

Diatom response to mid-Holocene climate change in Lago di Massaciuccoli (Tuscany, Italy)

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Abstract A sedimentary sequence from the Mediterranean coastal basin of Lago di Massaciuccoli (Tuscany, Italy) was analyzed for diatoms, covering two periods over the past ca. 7,000 years. The site was selected because it is situated in a sensitive position at the limit between Mediterranean and Central European climates and biomes. Our focus is on the impact of accelerated human activity during the recent past (water uptake in the catchment, sand extraction, wastewater discharge) and on a phase of evident change between 6,600 and 5,400 cal. BP. The diatom record suggests fresh-water conditions and rather high lake levels until ca. 6,000 years ago. The subsequent shift towards brackish conditions peaked at around 5,500 cal. BP. We relate this shift to a pervasive change towards a drier climate that has been observed elsewhere in the Mediterranean and Northern African regions, and stands in contrast to the shift towards a cooler and more humid climate in the nearby Alps (200–350 km distant) and in central Europe. Pollen and charcoal records from a previous study on the same sedimentary sequence were used to

gain additional insights about the causes of the changes in the diatom assemblages and apply numerical methods to search for common trends and correlations.

Keywords Paleolimnology · Lagoon · Holocene · Climate · Diatom

Introduction

In Europe, previous investigations have shown strong climate variability during the Holocene, but the timing, the magnitude and the direction of change might be different between Mediterranean and Alpine or Central European sites, particularly in regard to the precipitation regime. For example, Magny et al. (2003) found that cold and dry conditions in the Mediterranean south of 43° N had a tendency to correspond to cold and wet phases in the Alps.

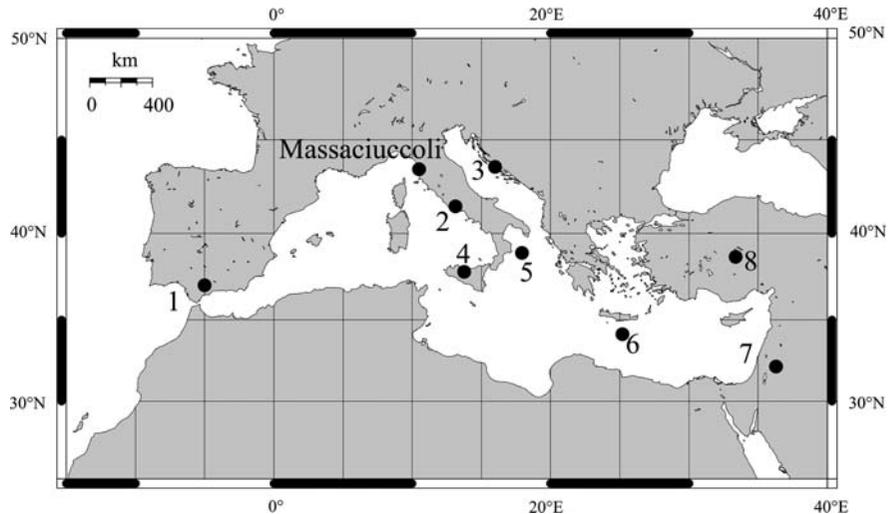
Lago di Massaciuccoli (43°50' N, 2°8' E) is a coastal lagoon located along the Mediterranean Sea shore of Tuscany (Central Italy), 15 km north of the town of Pisa, in the northernmost part of the Mediterranean climatic region, about 250 km south of the Alps (Fig. 1), and was selected to investigate its response to the climate variability at the border between those two climatic regions.

In the Alps, the period around 6,000 cal. BP was characterized by a climate that gradually shifted

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Fig. 1 Location of Lago di Massaciuccoli and other selected Mediterranean sites. 1. Laguna de Medina (Reed et al. 2001), 2. Lakes Albano and Nemi (Ryves et al. 1996), 3. Mljet (Wunsam et al. 1999), 4. Pergusa (Sadori and Narcisi 2001), 5. Sapropel S1 (Ariztegui et al. 2000), 6. East Mediterranean (Rossignol-Strick 1999), 7. Soreq Cave (Bar-Matthews et al. 2000), 8. Eski Acigöl (Roberts et al. 2001)



towards cooler and probably wetter conditions (e.g., Tinner and Theurillat 2003). In the Mediterranean region, the pattern is more complex, but some studies suggest a possible shift towards cooler and drier conditions in the Mediterranean region, or in some parts of it (e.g., Ariztegui et al. 2000; Reed et al. 2001). However, a complex pattern in the timing and duration of the millennial scale shift towards arid conditions in different parts of the Mediterranean climatic area has been found (reviewed by Magny et al. 2002). Superimposed on this millennial trend, century scale climatic changes occurred with a 1,000-year cyclicality in the Alps (Haas et al. 1998; Heiri et al. 2004).

