of silicoflagellate skeletons followed by pennate diatoms and amorphous organic matter rich in dinocysts, freshwater and marine diatom frustules, and bacteria. Lenses of ostracod and gastropod shells are also present. The mean thickness of the alternating organic-rich couplets is 8.10 mm (Stdev 7.60).

Palynomorphs

Three main vegetation groups growing in the surroundings of the lagoon, i.e., cultivated plants, halophytes and Mediterranean sclerophylls, account for ~75 % of the total pollen in each sample (Fig. 5a). In particular, the cultivated plants comprise Cerealia, *Olea* and *Vitis*. The halophyte group comprises taxa that thrive in salt marshes and coastal wetlands



◀**Fig. 5** Palynological and sedimentological data from core ETO12-2 plotted against chronology (years AD). **a** Selected pollen groups and **b** dinoflagellate cyst (dinocyst) percentages and accumulation rates; **c** position of the oxic/anoxic interface within the Etoliko water column based on instrumental data; **d** Fe/Mn reconstruction based on μ-XRF scanning of core ETO12-2; **e** total varve thickness; **f** Presence of dinocysts and bacteria sub-layers in varve microfacies. *Red stars* on the chronology axis show the position of reported fish mass mortality events; zonation is based on the downcore distribution of varve types

including (in alphabetical order) Amaranthaceae (former Chenopodiaceae), Cyperaceae, Plantaginaceae, Poaceae, Polygonaceae, and Ranunculaceae. Finally, the Mediterranean sclerophyll group comprises *Ephedra,* Ericaceae, *Juniperus, Laurus, Myrtus, Phillyrea, Pistacia,* evergreen *Quercus,* and *Rhamnus*. As depicted in Fig. 5a, the halophyte pollen percentages show a gradual decrease of ~8 % (from 20 to 12 % on average) towards the younger parts of the core, whereas that of Mediterranean sclerophylls a gradual increase by ~9 % (from 25 to 34 % on average). Maximum percentages of cultivated plants (up to ~37 %) and Mediterranean sclerophylls (ranging between 30 and 40 %), and minimum percentages of halophytes (~5 %) characterize core ETO12-2 after the early 1980s.

Dinocyst assemblages consist of both phototrophic (i.e., *Lingulodinium machaerophorum* and *Spiniferites* sp.) and heterotrophic (including *Brigantedinium* sp., *Dubridinium* sp., *Gymnodinium nolleri/microreticulatum*, *Polykrikos schwartzii*, *Protoperidinium* sp., *Stelladinium* sp., and *Votadinium calvum*) taxa. These dinoflagellates typically thrive in coastal marine areas and have been previously reported from the Mediterranean region (Sangiorgi and Donders 2004; Kotthoff et al. 2011; Zonneveld et al. 2013) including coastal settings in Greece (Kouli et al. 2009; Triantaphyllou et al. 2010). A major shift in the composition of the dinocyst assemblages is apparent for the early 1980s; it is marked by the abrupt increase and subsequent dominance of heterotrophic at the expense of phototrophic taxa as documented by changes in their percentages and accumulation rates (Fig. 5b).

Sediment geochemistry

Based on the μ-XRF data, the Fe/Mn ratio, which is an indicator of anoxia (Cohen 2003), is generally marked by short-term (seasonal-scale) variability. A pronounced shift towards a lower Fe/Mn ratio occurs during the mid-1970s, and similar ratios prevail throughout the younger part of the core (Fig. 5d). Moreover, Sr counts are low throughout the studied core interval. However, the Sr concentration, which is a measure for salinity (Cohen 2003), shows a strong increase (up to tenfold) during the 1990s (Fig. 6b).

