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The last 7 millennia of vegetation and climate changes at Lago di Pergusa (central Sicily, Italy)

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Abstract

The aim of this study is to investigate climate changes and human activities under the lens of palynology. Based on a new high-resolution pollen sequence (PG2) from Lago di Pergusa (667 m a.s.l., central Sicily, Italy) covering the last 6700 yr, we propose a reconstruction of climate and landscape changes over the recent past in central Sicily. Compared to former studies from Lago di Pergusa (Sadori and Narcisi, 2001), this work provides a reconstruction of the evolution of vegetation and climate over the last millennia in central Sicily, indeed completing previous results with new data which is particularly detailed on the last 3000 yr.

Joint actions of increasing dryness, climate oscillations, and human impact shaped the landscape of this privileged site. Lago di Pergusa, in fact, besides being the main inland lake of Sicily, is very sensitive to climate change and its territory was inhabited and exploited continuously since the prehistory. The lake sediments turned out to be a good observatory for the natural phenomena occurred in the last thousands of years.

Results of the pollen-based study are integrated with changes in magnetic susceptibility and a tephra layer characterization. The tephra layer was shown to be related to the Sicanians' event, radiocarbon dated at 3055 ± 75 yr BP (Sadori and Narcisi, 2001).

We performed palaeoclimate reconstructions by MAT and WA-PLS. Palaeoclimate reconstructions based on the core show important climate fluctuations throughout the Holocene. Climate reconstruction points out four phases of cooling and enhanced wetness in the last three millennia (2600–2000, 1650–1100, 850–550, 400–200 cal BP). This appears to be the evidence of local responses to global climate oscillations during the recent past.

1 Introduction

In the present-day debate, concerning possible effects of the on-going climate change, the understanding of biological responses to past climate variations assumes a great interest. Open questions remain on local responses to global climate changes during the recent past and possible evolution under future climate forcing (IPCC, 2007; Giorgi and Lionello, 2008). Palaeoclimate reconstruction gives a basis for predicting and limiting the effects of global warming on local vegetation and climate in highly sensitive areas.

Although the high interest for the understanding of climatic and environmental evolution under Mediterranean conditions, due to the scarcity of sites suitable for palaeoecological analyses there are only a few works that retrace the vegetation and climate history of south-central Mediterranean. Besides, they underline an important spatial variability of landscapes and local responses to climate changes (de Beaulieu et al., 2005; Carrión et al., 2010a, b; Magny et al., 2012). In this context, understanding responses to climate changes in Sicily, the largest Mediterranean island, is particularly interesting, as its central geographic position in the Mediterranean Basin makes it a key region for the understanding of Holocene climates and environments. Important and expected differences are found in Sicily itself, in particular, between the inland and the coast (Noti et al., 2009; Sadori and Narcisi, 2001; Tinner et al., 2009). Sicily was inhabited since the Palaeolithic and interactions between climate changes and human activities have to be expected. It is clear that in such sites a close relationship between humans and their environment exists, but the way individuals or groups adapt to or impact on their environment (or do both) must be considered on a different scientific base, case by case (Mercuri et al., 2011; Sadori et al., 2010).

In particular, Lago di Pergusa is, both for geographic location and human history, in a crucial and privileged position to study the landscape changes occurred since prehistory.

This peculiarity is mainly due to the strong seasonality and the heterogeneity of its climate (Zampino et al., 1997), the high rate of biodiversity and endemism (Brullo et al., 1995, 1996; Di Pasquale et al., 1992; Quezel et al., 1993), the long human history (Bernabò Brea, 1961) and the progressive aridification of last millenaries recorded in former studies (e.g. Frisia et al., 2006; Magny et al., 2011, 2012; Pérez-Obiol and Sadori, 2007; Sadori and Narcisi, 2001).

2 Study area

Lago di Pergusa is located in central Sicily, Southern Italy (37°31′ N, 14°18′ E), at 667 m a.s.l. (Fig. 1a). The study site features were already described (Sadori and Narcisi, 2001 and therein references) and are hereafter summarized. The lake (surface area 0.5 km^2, catchment ca. 7.5 km^2) occupies an endorheic basin with catchment composed by Pliocene marine (sandstone, claystone) deposits, solely fed by rainfall and groundwaters and has experienced strong lake-level variations imputed to evapotranspiration. This phenomenon made it very sensitive to seasonal and long-term climatic variations. At present the lake level surface is controlled.

Climate in the area of Pergusa is cooler and moister than along the coasts, with annual precipitation between 500–700 mm and mean annual temperature of 13.4 °C (Enna weather station). Archive data from three meteorological stations show that precipitation decreased during the second half of last century. The lake is particularly vulnerable to climate changes, lying at present at the border of three areas with different aridity indices (Fig. 1b, Duro et al., 1997). The lacustrine vegetation (Fig. 1c, Calvo et al., 1995) before the water body regulation of last years, consisted in several concentric belts: an external belt (Fig. 1c, a), some meters wide, of almost only *Phragmites australis* (Cav.) Trin., an inner discontinuous belt (Fig. 1c, b) of halophilous plants characterized by *Juncus maritimus* Lam., and an internal ephemeral zone directly depending on the lake-level fluctuations and constituted by halophilous and seasonal plant communities (c, d, and e belts), mainly characterized by chenopods as *Atriplex latifolia* Wahlenb. (belt c), *Suaeda maritima* (L.) Dumort. (belt d) and *Salicornia patula* Duval-Jouve and many nytrophilous Asteraceae, both Asteroideae and Cichorioideae (belt e).The lake is at present surrounded by open landscapes dominated by xerophytic grasslands (Pignatti, 1994) and crop cultures, often abandoned. The only

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traces of natural vegetation are represented by rare trees of *Quercus virgiliana* (Ten.) Ten., *Quercus ilex* L., *Quercus pubescens* Willd., *Quercus suber* L. and *Rhamnus alaternus* L.

Human activity is documented in central Sicily since the Palaeolithic Age (Tusa, 1992). Traces from the Eneolithic Age, besides others, are found in the nearby site of Cozzo Matrice, located on a hill at the edge of the catchment of the lake and active also during Greek times (Touring Club Italiano, 1989). In the close surroundings of the lake (Fig. 1d) the Bronze and Iron Age periods are well documented (Bernabò Brea, 1961; Giannitrapani and Pluciennik, 1999; Tusa, 1992). Diodorus Siculus (Library of History, V, 6, 2–4) reported that the area of Pergusa around 3000 yr ago was first settled by Sicanians, then by Siculis. Greeks, Siracusans and Carthaginians alternated in the territory. Under the Romans, Enna (*Castrum Hennae*) became a rich and important centre for wheat trade and remained so also under the Byzantines and the Arabs.

3 Methods

3.1 The sediment core

A 6.26 m long sediment record (composed core PG2) was retrieved from Lago di Pergusa (Fig. 1a) in 2006 with a UWITEC coring platform with a percussion piston coring technique. Particular care was paid to recover and store the top decimetres with a gravity corer. Twin cores were retrieved, and segments were extracted and stored at 4 °C at the University of Franche-Comte (France).