Non pollen-evidence of climatic change is still rare for the Mediterranean region. To disentangle the climatic signal from the response of vegetation, which also depends on human disturbance, more non-pollen climatic reconstructions along the Mediterranean are needed. Diatoms have proven to be valuable indicators of climatic change in semiarid Mediterranean lagoons, where inferred salinity or lake level can provide proxy data on changing precipitation regimes (e.g., Wunsam et al. 1999; Reed et al. 2001). In this context, Lago di Massaciuccoli (LM) represents one of the northernmost sites available for the reconstruction of Holocene Mediterranean climate.

In this paper we investigate the diatom response in two periods of major change in LM: the most recent centuries, characterized by strong human

impact, and a phase of significant vegetation change between 6,600 and 5,400 cal. BP (Colombaroli et al. 2007).

Description of the site studied

Lago di Massaciuccoli (LM) is located in the Versilia Plane, 4 km from the seashore (Fig. 1) and it is connected to the sea by a channel (Canale Burlamacca). Its surface area is 7 km² and the mean depth is 2 m. The lake originated as a retrodunal basin around 8,000 cal. BP, at the end of the Holocene transgression, which is also known as the Versilian Transgression in the Mediterranean (Blanc 1942).

The surrounding marsh was dried up in AD 1740, and the influx of seawater to the lake was limited. Analyses carried out in 2002 by the Regional Environmental Protection Agency (ARPA Toscana) showed that LM salinity is moderate (1.2 g l⁻¹). In the 19th century it was known to be rich in macrophytes and to host a large duck population. During the second half of the 20th century, macrophytes almost disappeared because of increased turbidity caused by a combination of sand extraction and lake eutrophication as a result of sewage discharge. Summer, chlorophyll *a* concentration reaches 36 µg l⁻¹ in the present lake, and Secchi disk depth is around 0.5 m. Cyanobacterial blooms are also frequently reported.

Materials and methods

Core and dating

Diatom analysis was carried out on samples obtained from two parallel long cores (LML and LMM) and one short core, collected in 2004 from the eastern part of the lake (43°53'33" N, 10°20'48" E), at 1.8 m depth using a modified Streif-Livingstone piston corer, with a tube diameter of 7 cm. LML was cut in six 1 m section (6–106, 106–206, 206–306, 306–406, 406–506 and 506–606 cm). To maintain sediment continuity, LMM (taken 20 m apart) was also cut in 1 m section, overlapping with the sections of LML (i.e., 56–156, 156–256, 256–356, 356–456 and 456–556 cm). They were correlated using lithostratigraphical markers, with a precision of ± 1 cm. The short core was also used to identify the depth of a surface gap in the long cores. All depths were then referred to core LML.

Samples from diatom analysis (1-cm slices) were obtained from LML (from 464 to 419 cm and at 364 cm), LMM (from 417 to 367 cm) and the short core (100 to 0 cm).

AMS (Accelerated Mass Spectrometry) ^{14}C dates were obtained for 8 terrestrial plant macrofossil taken from 5 samples of LML and 3 samples of LMM, and they were calibrated with the program CALIB version 5.0.2 (Stuiver and Reimer 1993; Reimer et al. 2004). One date was rejected and interpolation between radiocarbon dates was performed comparing

a general additive model (Birks and Heegaard 2003; Heegaard et al. 2005) and a LOWESS weighted regression, with 0.8 smoothing span. Details on cores and dating are provided by Colombaroli et al. (2007). AMS dates are reported in Table 1. Because of the lack of radiometric dates in the first two meters, approximate chronology was obtained by extrapolation, assuming a constant sediment accumulation rate of 1.1 mm year^{-1} . For this reason, dating of the topmost sections of core LM should be considered as indicative.