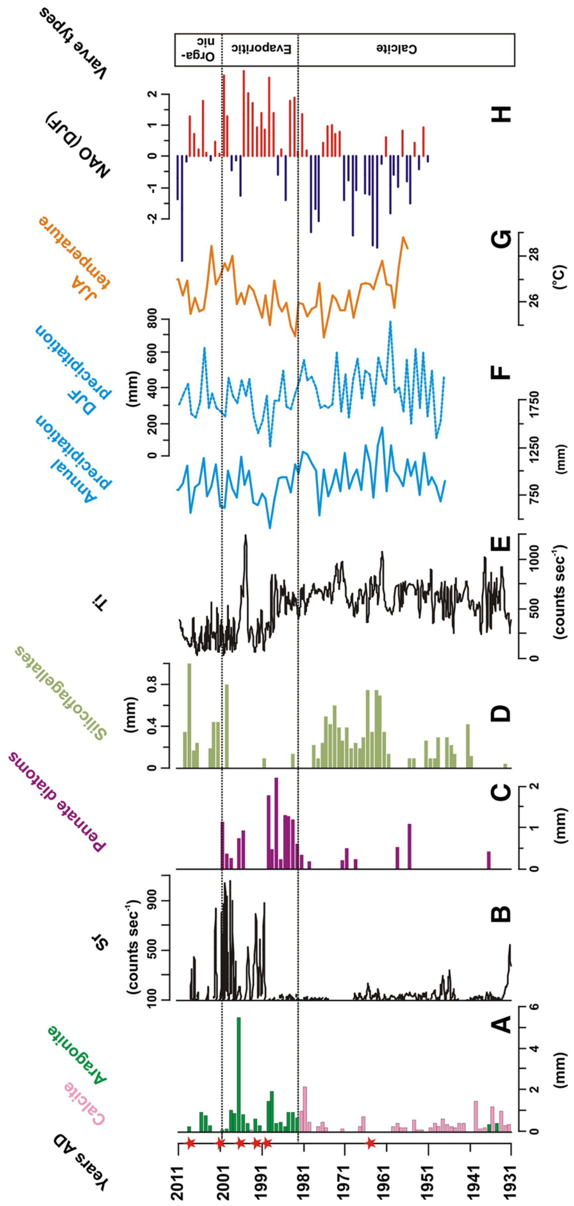


Fig. 6 Varve microfacies and μ-XRF results for core ETO12-2 paired with weather data plotted against chronology (years AD). **a** Thickness of calcite and aragonite layers; **b** μ-XRF-based Sr counts; **c–d** thickness of pennate diatom and silicoflagellate sub-layers; **e** μ-XRF-based Ti counts; **f** mean annual and mean winter precipitation and **g** mean summer temperature from meteorological stations in the towns of Agrinio and Etoliko; **h** North Atlantic Oscillation index as available through the "NOAA Climate Prediction Center" website (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/pna/nao.shtml); *DJF* December-January–February; *JJA* June-July–August; *Red stars* on the chronology axis show the position of reported fish mass mortality events; zonation is based on the downcore distribution of varve types

Finally, the Ti concentration, which is often used as a measure for erosion in the catchment (Cohen 2003), shows a stepwise decrease in the mid-1980s and has remained low since then (Fig. 6e).

Discussion

Varve formation and chronology

The alternating light and dark layer couplets preserved in core ETO12-2 indicate discrete seasonal sedimentation in the Etoliko lagoon, thereby suggesting the laminated sediments represent true varves. This is further supported by the direct comparison of the varve counting and the ^{137}Cs dating (Fig. 3). Hence, the combination of the ^{137}Cs measurements with the varve counting provides a robust age model for core ETO12-2 that allows insights into the environmental impact of the human activities since 1930 at an annual resolution. Based on the varve microfacies three different varve types have been deposited at Etoliko over the past ~80 years.

The first varve type was deposited between 1929 and 1982 and consists of calcite/organic-rich couplets that comprise biogenic varves of the calcite type (Brauer 2004). The light layers consist almost exclusively of μm-thick calcite crystals, which are typically formed by biologically induced calcite precipitation during spring/summer in several lake systems (Brauer 2004; Kienel et al. 2013). The calcite precipitation is directly related to algal blooms that consume CO_2 for respiration, which leads to a decrease of the CO_2/H_2CO^{-3} ratio in the water column until the solubility product for calcite is reached (Brauer 2004). In the case of Etoliko, the algal blooms are evident by the deposition of large centric diatom frustules closely before or while the calcite layer has been formed (Figs. 2a, 4b–c). These frustules comprise mainly *Coscinodiscus granii*, a species that typically blooms during spring in Greek coastal waters (Nikolaides and Moustaka-Gouni 1990).