Magnetic susceptibility (MS) was measured in the cores at 5 mm resolution with a Geotek multi-sensor core logger (Gunn and Best, 1998). MS was measured on split cores with the MS2E1 surface-scanning sensor from Bartington Instruments, which was adapted for fine-resolution volume magnetic-susceptibility measurements (Vannière et al., 2004). These analyses allow us to establish stratigraphic correlations

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useful for constructing the master sequences (PG2), guaranteeing complete records without any gaps or redundancies.

3.2 Dating

Plant macrofossils were not visible to the naked eye, so several sediment samples were processed to find plant macroremains suitable to be radiocarbon dated. Four plant samples (two seed samples ascribed to *Scirpus* sp. and two wood fragments) have been selected for AMS radiocarbon analysis.

A tephra layer, highlighted by magnetic susceptibility, was morphologically and geochemically analyzed. The sediment was washed, filtered, dried and then embedded in epoxy resin and screened for glass shards fragments using scanning electron microscopy (SEM). Energy-dispersive-spectrometry (EDS) analyses of glass shards and scoriae fragments were performed using an EDAX-DX micro-analyser mounted on a Philips SEM 515 at the Dipartimento di Scienze della Terra, University of Pisa, employing a 20 kV acceleration voltage, 100 s live time counting, 2100–2400 shots per second, and ZAF correction. To avoid alkali loss, especially Na, a window spot was used (usually with side ca. 10 µm). Performance of the instrument is extensively discussed elsewhere, especially in comparison with wave dispersion spectroscopy (Caron et al., 2010; Cioni et al., 1997; Marianelli and Sbrana, 1998; Sulpizio et al., 2010; Vogel et al., 2009), indicating comparable performances on major elements, and will not be discussed further. To perfectly compare our data with those obtained by Sadori and Narcisi (2001), the tephra layer found in core PRG1 was re-sampled and re-analyzed.

3.3 Pollen analysis

Pollen extraction from the sediment samples followed Goeury and de Beaulieu (1979). 300 terrestrial pollen grains were counted on average under a transmitted light microscope at a magnification of 400X. Pollen grain identification was based on photographs (Reille, 1992, 1995, 1998) and on the reference collection of Laboratoire

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Chrono-Environnement (Franche-Comté University, France). Pollen percentages were calculated on the basis of total arboreal and non-arboreal terrestrial pollen grains.

3.4 Climate reconstruction

Climate reconstructions inferred from pollen data are based on two different approaches: the modern analogue technique “MAT” (Guiot, 1990), based on a comparison of past assemblages to modern pollen assemblages, and the weighted average-partial least square method “WA-PLS” developed by ter Braak and Juggins (1993) which requires a real statistical calibration. The MAT has been used in a number of studies focusing Mediterranean regions (e.g. Desprat et al., 2013; Peyron et al., 2011, 2012; Pross et al., 2009) and the WA-PLS has recently been successfully tested in Mediterranean regions (Finsinger et al., 2010; Peyron et al., 2012), showing its reliability in linking modern pollen data to climate in the Italian area (Finsinger et al., 2007). More details on these two methods are given in Peyron et al. (2012). For the MAT and the WAPLS, we use the modern pollen dataset developed by Dormoy et al. (2009) restricted to the Mediterranean area (longitude: -10 to 40°, latitude: 30 to 45°) and containing 1146 samples. The number of selected analogues was 8 (MAT) and the number of components taken was 2 (WA-PLS), based on the results of the cross-validations (leave-one-out and bootstrap). As another validation test, we have distinguished two distinct subsets in the modern pollen database by applying a random samples selection. This step produced two modern datasets, each containing 573 samples that were used respectively for the training and the validation of transfer functions based on WA-PLS and MAT methods. Statistical processing and transfer functions were performed using R, especially packages “rioja” (http://www.r-project.org/) and “bioindic” (CEREGE Website).

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4 Results

4.1 The core and its chronology

Visual core description was carried out. From bottom core to 310 cm the sediment consists of olive grey to brownish mottled silty clay. The upper part of the core is composed of greyish silty clay and dark to very dark silty clay alternating with silty and sandy laminae. Some gradational contacts have been identified. Oxydised spots and very dark levels are present. Bioturbation and shell fragments occur at the bottom of the core. Variations in the sediment density were also highlighted by magnetic susceptibility analyses (Fig. 2). The magnetic susceptibility trend shows the presence of ashes dispersed in less than 10 cm of sediment of the composite core (between 465 and 475 cm), corresponding to the tephra between 47–53 cm in the core section 01-C2. In correspondence with the ashes, magnetic susceptibility peaks at 53 (the mean SI of the record is 2.9). The tephra comprises principally dark, brown, blocky fragments. Two types of fragments can be distinguished: the rarest, is characterized by a few spherical or ovoid vesicles and a prevailing glassy matrix, whereas the most common type is characterized by a crystalline groundmass mostly composed by plagioclase, and to a lesser extent by pyroxene and rarely by olivine. Ti-Fe oxides are also present. In this second type, glass is usually interstitial or can be absent. This makes the analyses particularly complex, producing a dispersion of chemical data of the glassy matrix (Table 1). Compositionally, a single-shard ranges principally from mugeritic and benmoreitic field, partially straddling the photephritic compositions.

The tephra characteristics and its chemical composition perfectly match with those determined by Sadori and Narcisi (2001), and particularly with the new set of data produced for comparison (Fig. 3, Table 1). As extensively discussed by Sadori and Narcisi (2001) the features of the tephra at Lago di Pergusa are similar to that from the Etna Volcano eruption, which was strong enough to make ashes reach the Balkans (Sulpizio et al., 2010; Wagner et al., 2008), and which was dated to 3150 ± 60 yr BP by radiocarbon on charred material from the top of the eruption (Coltelli et al., 2000). In

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core PRG1 Sadori and Narcisi (2001) obtained an age of 3055 ± 75 yr BP just below the tephra layer.

The four radiocarbon ages obtained from macroremains are consistent with the radiocarbon age available for the tephra (Sadori and Narcisi, 2001) and were used to elaborate an age/depth model based on linear interpolation (Fig. 2, Table 2).

Calculations were done using the program Clam (Blaauw, 2010), which calibrated the ^{14}C and tephra-inferred dates following IntCal09 (Reimer et al., 2009). The new core PG2 covers the last 6700 calendar years. Figure 2 shows that the sedimentation rate of core PG2 was lower in the deeper part of the core and that it increased since 3000 cal. BP appearing "constant" until present-day. Ages are expressed as calendar years BP (cal BP) unless differently stated.

4.2 Pollen results

A total of 123 pollen and spore types (including 35 tree and shrub taxa and 75 herbs) were identified. Due to the high sedimentation rate of the last 3000 yr, a quite good detail is obtained for the period, with an average of a sample every 6 cm (i.e. a temporal resolution of ca. 50 yr). Data from core PG2 are shown in Figs. 4 (arboreal and non arboreal taxa) and 5 ("ecological groups" and total concentration).

