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Pollen-based reconstruction of Holocene vegetation and climate in Southern Italy: the case of Lago di Trifoglietti

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Abstract

A high-resolution pollen record from Lake Trifoglietti in Calabria (Southern Italy) provides new insights into the paleoenvironmental and palaeoclimatic changes which characterise the Holocene period in the Southern Italy. The chronology is based on 11 AMS radiocarbon dates from terrestrial macro-remains. The Holocene history of the vegetation cover shows the persistence of an important and relatively stable *Fagus* forest present over that entire period, offering a rare example of a woodstand able to withstand climate changes for more than 11 000 yr. Probably in relation with early Holocene dry climate conditions which affected Southern Italy, the Trifoglietti pollen record supports a southward delay in thermophilous forest expansion dated to ca. 13 500 cal. BP at Monticchio, ca. 11 000 cal. BP at Trifoglietti, and finally ca. 9800 cal. BP in Sicily. Regarding the human impact history, the Trifoglietti pollen record shows only poor imprints of agricultural activities and anthopogenic indicators, apart from those indicating pastoralism activities beneath forest cover. The selective exploitation of *Abies* appears to have been the strongest human impact on the Trifoglietti surroundings. On the basis of (1) a specific ratio between hygrophilous and terrestrial taxa, and (2) the modern analogue technique, the pollen data collected at Lake Trifoglietti led to the establishment of two palaeoclimatic records tracing changes in (1) lake depth and (2) annual precipitation. On a millennial scale, these records give evidence of increasing moisture from ca. 11 000 to ca. 9400 cal. BP and maximum humidity from ca. 9400 to ca. 6200 cal. BP, prior to a general trend towards the drier climate conditions that have prevailed up to the present. In addition, several successive centennial-scale oscillations appear to have punctuated the entire Holocene. The identification of a cold dry event around 11 300 cal. BP, responsible for a marked decline in timberline altitude and possibly equivalent to the PBO, remains to be confirmed by further investigations verifying both chronology and magnitude. Two cold and possibly drier Boreal oscillations developed at ca. 9800 and 9200 cal. BP. At Trifoglietti, the 8.2 kyr event corresponded at Trifoglietti to the onset of cooler and drier climatic conditions which persisted until

ca. 7500 cal. BP. Finally, the second half of the Holocene was characterised by dry phases at ca. 6100–5200, 4400–3500, and 2500–1800 cal. BP, alternating with more humid phases at ca. 5200–4400 and ca. 3500–2500 cal. BP. Considered as a whole, these millennial-scale trends and centennial-scale climatic oscillations support contrasting patterns of palaeohydrological changes recognised between the North- and South-Central Mediterranean.

1 Introduction

The major climate changes which developed from the end of the last Glacial to the Holocene are now relatively well established in Europe (e.g. Björck et al., 1996, 1998). On the continent, climate history is recorded though different indicators including vegetation changes driven by variations in the orbitally-induced insolation change and associated variations in climate parameters such as precipitation and growing-season temperature. Whereas the Holocene climate may appear as a relatively stable temperate period, it was nethertheless punctuated by numerous rapid cold events such as the Preboreal and Boreal oscillations (Björck et al., 1997, 2001; Fleitmann et al., 2007; Yu et al., 2010), the 8.2 kyr event (Wiersma and Jongma, 2010) and the Neoglacial climate cooling at ca. 6000–5000 cal. BP (Magny et al., 2006b; Miller et al., 2010).

These events are also recorded in the Mediterranean area, where they suggest a strong connection between higher and lower latitude regions (e.g. Asioli et al., 1999; Magny et al., 2006a, 2007b, 2009). However, on closer examination, paleoenvironmental records point to regional diversity in the effects of rapid climate change throughout the Mediterranean region (e.g. Roberts et al., 2011a; Magny et al., 2011a). This underscores the complexity of the Mediterranean climate, which may reflect contrasting influences from both higher latitudes (e.g. deglacial events, the North Atlantic Oscillation) and lower latitudes (e.g. the tropical monsoon) which, for instance, may have affected westerly activity and associated precipitation changes over the Italian Peninsula (Magny et al., 2002, 2007a; Zanchetta et al., 2007).

Moreover, particularly in the Mediterranean regions where human impact has been widespread at least since the Neolithic (Guilaine, 2003), it is sometimes difficult to disentangle the climatic and anthropogenic forcing factors in palaeoenvironmental records (De Beaulieu et al., 2005; Roberts et al., 2011b). This complexity is reinforced by a possible climate determinism for human societies and by human-induced environmental changes (on a wider-than-local scale) which are expected to enhance regional climate impact (Jalut et al., 2009; Tinner et al., 2009). While the pollen proxy does not escape this ambiguity in paleoenvironmental reconstructions and interpretations (Sadori et al., 2010), it may be of great interest in providing direct and/or indirect evidence of anthropogenic activities (Mercuri et al., 2010).

Southern Italy is a place where climate and human influences are superimposed, with (1) orbitally induced long-term climate changes and possible short-term time-transgressive climate oscillations developing according to latitude (Di Rita and Magri, 2009), and (2) major cultural changes such as the Neolithic expansion in South-Eastern Italy between 9000 and 8000 cal. BP and in South-Western Italy between 8000 and 7500 cal. BP (Guilaine, 2003; Berger and Guilaine, 2009). Thus, Southern Italy is of great importance when discussing natural vs anthropogenic forcing of vegetation changes. However, on the other hand, pollen-based Holocene vegetation records from Southern Italy are still sparse and most of them are from low altitudes (Fig. 1). Only Lago di Monticchio (656 m a.s.l.; Allen et al., 2002) and Lago di Pergusa in Sicily (667 m a.s.l.; Sadori et al., 2011) are located in the collinean belt, but they are separated by 450 km and therefore provide a forest development asynchronism of ca. 4000 yr.