The subsequent organic-rich layers reflect the sedimentation processes during autumn/winter. This is testified by the observed distribution pattern of silicoflagellates (*Dictyocha fibula*) and marine dinocysts (Fig. 4d, f). Both these algal groups, which mainly bloom during autumn/winter in the Mediterranean region (Ignatiades 1970; Gotsis-Scretas et al. 1999; Rigual-Hernández et al. 2010), exhibit maximum abundances directly above the light (i.e., calcite-dominated) layers. The notion that the organic-rich layers were deposited during autumn/winter is further corroborated by the deposition of detrital layers within the organic material (Fig. 2a). In particular, detritus deposition of terrestrial origin reflects periods of increased runoff (Mangili et al. 2005) as they typically occur in the Mediterranean region during autumn and winter (Lionello et al. 2012). Additional evidence for the timing of the organic-rich layer deposition comes from the presence of lenses of benthic organisms such as bivalves, ostracods and gastropods (Fig. 2a). Considering that these organisms cannot thrive in anoxic settings, their deposition provides evidence for reworking from the oxygenated littoral zone of the lagoon under enhanced wind and wave activity predominantly in autumn/winter. Based on these lines of evidence, one calcite/organic-rich couplet represents one varve at Etoliko.

The second varve type, which is marked by the replacement of calcite by aragonite between 1983 and 2001 (Fig. 2b), comprises evaporitic (aragonite) varves (Brauer 2004). The deposition of aragonite is generally attributed to higher salinity owing to high evaporation, reduced freshwater input and/or strong marine influence, which ultimately enhances Mg precipitation (Müller et al. 1972). Aragonite deposition typically takes place in arid environments, e.g., in the Dead Sea (Brauer 2004) as well as in coastal lagoons (e.g., Butrint; Ariztegui et al. 2010) and temperate lakes (e.g., Lake Zoñar; Martín-Puertas et al. 2011). The aragonite layers are deposited in spring/summer; the organic-rich layers, which are also characterized by the presence of marine dinocysts and lenses of benthic organisms that thrive in oxygenated settings (i.e., bivalves, ostracods and gastropods), are deposited in autumn/winter similarly to the calcite varves.

The third varve type comprises organic varves, which were deposited from 2002 to 2011, with the exceptions of 2004–2006 and 2009 when evaporitic varves were formed. With regard to the organic varves, the absence of calcite/aragonite layers makes it difficult to determine the spring/summer layer. However, one varve year can be defined by the repeated deposition of silicoflagellate sub-layers, as these marine algae typically thrive in autumn/winter in Greek coastal waters (Ignatiades 1970; Gotsis-Scretas et al. 1999).

Human-induced ecosystem disturbances

The vegetation dynamics as reflected in the pollen assemblages from core ETO12-2 document changes in land use within the catchment area of the Etoliko lagoon starting in the mid-1950s and peaking during the 1980s–1990s. This is documented in the continuously increasing pollen percentages of Mediterranean sclerophylls after the mid-1950s and the decreasing percentages in halophyte pollen (Fig. 5a). Such changes in vegetation composition suggest a loss of wetland habitats and expansion of dry land around the lagoon as typically observed in late Holocene coastal lagoons from southern and western Greece (Kouli 2011). The major shift in land use during the 1980s and 1990s is documented by the peak in cultivated plant pollen percentages at the expense of the halophytes, which fall for the first time below the baseline percentages of the 1930s–1940s (Fig. 5a). This is further supported by the coeval peak in Mediterranean sclerophylls pollen percentages. These pollen-inferred land-use changes are in agreement with historical information, which highlights the systematic efforts for the expansion of housing areas and land for agriculture after World War II that led to loss of ~60 % of the natural marshes in the entire Messolonghi–Etoliko lagoon complex (Dimitriou 2007). They comprise the connection of the island on which the town of Etoliko was built with the mainland, the drainage of wetlands through installation of irrigation channels and pumping stations, and construction of artificial barriers for salt production and fish farming.