Diatom analysis

Diatoms were cleaned by H_2O_2 and HCl digestion, and mounted using Naphrax[®] (Renberg 1990). Frustule counts were made with a Zeiss Axioplane microscope at 1000 \times with phase contrast. Diatom identification mainly follows the nomenclature proposed by Krammer and Lange-Bertalot (1986, 1988, 1991a, b), while generic names were updated with DIATCODE (Williams et al. 1988). As is commonly the case in brackish lagoons, in some sections, frustule preservation was very poor, and fragments could not be assigned to a given species, although genera were usually identified. Fragments were enumerated as a frustule if it contained valve centre (for centric diatoms) or the central nodule (for raphid diatoms). In the case of araphid diatoms, a half frustule was enumerated if the fragment contained

Table 1 ^{14}C data of the Massaciuccoli core (from Colombaroli et al. 2007)

Core	Laboratory number	Material	Depth (cm)	Conventional radiocarbon date BP	Cal. year BP 95% limits ^a	Cal. year BP in diagram
LML	Poz-10663	Indet. Br	251.5–252.5	2,165 \pm 30	2,061–2,309	2,211.2
LML	Poz-10664	Indet. Br	343.5–344.5	4,425 \pm 35	4,871–5,276	5,030.6
LMM	Poz-11463	Indet. CH	374.5–377.5	4,900 \pm 60	5,479–5,855	5,592.9
LMM	Poz-11380	Indet. CH	397.5–400.5	5,215 \pm 35	5,908–6,173	5,908.2
LMM	Poz-11381	Indet. CM	416.5–419.5	5,325 \pm 35	5,994–6,258	6,090.5
LML	Poz-11382	Indet. B	426–430	5,360 \pm 35	6,002–6,276	6,249
LML	Poz-10665	Indet. CH	458.5–459.5	5,950 \pm 40	6,676–6,882	6,737.2
LML	Poz-10666	R	471.5–472.5 ^b	5,880 \pm 40	6,568–6,794	6,941.6 ^c

Br, branch; CH, charcoal; CM, charred material; B, bark; R, root

^a CALIB REV5.0.2 (Reimer et al. 2004)

^b Rejected date

^c Extrapolated date

one frustule end. Among the samples taken from core LML and prepared for diatom analysis, 28 samples are considered in this paper. A minimum of 250 fragments was generally enumerated for each sample, the actual number ranging from 68 to 664. The samples for which the minimum number was not reached were at depths of 364, 406 and 411 cm.

Core LML was also used for pollen and charcoal analyses, the methods follow standard procedures for palynology (e.g., Moore et al. 1991) and charcoal analysis (e.g., Tinner and Hu 2003). The detailed results of the pollen and charcoal analyses (including the pollen and charcoal diagrams) are reported elsewhere (Colombaroli et al. 2007).

Numerical analysis was carried out on the square-root transformed percentage relative abundances of the more frequent species (i.e., abundance higher than 3% in any sample) using CANOCO (ter Braak 1987–1992) and SYN-TAX (Podani 1994a).

Results

A total of 79 diatom taxa was found in the LM sediment, belonging to 33 genera. In most samples, frustule preservation was poor and limited to small fragments, so it was not possible to identify the species. We examined 51 samples along the core, but in twelve samples, no fragments were found, or they were too corroded for identification to the genus level. For this reason we focused the study on two sections where diatom frustules were relatively well

preserved: a deeper section between 467 and 364 cm and the topmost 72 cm.

Summary diatom diagrams (including species accounting for at least 5% of the diatom counts in any sample) are given in Figs. 2 and 3. The sequence is characterized by an alternation between planktonic and benthic dominance. Plankton dominates below 386 cm and above 10 cm. Most of the taxa are salinity tolerant, but freshwater species prevail below 370 cm, apart from a small section at the 434-cm depth, in which the diatom assemblage was almost completely represented by the marine planktonic species, *Paralia marina*, and between 10 and 0 cm.

The bottom of the core, below 468 cm, is formed by sand and no diatoms were found. This part is assumed to belong to marine environments at the end of the Versilian transgression (ca. 8000 cal. BP), and can be related to similar findings in a terrestrial core taken close to LM (Menozzi et al. 2002), where the age of the transition from marine to terrestrial environments was estimated between 5,400 and 6,200 BP (uncalibrated), corresponding to ca. 6,300 to 7,100 cal. BP.

Organic lacustrine sedimentation starts at a depth of 468 cm (ca. 7,000 cal. BP). In the bottom of the cores, four sections were distinguished:

- (1) Section D1, from 468 to 414 cm (ca. 6,100 cal. BP): diatom frustules were well preserved and mainly belonged to *Staurosira brevistriata*, *Fragilaria crotonensis* and *Cyclotella comensis*. The first taxon is a benthic tolerant diatom,