Pollen Zone 1 (PZ1): 6.26–5.7 m (ca. 6730–5375 cal BP). The bottom of the sequence is radiocarbon dated to 5780 ± 40 yr BP. AP % are between 60 and 80 %, pollen concentration ranges from 19 000 to 135 000, and the number of taxa from 27 to 37. Deciduous and evergreen oak (*Quercus*) pollen (both peaking at 40 %), olive-tree (*Olea*) and elm (*Ulmus*) between 5 to 10 %, beech (*Fagus*) and hazel (*Corylus*) at less than 5 % are the main taxa. Arboreal pollen is dominant in this pollen zone and Poaceae do not represent more than 20 % of the total pollen. Among herbaceous taxa, cerealia, Ranunculaceae, Chenopodiaceae, *Plantago*, *Rumex*, m *Artemisia*, Cichorioideae undiff., Apiaceae, Asteroideae undiff. and Labiatae are recorded as a continuous signal, with percentages higher than 1 %, since the bottom of the core.

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Pollen Zone 2 (PZ2): 5.7–4.7 m (ca. 5375–3150 cal BP). The Sicanian's tephra layer, radiocarbon dated at 3055 ± 75 yr BP in core PRG1 was detected between ca. 465 and 475 cm. AP % are between 30 and 65 %, pollen concentration ranges from 12 000 to 110 000, and the number of taxa from 28 to 45. The transition to this pollen zone is marked by an abrupt decrease of AP % from 80 to 50 %, involving both oak pollen types (from > 30 % to < 5 %) and a relative increase of Poaceae (ca. 10 to 30–40 %), becoming dominant from this zone to the top of the sequence; several herbs (in particular Chenopodiaceae, *Plantago*, Ranunculaceae, Apiaceae, Asteroideae undiff., *Artemisia*) show a slight increase. Undifferentiated cereals and *Secale* are currently recorded from this zone up to top core. *Papaver* and *Centaurea cyanus* pollen grains are recorded at the end of the zone. The zone is also characterized by the continuous presence of Cyperaceae (more than 1 %). Pollen percentages of dominant taxa (*Quercus* deciduous and evergreen types and Poaceae) show important and rapid variations within this zone; *Olea* and *Ulmus* show low percentages but also slight variations. *Fagus* and *Quercus* cf.*suber* are recorded continuously.

Pollen Zone 3 (PZ3) is split into two subzones. AP % are between 45 and 65 %, pollen concentration ranges from 16 000 to 85 000, and the number of taxa from 26 to 52. Pollen subzone 3a (PZ3a: 4.7–4.5 m; ca. 3150–3000 cal BP). AP % are between 50 and 65 %. This short zone is characterized by the sudden increase of *Olea* to ca. 20 %, while both *Quercus* dominant pollen types decrease as well as *Ulmus*. Poaceae and Chenopodiaceae decrease,while other herbs do not show significant changes. Pollen subzone 3b (PZ3b: 4.5–4 m; ca. 3000–2600 cal BP). AP % are between 45 and 60 %. *Olea*, dominating the previous subzone, shows a strong decrease. It seems first replaced by *Quercus ilex* type and *Pistacia*, then by *Quercus pubescens* type. *Ephedra fragilis* is continuously present from this zone to the top of the diagram. Poaceae also tend to increase despite many rapid variations. Among other herbs, Chenopodiaceae do not show significant changes.

Pollen zone 4 (PZ4): 4–3 m (ca. 2600–1885 cal BP). AP % are between 20 and 45 %, pollen concentration ranges from 9200 to 76000, and the number of taxa from 32 to

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46. The top of this zone is radiocarbon dated to 1961 ± 33 BP. An important further opening of the wood is found, tree pollen suddenly drops from 50 to 25 %, showing a decrease in both mesophilous (deciduous oaks and elm) and Mediterranean taxa (evergreen oaks, olive). Two shrub taxa show increase, namely *Pistacia* and *Ephedra fragilis*. A strong increase in anthropogenic pollen is worthy of mention. Poaceae are mainly between 25 and 35 %, showing many rapid variations. It is important to note the increase of Chenopodiaceae, first matching the one of Cichorioideae, and Asteroideae undiff. A consistent peak of Cichorioideae (20 %) just preceeds a slight expansion of Cyperaceae, becoming more important towards the top of the diagram. The end of the zone is marked by an abrupt peak of Chenopodiaceae (40 %).

Pollen Zone 5 (PZ5): 3–2 m. It is split into two subzones. AP % are between 20 and 45 %, pollen concentration ranges from 10 000 to 45 000, and the number of taxa from 33 to 48. Pollen subzone 5a (PZ5a): 3–2.7 m; ca. 1885–1620 cal BP): A slight recover of AP (> 45 %), mainly due to evergreen *Quercus* (5 to 20 %), and followed by a slight expansion of *Quercus pubescens* type, marks the transition to this new zone. Poaceae show a decrease at the beginning of this zone together with other herbs. Anthropogenic taxa show a decrease too. Pollen subzone 5b (PZ5b: 2.7–2 m; ca. 1620–1000 cal BP): it is mainly characterized by a lowering of arboreal taxa to 20 %, *Pistacia* included, and the correspondent increase of Poaceae and anthropogenic taxa. The slight but meaningful expansion of *Secale* is worthy of mention. Urticaceae show the start of a continuous curve. The zone ends with a peak of Chenopodiaceae.

Pollen Zone 6 (PZ6): 2–0.4 m (ca. 1000–170 cal BP). The bottom of this zone is radiocarbon dated to 1032 ± 30 yr BP. AP % are between 25 and 50 %, pollen concentration ranges from 3700 to 23 000, and the number of taxa from 34 to 53. This zone is characterized at its bottom by a phase of increase for both oak-types, followed by an increase of Poaceae, the dominant taxon. The zone ends with an expansion of evergreen *Quercus* (5 to 30 %) following an increase of deciduous *Quercus* and of Chenopodiaceae. Anthropogenic taxa seem to be less important than in the previous two zones.

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Pollen Zone 7 (PZ7): 0.4 m to surface (ca. 170 cal BP to present). AP % are around 40 %, pollen concentration ranges from 3400 to 5300, and the number of taxa from 40 to 43. The recovery of *Olea* (< 5 to 20 %), continuous percentages of cultivated trees (*Juglans*, *Castanea*) and percentages of 5 % of *Juniperus* characterize this last zone. It is also to note an increase in cerealia, *Plantago*, and anthropogenic taxa as a whole.