The expansion of agriculture can be expected to have intensified the nutrient input into the lagoon owing to the increased use of fertilizers, as shown by the increase in total phosphorus and Chlorophyll-*a* concentrations since the 1980s (Table 1; Danielidis 1991; Gianni et al. 2012), ultimately leading to an enhancement of algal productivity. This scenario is documented by a shift in dinocyst assemblages during the early 1980s towards a dominance of heterotrophic taxa at the expense of phototrophic ones (Fig. 5b). Although the increase in the percentages and accumulation rates of heterotrophic taxa may also partially reflect the higher preservation potential of heterotrophic cysts under anoxic conditions, the proportion of their cysts within dinocyst assemblages has repeatedly been shown to reflect increased eutrophication in coastal waters (Matsuoka 1999; Dale 2009). Alternatively, this assemblage shift may also represent a decrease of phototrophic dinocysts, which could be caused by decreased light penetration because of shading by largely increased diatom concentrations under eutrophic conditions and/or particulate matter from heavy pollution (e.g., sewage effluent) (Dale 2001, 2009). In any case, both these scenarios imply that the change in dinocyst assemblages may be related to increased diatom productivity due to higher nutrient input and perhaps also to increased amounts of particulate matter in the water column during the 1980s. This view is supported by the increased thickness of the organic-rich layers in the evaporitic and organic-rich varve types that were formed after 1983 (compare 'Microfacies' section) as well as by the formation of distinct diatom sub-layers in the 1980s (Fig. 6c). Based on historical data, the dinocyst signal registered in core ETO12-2 can be attributed to major human interventions in the catchment that caused a major change in the hydrology of the lagoon. These comprise a 10-year-long (1972–1982) connection of the Etoliko lagoon with Lysimachia lake (Fig. 1), a water body heavily polluted with waste from the town of Agrinio, and the installation of a water pumping station supplying Etoliko with irrigation water from the surrounding cultivated land continuously since 1973 (Albanakis et al. 1995; Gianni et al. 2011; Avramidis et al. 2012). Both the input of irrigation water and wastewater into the Etoliko lagoon may have significantly contributed to the eutrophication and reduced the light transmission in the water column.

Further support for enhanced eutrophication in the lagoon comes from instrumental data on the dissolved oxygen content in the water column that allow to locate the depth of the oxic/anoxic interface (Fig. 5c). They reveal a shift of this interface from ~19 m in 1951 to ~4 m in 2004 (Table 1; Fig. 5c). This displacement has been taken to indicate enhanced anoxia in the lagoon as a consequence of increased nutrient input (Leonardos and Sinis 1997; Gianni et al. 2011). Such a scenario is further corroborated by μ-XRF derived Fe/Mn ratios along core ETO12-2, which can be interpreted as a measure of anoxia in the lower water column considering that the solubility of Mn under dysaerobic conditions is higher than that of Fe (Cohen 2003). The Fe/Mn data show a sharp decline in the 1970s and a stepwise decrease in the 1980s after which the decline continues (Fig. 5d). This further testifies to a strengthening of anoxic conditions in the lagoon. In particular, the minimum in the Fe/Mn ratio is synchronous with the lowest depth of the oxic/anoxic interface during the 1990s as known from instrumental data. The enhancement of anoxic conditions since 1990 is further mirrored in the drastic increase in varve thickness from 1991 to 2006, from a mean of 2.95 mm (for the period 1930–1990) to 9.60 mm (for the period 1991–2006; maximum 23.60 mm in 2004) (Fig. 5e). Based on the microfacies analysis, the increase in varve thickness after 1990 is caused by the thickening of the organic-rich layers, which are composed by silicoflagellates, diatoms and bacteria. This testifies to an enhanced preservation of organic matter during 1990–2006, which is in agreement with the enhancement of the water-column anoxia in the Etoliko lagoon during that time.