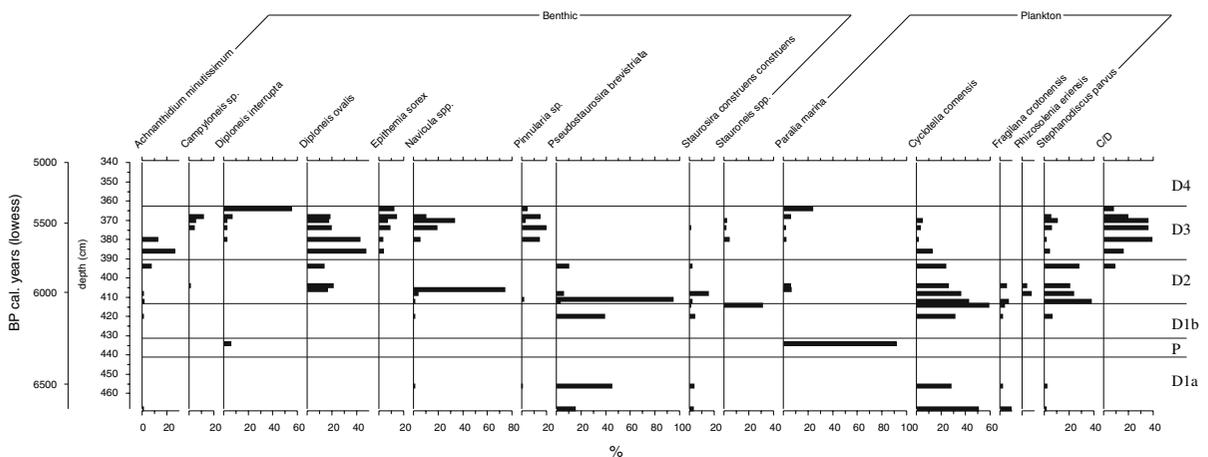


Fig. 2 Summary diatom diagram (taxa >5% abundance) for the mid-Holocene (ca. 6,800–5,000 cal. BP) phase of cores LML and LMM. C/D ratio between chrysophycean cysts and diatom frustules

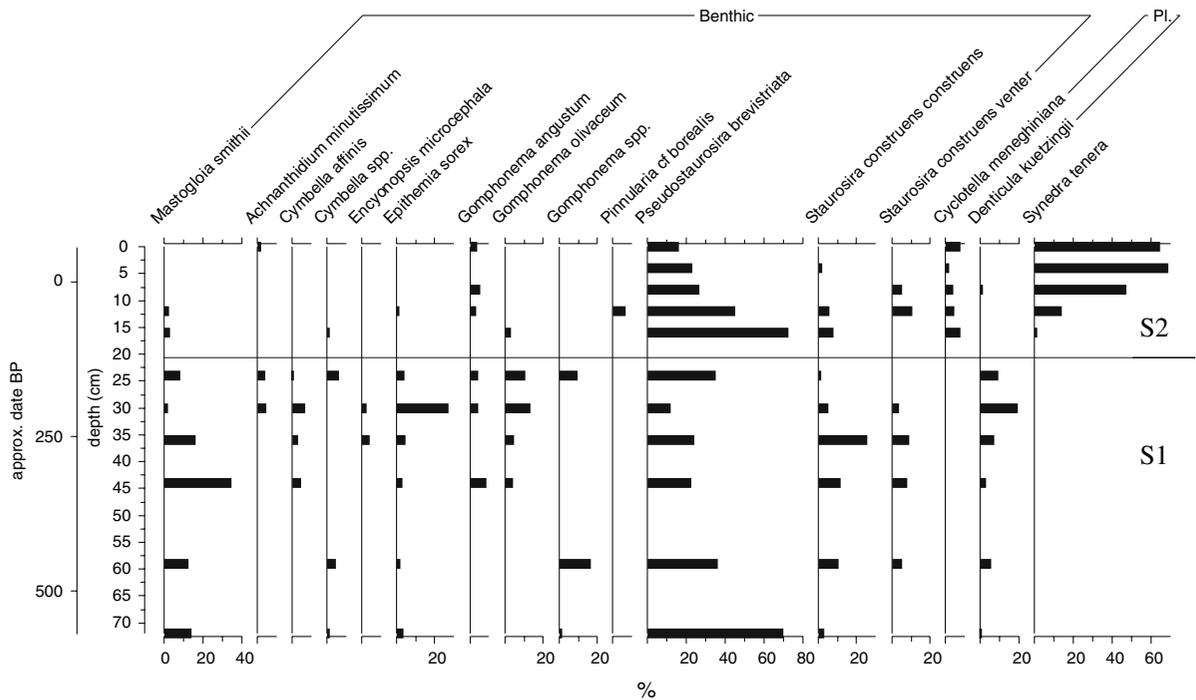


Fig. 3 Summary diatom diagram (taxa >5% abundance) for the topmost section of a short LM core. Pl.: planktonic

usually living in the epipsammon or in the epilithon, and the latter two are typical of the plankton of oligotrophic lakes. The diatom assemblage suggests a relatively deep and transparent freshwater lake, poor in nutrients. These conditions lasted ca. 1,000 years until ca. 6,000 cal. BP, with a transient interruption represented by a couple of samples (Section P), at around 434-cm depth (ca. 6,350 cal. BP), that were characterized by corroded frustules belonging almost exclusively to *Paralia marina*, a planktonic marine form indicating a brief input of saltwater.