Palynological study of the Trifoglietti site in the meridional part of the Apennines help to fill the gaps between previous studies. It may give evidence of elements characterising long-term vegetation dynamics in a place close to glacial refugia, as well as of the possible influences of Holocene rapid climate changes and the Neolithic expansion on vegetation. Finally, it may provide additional data for a better understanding of regional climate variability and possible contrasting changes in seasonality between Central and Southern Italy (Magny et al., 2011a).

Having been informed about the nearly-infilled Lake Trifoglietti by a short pollen study published in 1984 by Murgia et al., we have carried out new investigations there (1) to establish a new Holocene vegetation record in an intermediate location between Central Italy and Sicily, and (2) to reconstruct possible palaeohydrological (climatic) variations reflected by changes in vegetation.

2 General description of the site

2.1 Location

Lake Trifoglietti (39°33′ N, 16°01′ E; 1048 m a.s.l.) is located in Southern Italy (Fig. 1), near the town of Fagnano Castello in Cosenza province. Overlooked by Monte Caloria (1183 m), Lake Trifoglietti is part of a natural high-altitude lucustrine system inhabited by endemic amphibians (Amici della Terra, 2003). Thus protected within a Natura 2000 zone (SIC IT9310060 - Laghi di Fagnano), the lakes are located in the Catena Costiera Mountains which stretch parallel along the Tyrrhenian coast for 70 km with altitudes ranging from 1060 and 1541 m (Amici della Terra, 2004). This part of the Catena Costiera belongs to the Liguride complex outcrop, and is formed of metamorphic terrigenous deposits of a solid-textured green rock which is, consequently, only weakly eroded (Ogniben, 1973; Ogniben and Vezzani, 1976). The soils, classified as Dystric Cambisols by the World Reference Base (WRB) and as Dystrudept in Soil Taxonomy (Carta dei suoli Regione Calabria, 2007), are composed of high organic matter input to the mineral fraction units resulting in thin acid soils with a dark brown and lumpy texture.

The origin of the Catena Costiera lakes is not well established. Guerricchio (1985) suggests that they were created by large landslides and were filled by spring overflow. Initially, the lakes had an elongated shape, following the direction of subsidence, but subsequent infilling with material from mountain runoff progressively gave them in a round shape.

At Trifoglietti, a spring nowadays flows into the lake from the north; an outflow runs southward (Fig. 2a, b). To combat summer drought, the Municipality of Fagnano Castello built a small earthen dam in 2000. With a surface area of 0.973 ha and a catchment area covering 0.370 km^2, the lake reaches a depth of up to 1.50 m.

2.2 Climate and phytogeography

2.2.1 Climate

Due to its geographical position and to its relatively high elevation a.s.l., the climate of the Trifoglietti region is greatly influenced by warm and humid air masses from the Tyrrhenian Sea. Despite the strictly Mediterranean latitude of the study area, annual rainfall (including cloudiness) can reach more than 1800 mm yr^{-1} (Fig. 3), though a relatively short dry period develops in summer. According to the bioclimatic classification proposed by Rivas-Martinez (1993) and based on both corrected summer ombrothermic index (I_{ovc}) and the corrected thermic index (I_{tc}), the Trifoglietti area falls within the "lower mesotemperate bioclimate belt" of a temperate region and the ombrotype is "upper hyperhumid". Mean annual temperature is 15 °C, with 24 °C for August and 7.5 °C for January.

2.2.2 Phytogeography

The Catena Costiera vegetation is dominated by *Fagus sylvatica, Quercus cerris* and *Castanea sativa*. The lake is surrounded by a beech forest attributed to *Anemono apenninae-Fagetum* with some *Pinus nigra* subsp*. laricio*. Scrub vegetation, with *Erica arborea*, *Cistus salvifolius*, *Helychrysum italicum*, *Sarothamnus scoparius* and *Alnus cordata* trees, develops in the more open *Fagus* forests.

A schematic transect of present-day vegetation is presented in Fig. 4. The lake vegetation comprises a mosaic of different plant communities, partly linked with dynamic successions due to variations in water level and soil composition.

Most of the lake surface is occupied by a swamp of *Carex paniculata* swamp (D). This tall sedge grows in spaced tussocks protruding from the water surface, the living plant progressively build up around a small peaty hill, often covered by a carpet of *Sphagnum palustre* and *Aulacomnium palustre*. Between tussocks the water attains a depth of 60 cm, and since vegetal fibers accumulate in the ground, which tends to dry up, the sedge is thus progressively invaded by other helophyte and mesophyte species. In shallow areas (E), *Carex paniculata* develops with *Osmunda regalis*, *Angelica sylvestris*, *Carex pendula* and nemoral herbs such as *Lysimachia nemorum*, *Arisarum proboscideum* and *Oxalis acetosella*. The littoral mires are invaded by *Rubus hirtus* and *R. ulmifolius* (E) and two isolated bushy communities of *Salix caprea* very near the surrounding beech forest (F).

From the centre of the lake to the southern edge, the depth increases and the open surface is discontinuously colonised by communities of *Potamogeton natans* (C). The lake's western shore is supplied by the rills, where a belt of vegetation is found characterised by *Sparganium erectum* (A). *Alisma plantago-aquatica* and *Ranunculus fontanus* are rare in this community, the sedgebed being dominated by *Carex vesicaria* (B) within the belt and outside of the peaty soil.