The decrease of varve thickness to 3.70 mm after 2006 can be ascribed to a stronger oxidization of organic matter probably resulting from increased oxygen availability in the water column (Fig. 5d). This view is supported by a coeval increase of the Fe/Mn ratio (Fig. 5d), which points to reduced anoxia, and a transient increase in the phototrophic dinocysts percentages in 2006–2007 (Fig. 5b). These observations document a resumption of the water circulation at Etoliko after 2006, which can be attributed to the implementation of management plans for the restoration of the aquatic ecosystem. Specifically, the cross section of the channel connecting the Etoliko and Messolonghi lagoons (Fig. 1) was enlarged by ~30 % in May 2006 (Gianni et al. 2011). As a result, the incursion of marine waters increased, improving the oxygenation of the water column (Fig. 5c), with oxygen even transiently reaching the bottom of the lagoon in winter 2007 (Gianni et al. 2012). Despite this improvement, our data also show that the aquatic ecosystem has not yet returned to pre-1980s conditions. For instance, the dominance of heterotrophic dinocysts, the continuous presence of bacteria sub-layers in the varve microfacies and the still low Fe/Mn ratio indicate that the lagoon has remained highly eutrophic and more anoxic than prior to the 1980s (Fig. 5). Our sedimentological and palynological data indicate that Etoliko lagoon remains under severe stress and the implemented management measures

Table 2 Reports of H_2S release and related fish mass mortality events (marked with asterisks) in Etoliko lagoon

Year	Date	Location	Cause	Reference
2008*	December, 4th	Etoliko lagoon	Wind/wave activity	Gianni and Zacharias (2011)
2001*	September, 12th	Klisova lagoon	Algal blooms	Dimitriou (2007)
1995*	Unknown	Etoliko lagoon	Unknown	Leonardos and Sinis (1997)
1992*	Unknown	Etoliko lagoon	Unknown	Leonardos and Sinis (1997)
1990*	November, 16th	Etoliko lagoon	Wind/wave activity	Dassenakis et al. (1994); Leonardos and Sinis (1997)
1963*	Unknown	Etoliko lagoon	Unknown	Leonardos and Sinis (1997)
1934	Unknown	Etoliko lagoon	Unknown	Philippson (1958)
1890	March, 30th	Etoliko lagoon	Unknown	Philippson (1890)
1882	January, 13th	Etoliko lagoon	Earthquake	von Rath (1882)
1881*	December, 15th–16th	Etoliko lagoon	Wind/wave activity	von Rath (1882)
1650–1690	Unknown	Etoliko lagoon	Unknown	Meletios (1807)

have only marginally contributed to the aquatic ecosystem recovery.

Mass fish kills as an expression of extreme ecosystem degradation since 1990

Our integrated palynological, geochemical and sedimentological data document that the environmental stress on the aquatic ecosystem of the Etoliko lagoon reached a maximum since 1990. This is in close agreement with the occurrences of mass mortality events of fish over the last two decades (Fig. 5; Table 2), which are considered to reflect severe degradation of the Etoliko ecosystem (Leonardos and Sinis 1997; Gianni et al. 2011; Avramidis et al. 2014). Direct observations show that these mass mortality events were triggered by enhanced wave activity connected to S-SE winds during autumn/winter, which caused a stronger mixing of the water column and ultimately the upwelling of oxygen-depleted and H_2S-rich bottom waters (Dassenakis et al. 1994; Leonardos and Sinis 1997; Gianni and Zacharias 2011). It has been suggested that the underlying cause for these events is the displacement of the oxic/anoxic interface towards shallower depths, which facilitates the oxygen-depleted and H_2S-rich bottom waters to reach the surface during stormy weather conditions (Gianni et al. 2011; Gianni and Zacharias 2011). However, because storm weather episodes are a regular climate feature of western Greece, the fact that the fish mass mortality events have only randomly occurred after 1990 suggests that additional (e.g., biologically driven) processes may have enhanced or catalyzed them.