- (2) Section D2: at the depth of 412 cm (ca. 6,030 cal. BP), the relative abundance of small *Stephanodiscus* spp., mainly *S. parvus*, suddenly increases, indicating a strong increase in the trophic status of the lake. *S. parvus* and *C. comensis* have different trophic preferences, the first being found in eutrophic water and the latter preferring an oligotrophic state (e.g., Reynolds et al. 2002). Species optima for these species are reported by Wunsam and Schmidt (1995) to be 111 and 10 µg of total P, respectively.

The presence of both species in the same samples is intriguing. In lakes experiencing recent anthropogenic eutrophication, like Lago Maggiore (Marchetto and Musazzi 2001) or Lake Como (Marchetto and Bettinetti 1995) located 250 km north of LM, *Cyclotella comensis* was the dominant species during the oligotrophic sequence and it disappeared before the increase in abundance of the small *Stephanodiscus* spp. A similar pattern, with a *Cyclotella* species replaced by some small *Stephanodiscus*, was also found in lakes Albano and Nemi (300 km South of LM), which experienced natural eutrophication due to catchment soil development during the early postglacial (Ryves et al. 1996).

In the LM sequence, the presence of both species in the same samples may indicate strong seasonal or interannual variability in the trophic status, which could have been driven by long dry periods and episodic precipitation, as commonly found in present day Mediterranean lakes and reservoirs (e.g., Naselli-Flores and Barone 2005).

- (3) Section D3: after ca. 5780 cal. BP (390 cm), planktonic species declined, and the diatom

assemblages were dominated by the periphytic species *Diploneis ovalis* and *D. interrupta*, which are normally found in brackish water, indicating low water levels, rich macrophyte vegetation and input of saltwater. Frustule preservation also declines, and most valves are very corroded.

- (4) Section D4: very few fragments were found in the samples taken at depths between 362 and 340 cm (ca. 5,350–4,900 cal. BP). Diatom results for this section are therefore not shown in the profiles. Colombaroli et al. (2007) found pollen samples taken in the same section to be dominated by *Chenopodiaceae*, typical of salt marshes, indicating that salinity further increased.

In the short core, representing approximately the last five centuries, well preserved diatom valves were found. The assemblages were generally dominated by salinity-tolerant epipellic species, like *Staurosira* spp. and *Pseudostaurosira* spp., but some sections were rich in species characteristic of brackish water (such as *Mastogloia smithii*) suggesting low lake level, high transparency and variable salinity (Section S1).

In the uppermost 16 centimeters of the core (Section S2), which correspond approximately to the last 100 years, *Synedra tenera* appears and its relative abundance gradually increases reaching

values as high as 69%. This species can live in both the plankton and the epilithon of freshwater lakes, and it is known to be tolerant of metal pollution (e.g., Ruggiu et al. 1988). The increase in *Synedra tenera* is probably related to both the decrease in the salinity of LM caused by the building of protection towards the sea, and to the high anthropogenic disturbance to which LM was subject in the last century.

In detrended correspondence analysis (DCA), the first three axes account for 29.6% of the total variance. The first axis (accounting for 14.6% of the variance) mainly distinguishes the samples belonging to the deeper sections (D1, P, D2 and D3) from those from the recent sediment (Sections S1 and S2, Fig. 4a). The second axis (10%) can be considered a salinity gradient, as high scores were assigned to samples rich in species typical of seawater (*Paralia marina*) and of brackish conditions (*Mastogloia smithii* and *Diploneis* spp.), while low scores were assigned to samples dominated by freshwater species such as *Pseudostaurosira brevistriata*, *Cyclotella comensis*, *Stephanodiscus* spp. and *Synedra tenera*. The third axis (5%) represents trophic gradients, with scores decreasing from samples characterized by oligotrophic species (*Cyclotella comensis*) to eutrophic species (*Stephanodiscus* spp.) to species tolerant of strong human impact (*Synedra tenera*).