A limited stand of *Alnus cordata* (C) develops near the lake center (deeper water) and appears to be in regression. We hypothesise that this tree species grew in the sunniest area around the lake when the marshes were in a dry phase. The man-induced rise in water depth, however, is not compatible with the alder's ecological needs. The importance of Lake Trifoglietti depends on the presence of the endemic amphibians and on endangered aquatic and hygrophilous habitats in the Mediterranean area (Amici della Terra, 2003). The dam thus provides the appropriate water depth ensuring continuity of all interesting aquatic habitats and species. The increasing depth, however, has certainly submerged and damaged species such as *Sphagnum palustre* and *Osmunda regalis*.

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3 Methods

3.1 Core sampling and sedimentology

Coring was undertaken using a 1 m-long Russian peat corer with a 6.3 cm diameter. Three cores were taken (S1, S2 and S3; Fig. 2b) along a transect from centre of the lake toward the northeastern shore to find a sediment sequence capable of documenting the entire Holocene in high resolution. Thus, the core S2 sequence was chosen for laboratory investigation and was obtained from twin cores taken from the lake's northeast edge. Segments were extracted on site, wrapped in plastic, transported to the University of Franche-Comté and stored at 4 °C.

The cores were splitt longitudinally into two halves, photographed and logged with a GEOTEK Multi Sensor Core Logger in order to obtain geophysical measurements [scanning of lithology, measurements of magnetic susceptibility, (MS)] at 1 cm intervals. The master core (MC) was established based on lithological changes (with observation of key reference horizons) in combination with MS profiles. This study thus refers to the MC constructed from the twin cores (S2A and S2B).

The MS, mainly dependent on magnetite concentration in sediments, was measured in electromagnetic units to determine the inorganic allochthonous sediment content (Gedye et al., 2000). As the development of pedogenesis under forest cover may have favoured a mineral magnetic increase in soils (Jong et al., 1998), low MS recorded in sediments is to be expected during phases of stabilised vegetated slopes (Whitlock et al., 2011), while increased magnetic concentrations may be related to changes in sediment sources and to erosive processes of soils (Dearing et al., 1996; Jong et al., 1998; Vannière et al., 2003; Cruise et al., 2009). Nevertheless, when ferrimagnetic mineral concentration is low (magnetite and maghaemite), the value of MS may be largely influenced by diamagnetic minerals (quartz, carbonates) (Thompson and Oldfield, 1986).

3.2 Radiocarbon dating

The chronology is based on 11 Accelerator Mass Spectrometry (AMS) ^{14}C ages measured on terrestrial plant macrofossils (Table 1). The radiocarbon ages have been calibrated in years cal. BP by using IntCalib 6.0 (Reimer et al., 2009). Dates are expressed as intercepts with 2σ ranges. To confirm this chronology, the base of the core (843 cm depth, Table 1) was dated a second time and provides a similar age (9850 ± 50 BP). The age-depth model is constructed using a cubic-spline interpolation method (Fig. 5) according to the procedure standardised by Heegaard et al. (2005).

3.3 Pollen analysis

3.3.1 Surface samples

Five moss samples were collected (Fig. 2b) and treated both chemically (NaOH, HCl, HF, acetolysis) and physically (sieving 300 µm and 180 µm). To emphasise the correlation between pollen rain and vegetation, we provide the corresponding phytosociological relevés of actual vegetation (Pignatti, 1953) (Table 2) along with the five surface samples, using the TILIA 1.12 programme. A semi-detailed pollen diagram of surface samples is provided in Fig. 6.

3.3.2 Pollen samples

Sediment samples of 1 cm^3 of sediments were treated both chemically (HCl, KOH, HF, acetolysis) and physically (sieving) following standard procedures (Moore et al., 1991). *Lycopodium* tablets were added for estimating pollen concentrations (grains cm^{-3}). Samples were taken at four centimetres resolution on the 8.5 m of the core. A total of 170 pollen samples were analysed under a light microscope at a standard magnification of × 400. 178 pollen types were identified using photo atlases (Reille, 1992–1998; Beug, 2004) and the reference collection at the University of Franche-Comté. A sum of at least 300 terrestrial pollen grains was counted, excluding dominant terrestrial taxa along with water and wetland plants, as well as pteridophyte spores. Percentages were calculated based on the total pollen sum.

Using the TILIA 1.12 programme, a semi-detailed pollen diagram is provided in Fig. 7. Local pollen assemblage zones (LPAZ) were defined according to the CONISS function of the TILIA 1.12 programme. Two drawn and twelve dashed lines define limits between statistically first- and second-order splits. Table 3 sums the main, common and rare pollen types in each LPAZ. In order to describe vegetation changes, taxa have been grouped according to their present-day ecology, with the help of field observation and according to their affinities with human-induced activities. Figure 7 represents taxa as follows (from left to right): trees, total Arboreal Pollen (AP_t), plants from open-land vegetation, anthropogenic indicators (Apiaceae, *Apium*, *Meum*, *Peucedanum* tp., *Bupleurum* tp., *Plantago*, *Plantago major-media*, *Cannabaceae*, *Urticaceae*, *Papaver*, *Linum*) and *Cerealia* tp. (*Cereal* tp. 40–60 µm, *Triticum*, *Secale* tp.). All pollen taxa percentages have been calculated according to the total counted terrestrial pollen grains. Figure 8 presents a simplified pollen diagram with major arboreal and non-arboreal taxa and the sum of anthropogenic indicators.