Information on the causes of the fish mass mortality events comes from our seasonal-scale microfacies data. They indicate that biological activity, notably bacteria development, may have contributed to the mass fish kills since 1990. In particular, the organic-rich layers over the last two decades are marked by the formation of distinct bacteria sub-layers (up to 13.60 mm thick) (Figs. 4h, 5f). These sub-layers provide evidence for the expansion of bacteria communities on the bottom of the Etoliko lagoon during a period of enhanced anoxic conditions in the water column as reflected in the Fe/Mn ratios (Fig. 5d). This observation is in agreement with microbiological analyses, which showed that the Etoliko microbial concentration and diversity is higher under low-oxygen conditions particularly at the sediment/water interface and the lower water column of the lagoon (Chamalaki et al. 2014). The presence of sulfur-oxidizing bacteria, which are capable of oxidizing sulfide to elemental sulfur, has been previously reported at Etoliko (Hatzikakidis 1952; Rinke et al. 2013). Theroretical and experimental physicochemical studies suggest that such sulfur bacteria activity is responsible for the sulfur species speciation near the Etoliko bottom affecting the physicochemical equilibrium of the lagoon and enhancing H_2S release (Papadas et al. 2009). This notion is supported by isotopic gas analysis indicating that the sulfide and methane in the water column of Etoliko are of microbial origin (Friedrich et al. 2014). Based on this line of evidence, we suggest that the human-induced displacement of the oxic/anoxic interface over the last three decades has triggered the expansion of microbial communities as documented in the varve microfacies, which in turn enhanced the H_2S production and release in the water column during strong weather-related mixing events.

Markedly, the Etoliko varves from 1990 onwards are also characterized by the presence of calcareous dinocysts, i.e., *Scrippsiella trochoidea* (Fig. 4f), and marine diatoms, i.e., *Chaetoceros* sp. (Fig. 4g), which often form distinct sub-layers. Although not toxic, blooms of these marine algae have been associated with fish kills because they can cause oxygen depletion in the water column and can severely damage fish gills (Hallegraeff 1993). Therefore, their presence in the Etoliko sediments during a period of repeated occurrence of fish mass mortality events merits further attention. Supporting evidence for the role of harmful algae on such events comes from the neighbouring Klisova lagoon (Fig. 1). There, fish kills resulting from a harmful algal bloom of yet unknown composition have been reported for September 2001 (Table 2; Dimitriou 2007). Unfortunately, the lack of monitoring data on the phytoplankton composition at Etoliko prevents a direct comparison with our seasonal-scale data, hence precluding deeper insights into the potential role of harmful algal blooms in the lagoon.

In conclusion, our varve microfacies data document that unprecedented biological processes occurred in the Etoliko lagoon since 1990, notably the expansion of bacteria communities and blooms of potentially harmful algae. These observations indicate that biological processes may play a more important role in the triggering of fish mass mortality events than previously assumed.

Ecosystem response to climate change

Based on historical documentation, pulses of H_2S release are not only connected to human-induced anoxia since 1990, but have also occurred during the seventeenth and nineteenth centuries (Table 2). This underlines the sensitivity of the Etoliko ecosystem not only to anthropogenic, but also to natural processes. In turn, it raises the question whether—and if so, to what extent—climate change has contributed to the environmental stress at Etoliko particularly since the human pressure on the lagoon increased.