5 Discussion

5.1 Comparison between PG2 and PRG1 cores

The PRG1 core records the last 12 000 yr in 456 cm, while the new core, PG2, spans ca. 6700 yr in 626 cm. Comparison of the two cores (Fig. 6) shows that they record similar vegetation dynamics, but also important differences in the temporal resolution of the last 3 millennia, confirming that a hiatus/es or a strong reduction in the sedimentation rates must be present in the upper part of core PRG1, as supposed by Sadori and Narcisi (2001). The fall of *Quercus ilex* and *Olea* (at ca. 425 cm in PG2 and at ca. 100 cm in PRG1), followed by a peak of *Quercus pubescens* and a slight expansion of *Pistacia* can be easily found in both cores, while the peaks of *Quercus ilex* and of Chenopodiaceae recorded in PG2 are not detected in PRG1. Considering the chenopods vegetation belts that formed in case of lake level lowering (Calvo et al., 1997, Fig. 1c) the possibility that PRG1 was taken in a periodically emerged part of the lake is advanced. Repeated lake body reductions can explain why the last 2500 yr are recorded in 4 m of sediment in PG2, while this same period was entirely recorded in the upper 70 cm of the PRG1 core.

5.2 Vegetation history: climate versus human forcing

The pollen diagrams (Figs. 4 and 5) show, from bottom to top, a tendency to forest opening. Changes in forest canopy such as opening can be interpreted either as due to aridification and/or temperature decrease or to (human) forest clearance. It is clear that environments such as the Pergusa one are highly vulnerable and that minor climatic or human changes can provide the ignition of a never-ending drying process.

Except for the bottom of the PG2 pollen sequence (PZ1), which records a forested landscape around the site, the upper zones (PZ 2 to 7) show the evolution of an open landscape dominated by Poaceae and characterized also by many other herbs. In this environment, two possibilities for understanding the Poaceae expansions have to be considered. Poaceace could have either formed vast grasslands or a hydrophylous vegetation belt around the lake itself, or both. In the first case there is a clear indication of forest opening (either human or climate induced), in the second only a climatic clue. The position of the PG2 core, neither marginal nor central in the lake like the previous PRG1 core (Sadori and Narcisi, 2001) would in fact register water body reductions (a *Phragmites* belt closer to the lake centre would mean increasing Poaceae percentages in the diagram) and expansions. We also have to consider that a reduction of precipitation would cause both a forest opening and the lowering of the lake level and that this climate change could have been enhanced by a strong land-use (forest clearance, cultivation, pasture). A clear human impact can be seen in the diagrams (Figs. 4 and 5) only since 2600 cal BP (zone 4), while before, since around 3700 yr BP, there is evidence of human presence.

As a matter of fact prehistoric populations did not change the landscape on a broad scale and a widespread human impact is found only since the Roman period in Mediterranean environments (Mercuri et al., 2012; Roberts et al., 2011; Sadori, 2013; Sadori et al., 2004, 2011) and hardly detectable before the Bronze Age, when a number of peri-lacustrine settlements in the Italian peninsula were present, and the Terramare culture bloomed in the Po plain (Cremaschi et al., 2006; Mercuri et al., 2006, 2012) probably because water in that period became a less available resource (Sadori et al., 2004; Magny et al., 2009, 2011; Zanchetta et al., 2012a).

Two arguments (Sadori and Giardini, 2008) are used to explain this lack of evidence and delay in proofs coming from pollen records of the Mediterranean basin: natural vulnerability to climate change (forest clearance is not just produced by humans) and

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botanical issues (many anthropogenic indicators are indigenous and some others are often hard to distinguish from other plants).

Many edible plants such as cereals, pulses and fruit trees are in fact native to Mediterranean regions and their pollen grains, often not identifiable at a satisfying taxonomic level, are found during the whole Holocene and even before in the pollen diagrams. An exemplification can be made with cereal pollen type, which includes pollen of both cultivated and spontaneous cereals as well as of other grasses (Andersen, 1978). *Secale* (rye) is a cereal with a distinct pollen grain, distinguishable from that of other cereals. At present two species are found in the Italian flora (Pignatti, 1982): one is the cultivated *S. cereale*, the other is *S. stricta*, a Mediterranean mountain species native to Sicily (and of some central and southern Italian regions), named mountain or wild rye and growing from 600 to 1700 m a.s.l. Pollen grains of the two species cannot be distinguished. *Plantago lanceolata*, a synanthropic herb whose finding is attentively taken into account as evidence of human presence in central Europe, has pollen grains that cannot be distinguished from those of other *Plantago* species indigenous in Italy (Reille, 1992).

Under this light it is not certain at all that the increase of herbs recorded at 5400 cal BP is due to forest clearance. Also the presence of *Secale* since 4900 cal BP cannot be taken as an evidence of cultivation, even if the presence of a Copper age site, Cozzo Matrice, is documented at the edge of Lago di Pergusa catchment (Fig. 1d). A different scenario is found since ca. 3700 cal BP, when *Secale* and companion species of crops, like *Papaver* and *Centaurea cyanus*, as well as *Linum* and *Vitis* are found. Since 3200 cal BP an important and abrupt spread of *Olea* is of note. Wild olive-tree (*Olea europea* var. *oleaster*) is regarded as autochthonous in Sicily and requires a typical Mediterranean climate characterized by summer aridity with an average annual temperature of 14–20 °C and precipitation varying between 300 and 1000 mm yr^{-1} (Pignatti and Nimis, 1995). The cultivated olive tree (*Olea europea*) is now found in the whole area colonized by the evergreen oak-forests, but the wild natural olive-tree is typical of the warmest areas of Mediterranean. It is then difficult to consider as natural the

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findings of more than 20 % of *Olea* pollen at Pergusa, knowing that these percentages are comparable to the ones that were found at Gorgo Basso (Tinner et al., 2009), on the western coasts of Sicily, during the phases of wild olive-tree maximum development.

Even if the more obvious interpretation of pollen data points to human action as the main cause of olive expansion occurring at Pergusa between 3200 and 2800 cal BP, we have to consider that increased temperature and decreased precipitation might have favoured (or allowed) the spread of thermophilous and less moisture-demanding taxa. Cichorioideae and Asteroideae, strongly increasing since 3200 cal BP with abundant Chenopodiaceae and overwhelming Poaceae could in fact have formed the ephemeral vegetation belts occurring when the lake level decreased (Sect. 2, Fig. 1c) for a water shortage and a change towards drier climate conditions. In this case Cichorioideae and Asteroideae should not be considered as anthropic indicators (Figs. 4 and 5), but as dryness ones. Also mesophilous arboreal taxa like elm and deciduous oaks decrease in correspondence with the spread of olive. *Olea* decline is followed by a rapid succession of short increase in oaks, but it also coincides with the spread of *Pistacia* trees/shrubs and an increase of *Ephedra fragilis* (ca. 2800 cal BP), in parallel with the definitive decline of deciduous *Quercus*. These elements support the hypothesis of a transition at 3200 cal BP from mixed oak-forests to Mediterranean inland-forests infiltrated by typical scrub or "macchia" taxa, a sort of pioneer vegetation. The fact that *Pistacia* is found in both Pergusa sequences but it is never more than 5 % supports the hypothesis of more thermophilous and drier conditions around the site, or of intense grazing, but not the onset of the Mediterranean "macchia".