Hygrophilous plants have been placed separately in the illustrations (Table 3; Figs. 7 and 8). They are composed of aquatics (pollen and spore producers: *Cyperaceae*, *Carex* tp., *Scirpus* tp., *Cyperus* tp. *Alisma*, *Ceratophyllum* sp., *Cladium mariscus*, *Lysimachia*, *Mentha*, *Myriophyllum*, *Nymphaeaceae*, *Ranunculaceae* tp. *Batrachium*, *Sparganium*, *Typha latifolia*, *Typha minima*, *Lythrum*), of spore producers (*Osmunda*), of pollen producer (Ast. *Asteroideae Eupatorium*) and of algae (*Botryococcus*). Spores and algae have been added to the total counted palynomorphs in order to calculate their percentage. As modern alder development is mostly related to the lake environment, *Alnus* has therefore been placed together with the hygrophilous taxa in Fig. 8. In Table 3 and Figs. 7–8, an additional rate of arboreal pollen without *Alnus* (AP_{wa}) has been calculated by excluding main hygrophilous taxa (Aquatics and *Eupatorium*) from the NAP.

3.3.3 Pollen-based climate reconstruction

The Modern Analogue Technique (MAT: Guiot, 1990) is used to reconstruct climate changes in the Mediterranean area (e.g. Davis and Brewer, 2009; Joannin et al., 2011; Peyron et al., 2011; Dormoy et al., 2012). The MAT is based on a modern pollen dataset that contains more than 3500 modern spectra with 2000 samples from the Mediterranean area (Dormoy et al., 2009) and in which surface sample spectra from Lake Trifoglietti surroundings have been included. Additional information about the MAT methodology and its application to Trifoglietti's pollen record are available in Peyron et al. (2012). Annual precipitation has been reconstructed based on a pollen dataset from which *Alnus* is excluded, and represented using a dashed line in Fig. 9f.

4 Results and interpretation

4.1 Sediment and age model

4.1.1 Lithological and magnetic susceptibility changes

Gyttja and peaty sediments are the main components of core S2 at Trifoglietti (Fig. 7). The stratigraphy was as follows:
from 850 cm to 843 cm: gyttja layer,
from 843 to 805 cm: silt layer,
from 805 to 700 cm: mixed gyttja and silt layer,
from 700 to 530 cm: gyttja layer interrupted by a silt layer from 595 to 548 cm,
from 530 to 482 cm: dark peaty deposits,
from 482 to 380 cm: gyttja/peat layer,
from 380 cm to the top: deposits are characterised by an alternation of peat and dark peat sediments that include thin gyttja layers (292–289 cm, 213–200 cm and 100–97 cm) and gyttja/silt layers (162–152 cm, 122–117 cm and 107–100 cm).

In general, MS values measured in gyttja and peat sediments are low (Figs. 7 and 8). However, three major peaks are observed with strong values in the silt deposit at 844–804 cm, in a woody-remains layer at 173–169 cm, and in a silt layer at 122–117 cm. No volcanic minerals have been found in this last level.

4.1.2 Age-depth model

The two radiocarbon dates obtained for depth 843 cm provided consistent similar ages and indicate an early Holocene age for the basal part of the silt layer recorded from 840 to 805 cm depth. The age-depth curve (Fig. 5) evidences a broadly constant sedimentation rate from the beginning of the Holocene up to around 3000 cal. BP, giving an average temporal resolution of about 60 yr sample^{-1}. The rate decreases upwards. The average temporal resolution is estimated at ca. 70 yr sample^{-1} for the entire Holocene and attains a maximum of 37 yr sample^{-1} for the period 10 000–9000 cal. BP.

4.2 Pollen analysis

4.2.1 Surface samples

The five surface samples represent the different vegetation types that grow around the lake and contribute to the interpretation of the fossil pollen spectra. The pollen sum is about 500 grains (AP + NAP) per surface sample.

Lake Trifoglietti pollen rain broadly mimics the corresponding types of vegetation. On the whole, the *Pinus* rate recorded in open land (8 %) is in better accordance with reality than in *Fagus* wood (1 %). Pollen grains of *Quercus caduc.*, *Olea* and *Castanea* are produced by plants absent from around the lake. Pollen catchment is likely to include lower-altitude vegetation signals due to the topography of the Catena Costiera Mountains and by ascending air flow along the slopes. Hygrophilous vegetation with *Carex* (relevés 1 and 2) is represented with over 40 % of *Cyperaceae*. The *Osmunda* pollen rate (10–30 %) is in accordance with the *Osmunda* vegetation (20–60 %). *Lysimachia* *vulgaris* is represented by 10 % to 30 % of pollen. *Angelica* pollen is recorded by 1 to 15 %. *Eupatorium* pollen is present from 1 to 5 %. The trees of *Alnus cordata* are over-represented in the pollen rain (10–30 %). The transition of lake vegetation to *Fagus* vegetation (relevé 3) is dominated by *Rubus* and *Carex*, which are, however, under-represented in the pollen rain (<1 %). *Fagus* and *Alnus cordata* are normally- and over-represented, respectively. The *Fagus* wood (relevé 4) is well represented (60 %), whereas the other species are under-represented though *Alnus cordata* is over-represented (15 %). Under trees of *Alnus cordata* (relevé 5), this pollen grain is over-represented (70 %) while the scrub vegetation is under-represented (*Erica*, 2 %; *Clematis*, 2 %).

Pollen rain from relevés 1 and 2 faithfully reproduce the hygrophilous vegetation associated with the wet environment of Lake Trifoglietti while relevés 3 and 4 represent terrestrial vegetation (i.e. mixed beech-oak forest) growing independently of the lake.