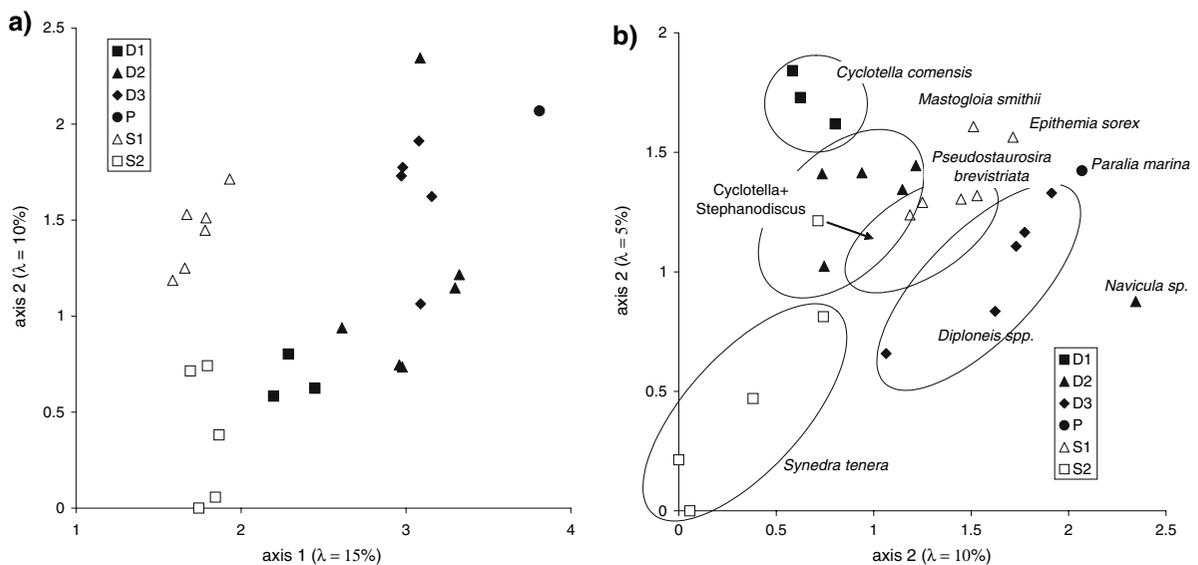


Fig. 4 Site scatter plots of (a) Axis 1 vs. Axis 2 and (b) Axis 3 vs. Axis 2 for detrended correspondence analysis (DCA) of the dataset of 34 species and 26 samples. Unit: standard deviations.

The section to which each site belongs is shown, together with the main diatom species (in the right panel)

Discussion

The diatom data indicate significant oscillations in the trophic and salinity status of LM. In the deeper part of the core, the major changes occurred at 6,350, 6,030 and 5,780 cal. BP. It is not simple to understand the causes that may have contributed to these shifts in aquatic ecosystems. For instance, increasing eutrophication may be related to low lake levels leading to a concentration of nutrients in the remnant water body or to increased nutrient input from agricultural activities such as animal husbandry, fertilization or slash-and-burn agriculture (Tinner et al. 1999).

The changes observed during the last century of the LM sequence appear clearly related to human impacts, while other shifts, such as the salinity changes, might be primarily climatically driven (Wunsam et al. 1999; Reed et al. 2001). Our sequence starts when Neolithic farming had already been established (Malone 2003) and thus it is likely that human impacts had already substantially altered the ecosystem of our area. Paleoeological and modeling studies from the neighboring southern Alps (ca. 250 km away) show that human-induced changes during the Neolithic included the collapse of important tree species (e.g., *Abies alba*), and the strong propagation of sprouters (e.g., *Corylus*, *Alnus*) and herbaceous species (e.g., *Plantago lanceolata*) in response to agricultural activities such as clear-cuttings, slash-and-burn, cultivation of cereals, and pasture farming (Tinner et al. 1999; Keller et al. 2002; Wick and Möhl 2006). Such human activities might have influenced the aquatic ecosystem as well.

Diatom and pollen records

A discussion of the pollen record may help to disentangle human and climatic effects on the aquatic ecosystem. In a previous paper (Colombaroli et al. 2007), we described the pollen profiles and we discussed their paleoclimatic implications, but we did not attempt to identify the existence of simultaneous trends or changes in the pollen and diatom profiles.

A numerical analyses of the LM diatom and pollen record was then performed, by carrying out separate correspondence analyses (CA) on the square-root transformed relative abundances of the most common diatom and pollen grains. After Procrustes rotation of

the latter ordination, a d^2 distance value (Podani 1994b) of 0.89 was calculated between the two CAs. This value was statistically significant ($P < 0.01$) in a Monte-Carlo simulation of the ordinations, suggesting that diatom communities and terrestrial vegetation were influenced by common environmental factors such as climatic change and human impact. To further explore the relationship, we also investigated the correlations between the relative abundance of key pollen and diatom taxa.