Based on the order of these events, the record suggests a successional dynamics following a human-induced perturbation of the local vegetation, whose effect might have amplified the aridification phase reconstructed in Sicily over the last three millennia by lake level oscillations (Magny et al., 2011, 2012). Stable isotope curves from previous cores from Lago di Pergusa (Sadori et al., 2008; Zanchetta et al., 2007) clearly show that the more arid period of the Holocene is found after 3000 cal. BP. The speleotheme portion from ca. 3600 to ca. 2800 cal BP from Grotta Carburangeli, a cave in northern Sicily (Frisia et al., 2006), shows lower oxygen and carbon isotope values than in the early Holocene and a small peak centered at ca. 3100 yr BP. The stalagmite stopped to grow after 2800 cal BP, suggesting enhanced dryness. An increase of *Olea* pollen soon before 3000 cal BP is found in Adriatic cores and in Italian continental ones (Combourieu-Nebout et al., 2013; Di Rita and Magri, 2009; Mercuri et al., 2012, 2013), indicating that this was a rather general change in the Mediterranean landscape. The exploitation of olive in Greece during the Bronze Age has been documented by both macroremains and pollen (Kouli, 2012). Presence of olive stones is documented at the early Iron Age archaeological site of Selinunte, southwestern Sicily (Stika et al., 2008), some centuries later than the pollen spread of Pergusa. No evidence of this step was found at Gorgo Basso (Tinner et al., 2009), inside the natural area of distribution of *Olea europea*, but we have to consider that Lago di Pergusa lies in a privileged position to observe past land-use, in a zone widely and strongly exploited in the Bronze Age (Fig. 1d).

At Lago di Pergusa the deterioration of climate conditions accompanies the evolution of human activities that become stronger over the last 2.5 millennia. Pollen indicators of cultures (*Secale, Linum, Vitis*) are found as a continuous signal over the last millennia. Moreover, herbaceous taxa found nowadays in the lacustrine vegetation belts in the case of water decrease, are quite important.

5.3 Climate reconstruction

Table 3 shows that the reliability of both methods is good, in particular for the reconstruction of summer precipitation and winter temperature. Quantitative climate reconstructions for PG2 were performed for annual temperature and precipitation, and summer/winter temperature and precipitation (Fig. 7). Values of the seasonal temperature and precipitation parameters are expressed as anomalies and thus can be compared with the results obtained from PG1 core (Peyron et al., 2012) and with the reconstruction of temperatures of the warmest/coldest month for South-Western Europe (Davis et al., 2003). It is clear that although similarities exist, there are distinct differences between methods. The most important difference between methods occurs over the last 3000 yr (Fig. 7) with more marked changes using the MAT. These strong oscillations can be due to human impact and to the fact that MAT is more sensitive than WA-PLS, particularly when the variability of modern pollen spectra is highly due to human impact. For the last 3000 yr, the amplitude of the changes reconstructed with the MAT needs to be interpreted with caution. However, if high criticism was often addressed to the reliability of modern pollen data for the reconstruction of climate, given that human impacts may influence these modern pollen samples, our pollen-based climate reconstructions appears to show solid results and a consistent trend through time.

Despite differences in the reconstruction of the amplitude of changes, both methods underline a clear climate trend towards aridification and warming over the last 3 millennia. This trend was interrupted by several phases characterized by cooling and moisture. A first cooling phase is reconstructed between 2600 and 2000 cal BP, which corresponds to a maximum of precipitation. Other phases of cooling and moisture are found at 1650–1100, 850–550, 400–200 cal BP.

Enough precipitation should have been available in the ancient Greek site of Morgantina, nearby Pergusa, as a public fountain was fed only by rainy water in the 4th cent. BC (Malcolm Bell, personal communication, 31 January 2013). It is interesting to note what happened in other Mediterranean sites: the lake level at lake Malik (Albania) is medium/high between 2600 and 2000 cal BP (Fouache et al., 2010) and at lake Accesa (central Italy) between ca. 2800 and 2000 cal BP (Magny et al., 2007). Most importantly this period roughly coincides with the highest phase of the lake level and the amount of precipitation (2500–2140 cal BP) in southern Spain as reconstructed in Zoñar Lake (Martín-Puertas et al., 2009). Stable isotope records from lake Shkodra (Albania) show the wettest period of the last 4500 cal BP at ca. 2500–2000 cal BP (Zanchetta et al., 2012b). The first two phases of cooling (2600–2000, 1650–1100 cal BP) chronologically comprehend the last two periods of the Calderone glacier expansion (Giraudi et al., 2011). A general correlation is found with climate trends reconstructed in Morocco (Cheddadi et al., 1998) and with the phases of more important erosional activity in Tunisia (Marquer et al., 2008), which seems well correlated with phases of precipitation increase that we reconstruct in Sicily.

These arguments support the hypothesis that landscape changes recorded at Pergusa over the recent past were mainly related to climate stress more than to human impact on vegetation.

6 Conclusions

In order to assess the degree of human-environment interactions there is the urgent and unavoidable need to carry out scientific investigations on natural archives linked to human history like Lago di Pergusa. Lago di Pergusa turned out to be a privileged observatory for climate changes and human activity, even if the two signals cannot be easily distinguished only by pollen. This is not a negative issue at all, but a positive one. Failure to consider the complex interactions between humans and their environment could have lead either to an environmentally deterministic view of socio-cultural change or to a complete neglect of possible environmental impact on human action and history.

Our data show that the first phase of opening of forests recorded in the core lasted for more than two millennia, from ca. 5400 to ca. 3200 cal BP, a period characterized by frequent though slight vegetation changes. A strong change of the environment occurred around 3200 cal BP, when an expansion of *Olea* is found. After 2700 cal BP human impact is uncontested and overlapped a natural change. We were in fact able to get two different, mixed and hard to disentangle, clues from pollen, signalling both a climatic and a human impact.

A solution to come over from this impasse was to use present-day lacustrine vegetation studies, climate reconstructions from pollen using different methods and other proxies from the same site and from nearby sites. Preliminary data from isotope analyses of the sediments (Zanchetta et al., 2013) show several anomalies between $\delta^{18}O$

and $\delta^{13}C$ curves and the vegetation changes, probably to correlate with periods of intense land exploitation.

The important fluctuations of vegetation around Lago di Pergusa seem to be mostly dependent from climate variations even over the recent past, but cannot be regarded as totally independent from human activities.

Our climate reconstruction is inevitably influenced by human-induced changes of the landscape and the amplitude of the reconstructed changes might be overestimated in our work. However, our results are consistent with former works from various sites all around the Mediterranean basin, which were based on independent proxies.

Our data underlines a synergy between human activities and climate in shaping the landscape in Sicily in the recent past. We also propose that climate had an effect on human activities, which could have been oriented towards the culture of olive-trees in the Sicilian inlands, during a period of climate conditions favorable to its spread.