4.2.2 Pollen sequence and terrestrial vegetation dynamics

According to the ^{14}C dates, the sequence starts with the beginning of the Holocene (zone T-1, <11 400 cal. BP; Table 3). The pollen record identifies the regional presence of *Fagus, Abies, Ostrya* and several temperate trees. Thoughf oaks and beech pollen grains are abundant (more than 25 % and 10 %, respectively), NAP percentages (ca. 60 %), diversity of herbaceous taxa and occurrences of *Juniperus* and *Ephedra* all indicate that the site is probably above the timberline, surrounded by oro-Mediterranean meadows. Oaks and beech were likely not far off, on the steep slopes between the sea and the lake (9 km from Cetrano, on the seaside). Ascending winds from the west probably explain the high amount of well-dispersed oak pollen at Trifoglietti.

From ca. 11 400 to ca. 11 000 cal. BP (zone T-2), an increase in percentages of *Cichorioïdeae*, *Caryophyllaceae* and *Artemisia* suggest a strong cooling. NAP reach 75 % and suggest that the site may have been above the timberline at that time, with a long persistence of meadows during the early Holocene at the Trifoglietti altitude. In spite of the cooling, *Abies* expands slightly. Noteworthy also is the quasi-absence of *Pinus* during the early Holocene (the percentages are lower than 10 % in T-1 and T-2, and even less after 11 000 cal. BP). The few pollen grains observed must correspond to a wind transport, possibly from the Mediterranean belt. But less than 100 km to the north, in mountains such as the Pollino Ridge, biogeographers have described populations of an indigenous *Pinus nigra* subsp. *laricio* (Conti et al., 2005; Tomaselli, 2007). These endemic trees must have occupied extremely restricted surfaces at least since the end of the Last Glacial. If so, as mentioned in the case of Corsica today (Reille, 1992–1998), the absence of subalpine tree species may explain a relatively low timberline.

At around 11 000 cal. BP (zone T-3) the rapid increase in *Fagus* corresponds to local settlement of a mountain forest ecosystem dominated by beech and fir trees. High values of AP suggest that the site is now below the timberline. Fir percentages also increase progressively to ca. 20 % and always remain lower than those of beech. Nevertheless, regular occurrences of fir stomata ensure that the trees grew alongside beech in the lake's immediate surroundings. Considering the poor dispersal of fir pollen grains (Mazier, 2006), this conifer was probably as abundant as beech. The present beech forest is directly inherited from the remote early Holocene, thus furnishing a rare example of woodstands maintained in the same place for more than 11 000 yr. The beech forests or stands, nowadays scattered across the mountain belt from the Central Apennines to Monte Madonie in Sicily, are the relicts of long continuous presence as confirmed by genetic inheritance (Magri et al., 2006).

CONISS software identifies three subzones (Table 3). The first is characterised by relatively abundant oak pollen grains and increased *Ostrya/Carpinus orientalis* pollen grains, indicating that the oak belt must have been closer on the mountain slope. In spite of the vicinity of the Mediterranean belt, sclerophilous taxa (*Olea*, *Quercus ilex* type) which appear at the beginning of zone T-3 are scarce (which will be the case until the top of the sequence). Their pollen transportation by ascending winds was not efficient here. This is also the extremely rare *Pistacia*. Three hypotheses may explain this evidence: (1) due to the steep slope, the surface occupied by the Mediterranean belt was limited to a narrow fringe near the sea, unable to produce and disperse a large quantity of pollen grains, (2) westerly winds from the sea brought heavy rainfall to the Catena Costiera Mountains, thus limiting surfaces occupied by dry Mediterranean ecosystems, and (3) the dense fir/beech forest around the lake acted as a filter for regional rainfall.

Zones T-3b and T-3c (ca. 10 000–8900 cal. BP) correspond to an optimum for beech and a regression for oak. Two sharp drops in the AP_t rate which are centred at ca. 9800 and 9200 cal. BP (Fig. 8) suggest beech forest openings. In T-4 (ca. 8900–7300 cal. BP), terrestrial vegetation was stable before the 8200–7500 cal. BP interval which is marked by a regression of both *Abies* and *Fagus*. In zone T-5 (ca. 7300–6150 cal. BP) fir becomes more abundant than beech.

In zone T-6 (ca. 6150–5100 cal. BP), the regression of fir to the benefit of beech also suggests a dry episode. Zone T-7 (ca. 4650–3950 cal. BP) is mainly characterised by an apparent reduction in mountain trees but this is partly influenced by the autocorrelation between taxa percentages due to the high percent of aquatic plants and *Osmunda*. However, after stabilisation of beech and fir in T-8, T-9 marks the beginnning of forest regression at ca. 4000 cal. BP. This change is probably due to generalised forest opening by Bronze Age populations, though the anthropogenic indicators are almost absent (possibly due to the filter role of the *Alnus* fen); a puff of *Pteridium* spores is nevertheless observed in this zone: known to take advantage of forest fires, this fern is an indicator of human disturbances.

Zone T-10 (ca. 3500–2100 cal. BP) is characterised by a moderate beech/fir forest restoration which remains unstable; frequent occurrences of *Rumex, Chenopodiaceae* and *Plantago* suggest pastoral activities in the woods.

The major event during zone T-11 (ca. 2100–800 cal. BP) is the quasi-disappearance of *Abies* from the local forest, probably due to timber exploitation beginning in Roman times. A positive correlation between *Ostrya*/*Carpinus orientalis* and *Hedera helix* ($r = 0.52$; $p < 0.001$) is observed as these two taxa had developed and co-varied since 10 500 cal. BP. In present-day Calabria, particularly in the Catena Costiera, *Hedera* *helix* is very common in the *Ostrya* wood communities where mesophilous underwood development is favoured by high atmospheric moisture (Blasi et al., 2006). The quasi-disappearance of *Hedera*, however, seems more concomitant with that of fir, and therefore underscores lower moisture or pastoral activities within the woods. In the upper part of T-11 also begin the continuous occurrences of *Castanea* and *Juglans*. Rare but regular *Castanea* pollen grains are identified all along the Holocene. The early presence of chestnut reported in Central and Southern Italy (Lago di Lagdei, Bertoldi, 1980; Schneider, 1985; Mercuri et al., 2012) strengthens the hypothesis of an indigenous chestnut in these areas. Nowadays, it is intensively cultivated on the Monte Caloria slopes around Fagnano Castello where it has played an important economic role since medieval times, but it was apparently neglected by the Roman civilisation. On the contrary, there is no indication of the presence of *Juglans* before its early medieval introduction.