LM formed as an oligotrophic, relatively deep and stratified lake. After 6,030 cal. BP the lake shifted from oligotrophic to more eutrophic conditions. The relative abundance of *Cyclotella comensis*, the most important oligotrophic indicator in the LM planktonic diatom community, is related to the pollen abundance of *Abies alba* ($r = 0.78$), a species which prefers oceanic conditions, with relatively moist environments, and is very sensitive to drought (Ellenberg, 1996). This link could indicate that before ca. 6,000 cal. BP, high lake levels were coupled with higher precipitations that would have favored *Abies alba*.

On the other hand, *Cyclotella comensis* is also highly correlated with *Corylus avellana* ($r = 0.72$), that had coexisted together with *Abies* before 6,000 cal. BP but had reached its maximal expansion after the collapse of *Abies alba* at ca. 6,000 cal. BP (Colombaroli et al. 2007). This heliophilous shrub species is strongly favored by (fire) disturbance (Clark et al. 1989; Tinner et al. 2000) and adapted to drought (Pigott and Pigott 1993), and is positively correlated with charcoal abundances at LM. When *Corylus avellana* peaks, the diatom assemblage is co-dominated by *Cyclotella comensis*, which prefers oligotrophic waters, and by small *Stephanodiscus* spp., typical of eutrophic lakes. As mentioned above, this pattern suggests periodic variation in the trophic status of LM, driven by dry periods and episodic precipitation, as commonly found in present day Mediterranean lakes and reservoirs.

Taken together, our results suggest that high lake-levels occurred during phases when precipitation was high enough to support the occurrence of *Abies alba* at the Mediterranean Sea shore, a vegetational situation which is without any modern analogue today. The simultaneous occurrence of the collapse of *Abies alba* and of the increase in the abundance of diatoms preferring eutrophic conditions suggests a direct link to climatic change. However, charcoal

analysis (Colombaroli et al. 2007) showed that fire disturbance was also present, inducing *Corylus avellana* expansion and probably nutrient release from the catchment, leading in turn to an increase in the trophic status of LM. In fact, we cannot exclude that increased fire incidence could have directly resulted from a shift towards drier climatic conditions.

Over the entire sequence, *Chenopodiaceae* was significantly correlated with the abundance of saltwater diatoms *Paralia marina* ($r = 0.88$) and *Diploneis interrupta* ($r = 0.83$). The pollen record of LM suggests an extremely large expansion of *Chenopodiaceae* (peak values reached ca. 30% at 5,400 and 5,100 cal. BP, when regional fire activity was very high and forests declined). Unfortunately, in the following Section (D4) diatom preservation was very poor, and only some small fragments were found in the sediment samples. We hypothesize that a drop in the level of the water table in response to drier climatic conditions caused the infiltration of seawater through the dune system separating LM from the sea, inducing an increase of saline environments in and around the lake. Similar processes have been inferred for coastal lakes in Croatia (Wunsam et al. 1999).

Interestingly, numerical analyses show a statistically significant correlation between *Mastogloia smithii* and some species indicative of human activities (Behre 1981). For instance, the correlation with *Plantago lanceolata* ($r = 0.73$) and *Cerealia* ($r = 0.64$), a primary indicator for agricultural activity (Behre 1981), suggests a relationship between human impact and slightly brackish conditions. Given that *Mastogloia smithii* and *Plantago lanceolata* are particularly abundant in the short core, representing the last centuries, this finding may reflect anthropogenically induced changes of the water table, such as due to changes in drainage, or alternatively that the level of the lagoon fell and marshland was exposed, allowing the cultivation of the land in the vicinity of the lake edge. In fact, a further correlation between *Mastogloia smithii* and *Poaceae* ($r = 0.92$) can also be related to the expansion of local marshland vegetation as a consequence of a lake-level lowering.

Paleoclimatic implications

In the Mediterranean Sea, sapropel deposition, palynological and speleothem data suggest relatively

humid conditions during the period ca. 10,000–7,000 cal. BP (Ariztegui et al. 2000; Bar-Matthews et al. 2000). After ca. 7,000–6,000 cal. BP, conditions gradually became drier, a tendency which is also suggested by paleorecords from northern Africa (Damnati 2000) and the eastern Mediterranean (Roberts et al. 2001; Schilman et al. 2001).