Climate reconstruction points out four phases of cooling and enhanced wetness in the last three millennia (2600–2000, 1650–1100, 850–550, 400–200 cal BP). They are consistent with other climate proxies from the Mediterranean area, once more indicating that a close relation existed between climate and human history.

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Table 1. Lago di Pergusa. Chemical data for the tephra layer from core PG2 (this paper) and PGR1 (Sadori and Narcisi, 2001). Samples from PRG1 were newly analysed.

	SiO_2	TiO_2	Al_2O_3	FeO_{tot}	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	ClO	Total	K_2O+ Na_2O	K_2O/ Na_2O
PG2-2	54.59	2.40	17.53	7.31	0.32	2.07	4.49	5.82	4.54	0.55	0.38	100	10.36	0.78
PG2-3	53.81	1.78	17.67	8.26	0.05	3.09	5.67	5.15	3.77	0.5	0.25	100	8.92	0.73
PG2-4	52.47	1.95	16.65	9.84	0.19	3.42	7.38	4.76	2.59	0.52	0.23	100	7.35	0.54
PG2-5	52.09	1.94	16.58	9.74	0.17	3.36	5.94	5.27	4.20	0.48	0.23	100	9.47	0.80
PG2-6	52.86	1.90	17.31	9.09	0.16	3.22	6.16	4.20	4.74	0.58	0.18	100	8.54	0.80
PG2-7	51.86	1.95	16.98	10.34	0.17	3.42	7.24	4.61	2.82	0.38	0.23	100	7.43	0.61
PG2-9	52.47	2.07	16.46	9.56	0.35	3.43	6.48	5.06	3.57	0.34	0.21	100	8.63	0.71
PG2-10	52.81	1.97	16.73	9.80	0.21	3.52	6.94	4.49	2.88	0.43	0.22	100	7.37	0.64
PG2-11	52.92	2.21	16.19	9.97	0.32	2.95	6.60	5.10	3.04	0.42	0.28	100	8.14	0.60
PG2-12	53.21	2.12	16.78	9.81	0.38	3.29	4.16	5.14	4.40	0.41	0.30	100	9.54	0.86
PG2-13	51.98	2.11	16.53	10.06	0.26	3.55	6.36	4.74	3.73	0.52	0.16	100	8.47	0.79
PRG1-1	55.56	2.04	16.72	9.16	0.19	3.42	6.17	4.88	4.20	0.51	0.15	100	9.08	0.86
PRG1-2	55.56	2.44	16.23	8.58	0.10	2.22	3.63	5.31	4.98	0.78	0.17	100	10.29	0.97
PRG1-3	55.19	2.12	16.53	9.46	0.07	2.60	4.53	4.36	3.97	0.44	0.46	100	8.6	0.86
PRG1-5	52.31	2.00	16.72	8.84	0.20	3.18	6.30	5.47	4.36	0.45	0.17	100	9.83	0.80
PRG1-6	52.84	2.01	16.31	9.95	0.10	3.25	6.27	4.86	3.71	0.46	0.24	100	8.57	0.76
PRG1-6b	52.99	2.16	16.07	10.2	0.27	3.33	6.45	4.47	3.42	0.42	0.22	100	7.89	0.76
PRG1-7	52.94	1.90	16.94	9.2	0.28	3.56	6.74	5.18	2.65	0.40	0.21	100	7.83	0.51
PRG1-8	52.53	2.18	16.55	9.77	0.31	3.47	7.19	4.66	2.76	0.38	0.20	100	7.42	0.59

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Table 2. Lago di Pergusa (core PG2). AMS radiocarbon dates.

Laboratory code	Material	Depth (cm)	^{14}C yr BP	Calendar age BP (2σ)
Poz-36022	wood	36	130 ± 30	57–151
Ua-42145	seeds	194	1032 ± 30	911–988
Ua-42146	seeds	302–310	1961 ± 33	1863–1989
Poz-36023	wood	618	5780 ± 40	6485–6670

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Table 3. Lago di Pergusa. Climate reconstructions inferred from pollen data based on the modern analogue technique "MAT" (Guiot, 1990) and the weighted average-partial least square method "WA-PLS" developed by ter Braak and Juggins (1993).

Climatic parameter	WA-PLS (2 components)		MAT (8 analogous)	
Apparent Performance	r^2	RMSE	r^2	RMSE
Winter T (°C)	0.5674	2.8169	0.724	2.2510
Summer T (°C)	0.5085	2.7423	0.6861	2.1922
Tann (°C)	0.5778	2.5040	0.7225	2.0308
Winter Prec (mm/season)	0.3105	77.57	0.5401	63.379
Summer Prec (mm/season)	0.5799	48.555	0.8232	31.509
Pann (mm yr^{-1})	0.4255	169.84	0.6098	140.02
Empirical validation	r^2	RMSE	r^2	RMSE
Winter T (°C)	0.5505	3.7689	0.6916	3.8203
Summer T (°C)	0.5267	3.3858	0.5842	3.5166
Tann (°C)	0.5716	3.3719	0.6673	3.4569
Winter Prec (mm/season)	0.2512	74.0907	0.4817	79.956
Summer Prec (mm/season)	0.5815	67.2396	0.797	70.438
Pann (mm yr^{-1})	0.3695	191.0206	0.5815	197.11

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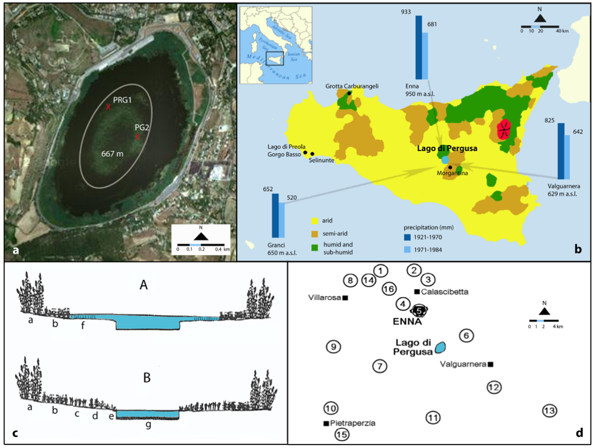

Fig. 1. Lago di Pergusa: **(a)** Location map of cores PG2 and PRG1. The ellipsis roughly marks the lake perimeter when core PRG1 (Sadori and Narcisi, 2001) was sampled. **(b)** Aridity map of Sicily and selected mean annual precipitation for three selected meteorological stations (from Duro et al., 1997, redrawn). **(c)** Sketches of lacustrine vegetation: A. maximum lake level, B. minimum lake level. Dominant taxa of the lacustrine vegetation concentric belts: a – *Phragmites australis*, b – *Juncus maritimus*, c – *Atriplex*, *latifolia* d - *Suaeda maritima*, e – *Salicornia*, f – *Chara*; g – microbial mat (from Calvo et al., 1995, modified). 1d. Main archaeological sites around Lago di Pergusa: 1 – Case Bastione (Neolithic Age, Copper Age); 2 – Realmese (Bronze Age, Iron Age); 3 – Malpasso (Iron Age); 4 – Calcarella (Bronze Age, Iron Age); 5 – Enna (Copper Age, Bronze Age, Greek period, Middle Ages); 6 – Cozzo Matrice (Copper Age, Greek period); 7 – Riparo di Contrada S. Tommaso (Bronze Age); 8 - Monte Giulfo (Greek period); 9 – Capodarso (Copper Age, Bronze Age, Greek period); 10 – Rocche (Greek period); 11 – Montagna di Marzo (Greek period); 12 – Rossomanno (Greek period, Middle Ages); 13 – Morgantina (Greek and Roman periods); 14 – Contrada Gaspa (Roman period); 15 – Contrada Runzi (Roman period); 16 – Canalotto (Middle Ages) (from Sadori and Giardini, 2008, modified).