Zone T-12 (ca. 800–33 cal. BP) is characterised by regional mixed-oak forest reduction and by anthropogenic indicators that are more frequent though not abundant. In Zone T-13, the collapse of *Alnus* and the increase of aquatic plants strongly influence pollen assemblages and prevent a reasonable reading of vegetation changes.

4.2.3 Pollen sequence and hygrophilous vegetation

From ca. 11 500 to ca. 11 000 cal. BP (zones T-1 and T-2), hygrophilous taxa are represented by sparse aquatics indicating shallow water (Table 3). From 11 000 to 8900 cal. BP (T-3), abundant *Botryococcus* are recorded, typical of an open lake with deep water and gyttja sedimentation.

In zone T-4 (ca. 8900–7300 cal. BP), open water receded to the benefit of a marginal swamp as illustrated by the abrupt reduction of the *Botryococcus* algal colonies and the expansion of marsh plants. Close attention to the abundant *Asteroïdeae* pollen grains shows them to belong to the genus *Eupatorium*; this plant still grows on the lake shore (*Eupatorium cannabinum*). The continuous curve of *Osmunda* confirms the infilling of the lake towards a pond as well as the sediment types, that records a change from gyttja to peat at ca. 8200 cal. BP, and is contemporaneous with *Eupatorium* expansion. In zone T-5 (7300–6150 cal. BP) the marsh is invaded by *Osmunda*; the *Cyperaceae* curve shows a slight expansion of *Carex paniculata* which is still abundant on the site today.

In zone T-6 (ca. 6150–5100 cal. BP), for the first time *Alnus* invades the margins of the pond. The rise in the *Alnus* pollen curve occurs when the sediment is still a detritus gyttja, later replaced latter by a wooded peat guaranteeing that the tree was present at the coring point. This alder expansion may correspond to a terminal phase of lake infilling tending towards peatland, but the regression of fir to the benefit of beech also suggests a dry episode. The deeper water recorded between ca. 5100 and 4650 cal. BP (zone T-7) extinguished the *Alnus* fen to the benefit of *Osmunda*, *Cyperaceae* and *Poaceae* (which may correspond to *Phragmites* nowadays being well developed in the Lake dei Due Uomini; Fig. 2). During zone T-8 (ca. 4650–3950 cal. BP), *Alnus* again invades the marsh, arriving at an optimum during zone T-9 (ca. 3950–3500 cal. BP). Zone T-10 (ca. 3500–2100 cal. BP) corresponds to a new period of deep water marked by alder decline to the benefit of aquatic plants and *Osmunda*. Unfortunately, CONISS software did not identify within T-11 (ca. 2100–800 cal. BP) the two sub-zones T-11a (ca. 2300–1500 cal. BP) and T-11b (ca. 1500–800 cal. BP) (Fig. 8), the first characterised by a decrease in water depth with abundant *Alnus,* the second, by a return to sedges hummocks and deeper water. Zone T-12 (ca. 800–33 cal. BP) is characterised by new alder expansion. This phase probably corresponds to a final episode in progressive lake infilling, abruptly stopped in zone T-13 reflecting the artificial present-day damming of the lake in order to maintain the hygrophilous ecosystem. The collapse of *Alnus* and increase of aquatic plants suggest that the objectives of recent anthropogenic lake restoration have been attained.

4.2.4 Changes in water-depth

Variations in the hygrophilous taxa shown by the Trifoglietti pollen record reflect fluctuations in water depth. These can be reconstructed using ratios between indicators of lake development and those characteristic of peatland. This hygrophilous group was mainly composed of algae, fern spores (*Osmunda* and monoletes) and *Alnus*. CONISS analysis clearly identified a first order opposition between algae (*Botryococcus*) and more terrestrial taxa (spores and *Alnus*). Thus, a first ratio can be proposed: (*Botryococcus* + 1)/(*Alnus* + spores + 1). A second ratio of (*Alnus* + 1)/(spores + 1) is established to synthesise the opposition between *Alnus* and spores. In those mathematic ratios, the value 1 is used so as to avoid values nullification. Finally, a ratio using the logarithmic representation illustrated in Fig. 9d and combining these two ratios, is generated in order to define environmental evolution.

The pollen-based water-depth curve shows relatively deep water conditions from ca. 11 000 to 9000 cal. BP, intermediate water depth from ca. 9000 to ca. 6000 cal. BP, and shallower water from ca. 6000 cal. BP to the present. This latest phase also gives evidence of second-order variations with shallower water episodes at ca. 6100–5200, 4650–3500 and 2400–1700 cal. BP, and deeper water episodes at ca. 5100–4650, 3500–2500 and after 1700 cal. BP. Such a general decreasing trend since ca. 11 000 cal. BP (Fig. 9d) is consistent with the lithological change from silty-gyttja to peat sediments that may reflect natural lake infilling with detritic particles and organic matter. The progressive overgrowth of the lake favoured the development of alder carr. However, both long- and short-term changes in water-depth may also reflect climate-induced paleohydrological changes as evidenced in Central Italy and in Sicily (Ariztegui et al., 2000; Giraudi et al., 2011; Magny et al., 2007a, 2011a, b).