To analyze the potential effects of climatic forcing on the aquatic ecosystem of Etoliko, we focus on the interval between 1983 and 2001, which is marked by a prominent shift in the varve composition, i.e., the deposition of evaporitic varves (Fig. 6a). Such varves are indicative of a depositional environment with increased salinity (Müller et al. 1972). This high-salinity scenario is further supported by the μ-XRF-derived Sr increase in the respective part of the core (Fig. 6b). Sr is typically accommodated in the crystalline lattice of aragonite (Cohen 2003), and high Sr concentrations have been previously reported from lake/lagoon sediments with high salinities caused during periods of strong evaporation (Kienel et al. 2009; Ariztegui et al. 2010; Martín-Puertas et al. 2011). In addition, the aragonite varves at Etoliko are characterized by the formation of pennate diatom sub-layers, predominantly of *Nitzschia* sp. (Figs. 2b, 4e, 6c), and the absence of silicoflagellate sub-layers (Fig. 6d) after aragonite deposition. Because *Nitzschia* sp. grows in shallow settings at Etoliko (Danielidis 1991), its abundance increase suggests a lowering of the water level. The increased evaporation and the lowered water level suggest a reduced freshwater runoff into the lagoon during autumn/winter, a view that is supported by the decline of the Ti concentration in the mid-1980s (Fig. 6e), and/or an increase in air temperature. Such conditions are expected to have increased the surface water temperature, hence, minimizing the silicoflagellates blooms (Ignatiades 1970; Rigual-Hernández et al. 2010).

Conspicuously, based on local meteorological data from the towns of Agrinio and Etoliko, the interval of evaporitic varve formation is characterized by notable changes in precipitation and temperature. Specifically, the interval between 1983 and 2001 is marked by a ~95 mm decrease in annual precipitation with regard to the long-term (1947–2012) mean (from ~915 to ~810 mm). A closer inspection of the meteorological data shows this decrease was confined to the winter season (~70 mm lower precipitation during December to February), with the absolute minimum occurring in 1989 (Fig. 6f). Moreover, this interval is characterized by a gradual increase in mean summer temperature with peak values being recorded during 1998–2003 (Fig. 6g). Notably, the period of evaporitic varve formation is generally characterized by a positive North Atlantic Oscillation (NAO) index (NOAA, Climate Prediction Center; Fig. 6h). The

NAO is a hemispheric meridional oscillation in atmospheric masses centered near Iceland and the subtropical Atlantic Ocean, which affects European climate particularly between December and March (Wanner et al. 2001). It is characterized by a positive mode with drier-than-average conditions in the Mediterranean region and wetter conditions in northern Europe, and a negative mode with a reversed signature. Based on the above, it appears possible that the decrease in the mean annual and winter precipitation between 1983 and 2001 at Etoliko was related to the persistence of a positive NAO mode. We suggest that the precipitation decrease, in concert with a gradual rise in summer temperature, has intensified the saline conditions at Etoliko from 1983 onwards. To conclude, the integration of the sedimentological and meteorological data suggest that climate change may also have affected the aquatic ecosystem of the Etoliko lagoon on top of the anthropogenic influence.

Conclusions

Microfacies and palynomorph analyses yield insights into the evolution of a coastal wetland in the Eastern Mediterranean over the last century. Notably, this study shows that the Etoliko lagoon has been under human-induced pressure since the 1950s, with the environmental stress gradually increasing over the decades and peaking from the 1980s onwards. Moreover, paired sedimentological and geochemical analyses indicate that both biotic (e.g., algal productivity) and abiotic parameters (e.g., sediment microfacies) of the Etoliko lagoon are highly susceptible to climate change, which can enhance the human-induced ecosystem degradation.

Our data support the notion that multi-proxy analyses of annually laminated sediments can contribute to understanding the anthropogenic and natural processes involved in aquatic ecosystems deterioration for which environmental monitoring data are lacking. This analytical approach can provide a valuable tool to test the effectiveness of implemented management measures. As such, it is essential for the successful conservation of vulnerable settings, such as the Mediterranean region, that receive excessive human pressure and lack sufficient environmental protection planning.

Acknowledgments Discussions with Pavlos Avramidis, Areti Gianni and Ingmar Unkel, and technical support by Brian Brademann and Bärbel Schminke are gratefully acknowledged. We also thank two anonymous reviewers, Associate Editor Sarah Metcalfe and Editor Thomas Whitmore for their valuable comments.

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