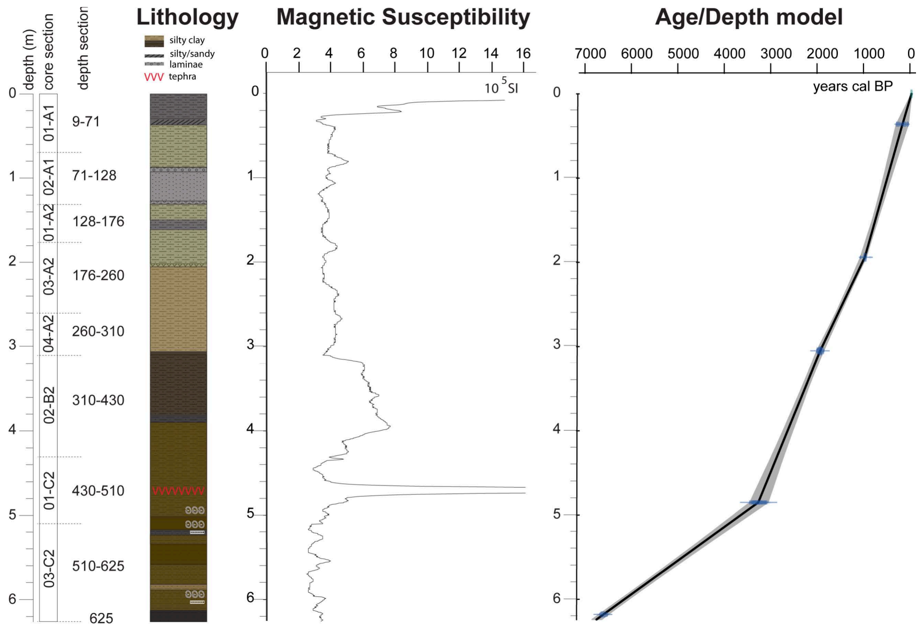

Fig. 2. Lago di Pergusa: PG2 core. Lithology, Uncalibrated Volume susceptibility, linear interpolation of AMS calibrated dates. A thin black layer, observed in the section 01-C2, corresponds to the ash event dated in PRG1 at 3055 ± 75 yr BP (Sadori and Narcisi, 2001).

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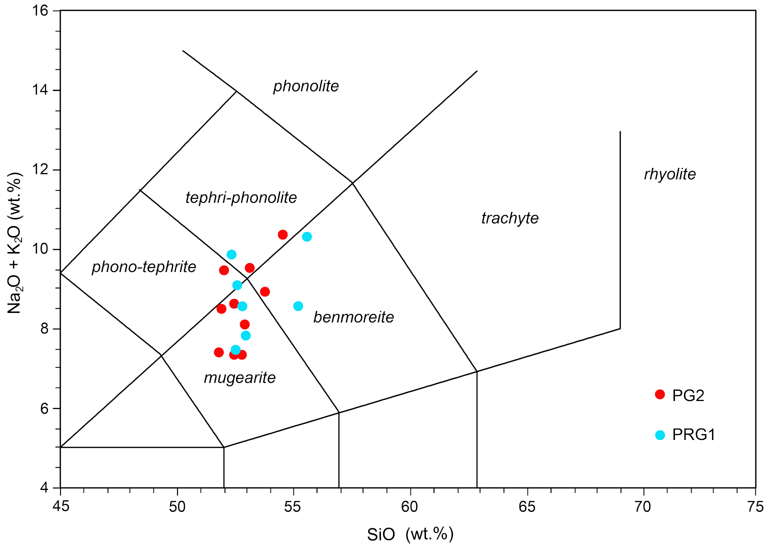

Fig. 3. Lago di Pergusa: total Alkaly vs Silica diagram (Le Bas et al., 1986) for tephra in Pergusa cores (PRG1 and PG2).

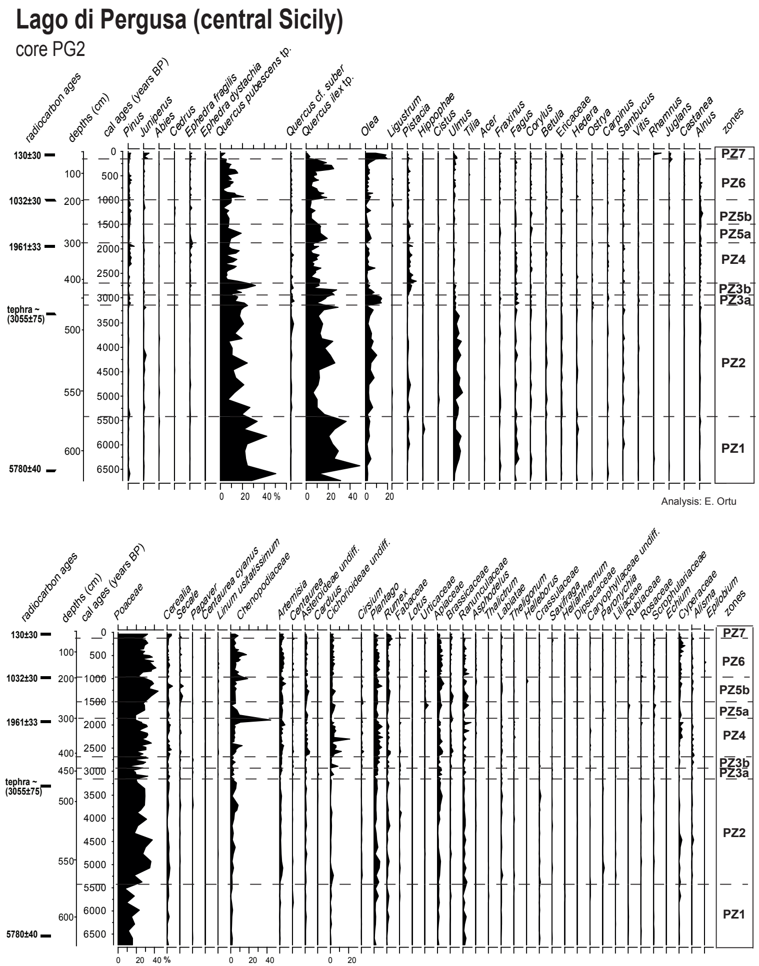

Fig. 4. Lago di Pergusa: pollen percentage diagram.