4.2.5 Pollen-based quantitative reconstruction of precipitation

From ca. 11 500 to ca. 11 200 cal. BP (Fig. 9f, Peyron et al., 2012), annual precipitation reconstructed at Trifoglietti illustrates a marked drying phase (500 $\mathrm{mm\,yr^{-1}}$). The abrupt beech re-development at ca. 11 200 cal. BP coincided with a rapid increase in annual rainfall (Δ 200 mm). This increase then continued progressively from ca. 10 700 to ca. 8300 cal. BP (Δ 200 mm) which favoured fir expansion.

The precipitation record shows a long-term progressive drying from ca. 9400 to 1700 cal. BP. Contrary to local hygrophilous vegetation dynamics which can be influenced by the lake-basin infilling, the climate reconstruction is quantified on the basis of terrestrial vegetation and therefore supports the Holocene drying trend observed in Southern Italy and Sicily (Magny et al., 2007a, 2011a, b). Pluri-secular variations also appear to be superimposed on this millennial-scale trend such as a relatively humid period during the mid-Holocene climate optimum (ca. 9000 to 6000 cal. BP), drying phases (with low fir values) at around 11 300 cal. BP, ca. 8200–7500 cal. BP, and ca. 6100–5400 cal. BP (fir regression and alder carr development), and a marked drying around 4400 cal. BP.

Since 1700 cal. BP, and despite fir disappearance as well as oak regression and AP_{wa} decrease, beech forest again attains the prevalence attested at the Early Holocene and probably explains the final increase in the Pann (Δ 200 mm). However, this increase did not prevent the terminal colonisation of alder as the lake was finally overgrown.

5 Discussion

5.1 Millennial-scale environmental and climatic trends

During the last decade several pollen studies have shed new light on Southern Italy's vegetation history (e.g. Lago Alimini Piccolo, Di Rita and Magri, 2009; Lago Grande di Monticchio, Allen et al., 2002; Lago di Pergusa, Sadori et al., 2008; Fig. 1), though most of these concern lowlands. Lake Trifoglietti, however, appears as a unique example of well-dated pollen sequences from the mountain belt of Southern Italy.

On a millennial scale, given the relatively late and weak human impact observed in the Trifoglietti pollen record, changes in the vegetation as well as in the water-depth and annual precipitation may help to recognize long-term climate variations which have affected Southern Italy since the early Holocene.

5.1.1 Early Holocene expansion of mesophillous forests in Southern Italy

The Trifoglietti pollen record with NAP values near 60 % (see above, Sect. 4.2.2) suggests that the site was above the timberline at the beginning of the Holocene. At Monticchio (ca. 656 m a.s.l.), an abrupt expansion of the mesophillous forests is recorded for the beginning of the lateglacial interstadial (LGI) (Watts et al., 1996; Allen et al., 2002). There, deciduous oaks arrive at an optimum (with abundant *Tilia* and *Fagus* continuous pollen curves) just before the Younger Dryas (zone 2). Thus, it may be that, on the Catena Costiera Mountains around Lake Trifoglietti, the tree line reached at least the same altitude. Nevertheless, the status above the timberline (and probably the tree line) of Trifoglietti is surprising if we compare this site with those of the Northern Apennines such as Prato Spilla A (1550 m a.s.l.) or Lago Padule (1187 m a.s.l.) (Lowe and Watson, 1993; Watson, 1996; Fig. 1) where *Pinus* and *Abie*s are quite abundant during the LGI and where the very beginning of the Holocene is marked by expansion of deciduous forests and persistence of fir in the mountains. At Padule, AP percentages above 80 % indicate that the site was below the timberline. How does one thus explain a lower early-Holocene timberline at Trifoglietti in spite of lower latitude? In Sicily, at Lago di Pergusa (667 m a.s.l., Sadori and Narcisi, 2001; Sadori et al., 2011), oak expansion occurs progressively during the early Holocene (with abrupt development at ca. 9800 cal. BP, Fig. 9h), along with low pollen-inferred precipitation (Magny et al., 2011a). In the littoral sites of Sicily, such as Preola and Gorgo Basso (Tinner et al., 2009; Magny et al., 2011b) or Biviere di Gela (Noti et al., 2009), open Mediterranean sclerophyllous shrubs were dominant and low lake-levels are recorded for the first part of the Holocene (Fig. 9g). All these observations suggest an increasing delay from Northern to Southern Italy where arid conditions persisted during a large part of the early Holocene (Magny et al., 2011b). These relatively dry conditions in the early Holocene may also have affected Calabria and may explain both a low-altitude tree line and a later expansion of *Fagus* at Trifoglietti.