Our new data support the interpretation that, before ca. 6,000 cal. BP, the Massaciuccoli area was wetter than in the last centuries, allowing LM to support a planktonic freshwater community. The aridification process started at around 6,000 cal. BP and peaked at 5,400–5,100 cal. BP. This finding is in agreement with many other records that document a gradual aridification process in the Mediterranean area that started at ca. 7,000–5,000 cal. BP depending on the location of the site and the proxy used (Rossignol-Strick 1999; Ariztegui et al. 2000; Reed et al. 2001; Sadori and Narcisi 2001). Large differences in the estimated dating of the aridification can partially be due to the different sensitivity of the sites to the climatic signal, as it is unlikely that thresholds of response will be similar across the region.

The Mediterranean region, in fact, has a very complex topography, with several mountain chains facing the sea and receiving orographic precipitation. On the Iberian Peninsula, for example, local climatic complexity is also related to the gradual shift from Atlantic to Mediterranean climate regimes from the north-west to the south-east. In Central Italy, precipitation is mainly related to the flow of extra-tropical westerlies, and the dry summer season is caused by the Azores subtropical high. Strong African monsoonal storms can exceptionally reach the Italian peninsula, delivering strong orographic precipitation in the Central Alps, 250 km North of LM.

The above large-scale climatic shifts in our region were probably coupled to planetary changes in air circulation. In fact, the North African humid period terminated abruptly at about 5,500–5,000 cal. BP, probably as a consequence of a weakening of the African monsoon that primarily resulted from Earth orbital changes which decreased summer season insolation (deMenocal et al. 2000). On the contrary, in the nearby Alps and their forelands (e.g., also on the Swiss Plateau), the mid and late Holocene was characterized by a millennial trend towards cooler and more oceanic (i.e., more humid) conditions. Insolation changes were not abrupt, but substantial

ocean-vegetation feedbacks could have led to an abrupt weakening of the monsoonal precipitation (deMenocal et al. 2000). A strong link between monsoon precipitation and solar activity is also suggested by stalagmite oxygen-isotope records from southern Oman (Fleitmann et al. 2003); however, in our area the precipitation in summer was not delivered by the monsoons, instead it came with the flow of extratropical westerlies in summer, which was probably combined with a weakening of the Azores subtropical high (Rossignol-Strick 1999) that is today the cause of the dry Mediterranean summer season.

Superimposed on this millennial aridification trend in North Africa, south-western Asia and the Mediterranean, century to decadal-scale oscillations occurred (Reed et al. 2001; Fleitmann et al. 2003) and it has recently been proposed that cool-humid century scale oscillations recorded in the Alps and Central Europe (Haas et al. 1998; Magny 2001) corresponded to cool-dry phases in the Mediterranean south of 43° N (Magny et al. 2003). Although relatively close to the Alps, our site seems to be more closely related to the Mediterranean climatic system. For instance, the period 5,400–5,100 cal. BP, for which we infer a pronounced dry phase at LM, was cold and humid in and around the Alps (CE-6, 5,350–5,100 cal. BP, in Haas et al. 1998). Similarly, the period around 6,000 cal. BP was probably characterized by rather dry climatic conditions at LM, but cold-humid ones in and around the Alps (CE-5, 6,100–5,700 cal. BP, in Haas et al. 1998). Given the position at the northernmost edge of the Mediterranean climatic area, this finding confirms the century to decadal scale spatial pattern found by Magny et al. (2002) and implies a steep gradient with a rather sharp transition between the Mediterranean and the Central European climatic sub-systems during the past 7,000 years. However, it is likely that this contrast was less accentuated or even inactive during the early Holocene (c. before 8,000 cal. BP), when Central Europe experienced much drier and more continental conditions than today (Guiot et al. 1993; Tinner and Lotter 2001, 2006).

Conclusions

Diatom data such as the LM-record are a valuable proxy for the reconstruction of the environmental evolution of coastal lakes in the Mediterranean area.

The significant correlation between changes in terrestrial and aquatic remains showed that both systems were (simultaneously) affected by similar processes. The change in diatom assemblages points to a climatic shift towards drier conditions between 6,000 and 5,400 cal. BP, while the pollen records showed that aridification culminated in the establishment of brackish marshlands environments around 5,400–5,100 cal. BP.

The rapid changes in aquatic and terrestrial ecosystems were also related to other key factors such as fire disturbance and an intensification of land-use activities. However, the climatic-induced changes in the diatom communities of LM were related to paleoclimatic shifts that had a continental to global extent. On millennial scales, it is likely that the climatic changes observed in the Mediterranean area were closely linked to those in Northern Africa and Central Europe. In agreement with previous studies, we suggest that similar linkages between Mediterranean and Central European climatic changes occurred also at century scales.

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