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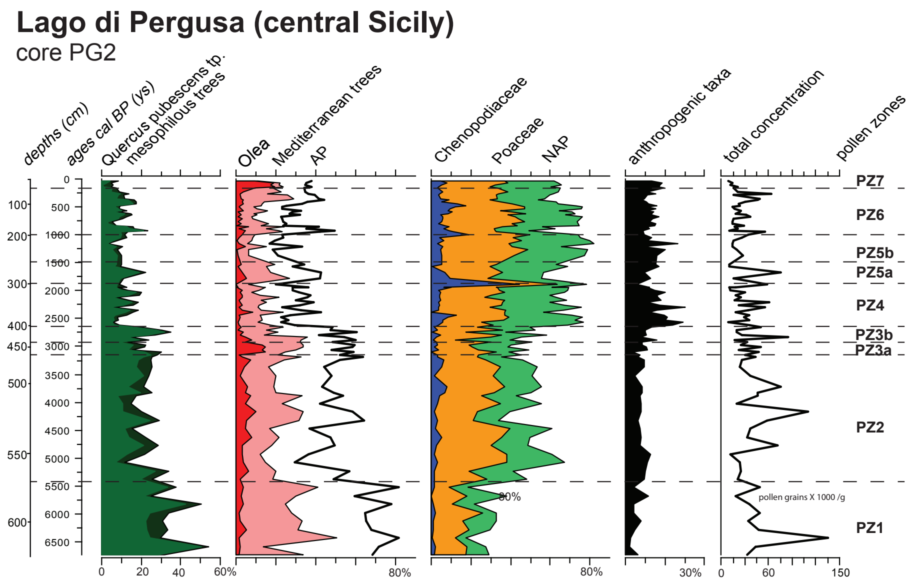

Fig. 5. Lago di Pergusa: pollen diagram. Selected cumulative curves and total pollen concentration. Mesophilous taxa = *Acer*, *Carpinus*, *Ostrya*, *Corylus*, *Fagus*, *Fraxinus*, *Quercus pubescens* type, *Sambucus*, *Tilia*, *Ulmus*. Mediterranean taxa = *Ligustrum*, *Olea*, *Pistacia*, *Phyllirea*, *Quercus ilex*, *Quercus suber*. Anthropogenic taxa = *Castanea*, *Juglans*, *Vitis*, Asteroideae, Caryophyllaceae, *Centaurea cyanus*, Cerealia, Cichorioideae, *Lavanda*, *Linum usitatissimum*, *Papaver*, *Plantago*, *Polygonum bistorta*, *Rumex*, *Secale*, *Trifolium*, Urticaceae.

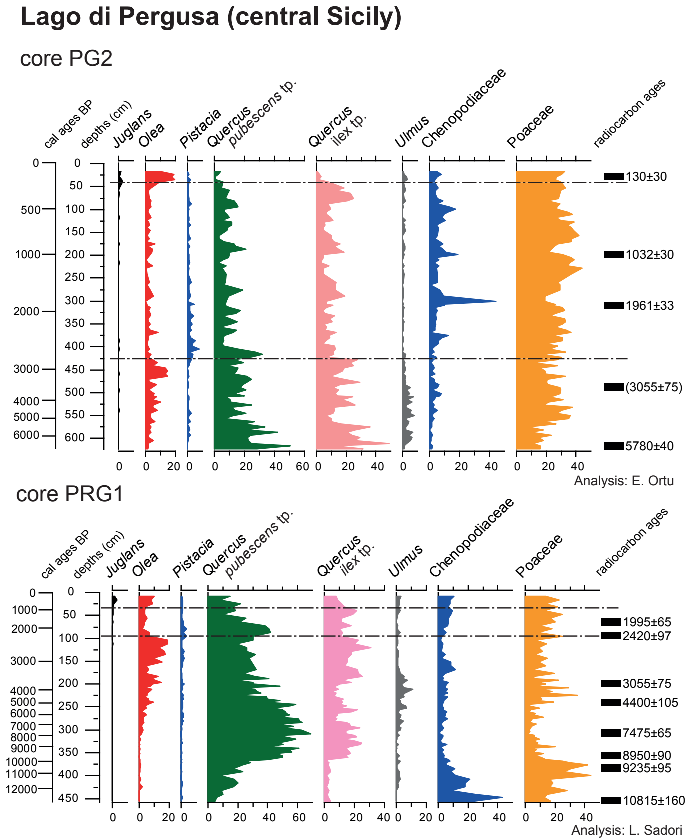

Fig. 6. Lago di Pergusa: comparison between pollen diagrams PG2 (this work) and PRG1 (Sadori and Narcisi, 2001). The diagram portions comprehended between the dotted lines probably cover the same time interval.

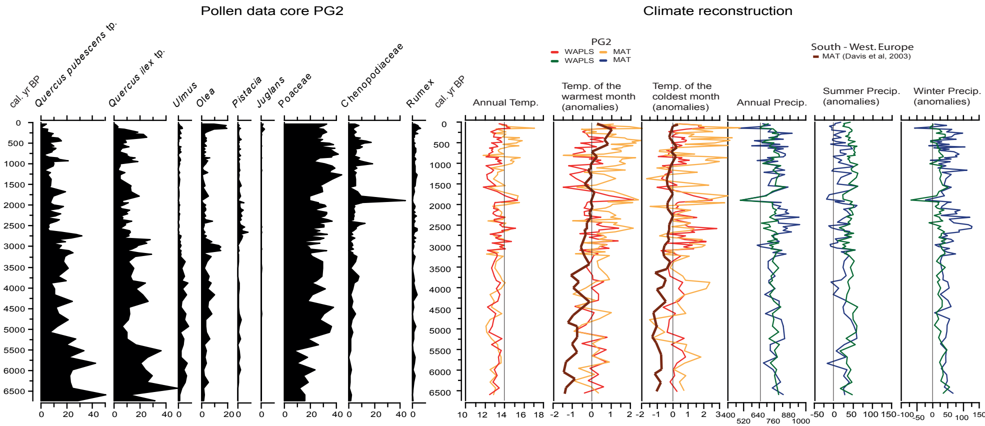

Fig. 7. Pollen-based climate reconstructions for the Pergusa PG2 with special attention to reconstructions of temperature and precipitation seasonality. Climate values are estimated using two methods: the Modern Analogues Technique (MAT), and Weighted Average Partial Least Squares regression (WAPLS). Warmest and coldest month temperatures (°C) are plotted together with the seasonal precipitation (winter = sum of December, January, February precipitation, and summer = sum of June, July, August precipitation, in mm) values. A comparison between PG2 (this study) and the reconstruction of temperatures of the warmest/coldest month (anomalies) for South Europe (Davis et al., 2003) is also shown.