5.1.2 A Preboreal oscillation cold event?

The closest available pollen record of the lower-altitude Monticchio (656 m a.s.l.), shows that the forests did not retract much during the Younger Dryas which was marked by a succession of little oscillations in the AP curve (Allen et al., 2002). Thus, we initially believed that the major cooling observed in zone T-2 of the Trifoglietti pollen record may have been contemporary with the Younger Dryas cold event. Yet three consistent ^{14}C dates obtained at levels 843 and 806 cm suggest correlation it with the Preboreal oscillation (PBO; Björck et al., 1997) and Bond event 8 (Bond et al., 2001). Consequently, our zone T-2 may be contemporary with a short and late increase in NAP (mostly *Poaceae*), dated between 11 500–11 300 cal. BP, at the end of zone 2 in the Monticchio sequence (Fig. 9b; Allen et al., 2002); this is supported by the fact that, at the two sites, this cooling is immediately followed by beech expansion. The PBO is sometimes considered as difficult to identify from Mediterranean paleoenvironmental records (Di Rita et al., 2012). At Lake Accesa in Central Italy, the climate conditions prevailing during the PBO around 11 300 to 11 150 cal. BP are characterised by increased *Artemisia* and by low lake level (Magny et al., 2007a; Finsinger et al., 2010). Further south, a PBO has recently been reported in Valle di Castiglione where it corresponded to a decrease in AP at ca. 11 450–11 200 cal. BP and to dry climate conditions (Fig. 9a; Di Rita et al., 2012). At Trifoglietti, the return of an open vegetation landscape (probably situated above the timberline) is synchronous with the deposition of a silt layer in the lake basin. Furthermore, pollen-inferred annual precipitation is marked by a minimum while the reconstructed water depth (Fig. 9d) shows a dry interval. Thus, a growing body of records support the past occurrence of a dry PBO in Central and Southern Italy (Magny et al., 2007b). Nevertheless, the magnitude of the PBO observed at Trifoglietti, in terms of both NAP increase (and associated timberline decline) and water-table lowering, may appear to be excessive in comparison with other regional records. Further investigations at Trifoglietti and elsewhere in the Southern Italy will be needed to replicate the data presented above, so as to control the chronology of the Trifoglietti record by additional radiocarbon dates and to check whether or not the marked palaeoenvironmental changes observed at Trifoglietti were simply a strong response to the PBO due to local particularities.

5.1.3 The early Holocene (ca. 11 000–9000 cal. BP)

Regarding the vegetation history for the period following the PBO, pollen records from mountainous zones remain scarce in Southern Italy. As noted above, one can mention lakes Zapano (1420 m a.s.l.) and Remmo (1525 m a.s.l.) in Monte Sirino, studied in 1937 by Chiarugi and by Reille in the seventies (communication of unpublished data) showing dominant beech forests during the late Holocene. In Calabria also, at Canolo Nuovo (900 m a.s.l.) a simplified diagram by Schneider (1985) suggests a landscape shared between oak and beech forests throughout the Holocene. The interval corresponding to zone T-3 (major phase of beech expansion, between ca. 11 000 and 8900 cal. BP) is marked at Monticchio and Pergusa by a moderate maximum of *Corylus* which is scarce in the Trifoglietti pollen record. This suggests that *Corylus* and its associated mesophilous mixed-oak forest were not able to penetrate the fir/beech belt. At Monticchio, *Ostrya/ Carpinus orientalis* is present during the LGI, but begins to expand at ca. 10 500 cal. BP, i.e. at the same time as at Trifoglietti. It was favoured by increasing annual precipitation at Trifoglietti and synchronous with higher lake level at Preola in Sicily (Magny et al., 2011b). Sclerophilous taxa (*Olea*, *Quercus ilex* type) are very scarce as their pollen transportation by ascending winds was probably insufficient here. This is also the case for *Pistacia*, abundant in the coastal sites of Sicily (Noti et al., 2009; Tinner et al., 2009) but extremely rare in the Trifoglietti record.

5.1.4 The mid-Holocene climate optimum (9000–6000 cal. BP)

Annual precipitation reconstructed at Trifoglietti is high from ca. 9000 to 6000 cal. BP and attain its maximum at ca. 8500 cal. BP. The wettest conditions are reported throughout the Central Mediterranean region (e.g. Ariztegui et al., 2000; Sadori and

Narcisi, 2001; Drescher-Schneider et al., 2007; Frisia et al., 2006; Sadori et al., 2008; Colonese et al., 2010; Finsinger et al., 2010) and are contemporary with enhanced rainfalls over the northern borderlands during the deposition of sapropel (organic-carbon-rich sediments) S1 in the Adriatic Sea (Siani et al., 2010) and in the Central-Eastern Mediterranean Basin (e.g. Ariztegui et al., 2000).

More to the point, despite the natural lake-infilling dynamic at Trifoglietti, the pollen-based water-depth record suggests deep water in the context of increasing annual precipitation up to 8500 cal. BP. This is broadly consistent with changes in the clay mineral assemblage from the Gulf of Salerno (core C106 in the Tyrrhenian Sea; Fig. 1), which indicate increasing precipitation in the source area but at longer time intervals (i.e. 9500 to 6000 cal. BP; Naimo et al., 2005). It is also consistent with lower salinity reconstructed from δ^{18}O record in the marine core MD91–917 (Siani et al., 2012) and is in accordance with snail shell composition recorded from the Latronico 3 cave in Southern Italy (Fig. 1). There, decreasing measured δ^{18}O values are associated with enhanced rainfall and lower evaporation rates, possibly triggered by increases in westerly activity (Colonese et al., 2010).

From the Mid- to the Late Holocene, water depth as well as annual precipitation show a general decrease at Trifoglietti. This is consistent with a fall in lake level observed in Sicily (Fig. 9g; Magny et al., 2011b) while a contrasting paleohydrological pattern has been reconstructed for Central Italy (Magny et al., 2007a). Thus, the water-depth decrease since 8500 cal. BP at Trifoglietti may have resulted from the combined effects of lake-basin infilling and a generaly dryier climate in the South-Central Mediterranean. Considering its intermediate location between palaeohydrological records from Central Italy and Sicily, the water-depth record of Lake Trifoglietti (Fig. 9d) supports the working hypothesis discussed by Magny et al. (2011a) of contrasting patterns in precipitation seasonality north and south of latitude 40° N in the Central Mediterranean in response to orbitally-induced climate changes.

5.1.5 Towards the late Holocene (from ca. 6000 cal. BP to the present)

Since ca. 6000 cal. BP, Trifoglietti has become a peatland (Fig. 8) with shallow water (Fig. 9d), probably due to the persisting and joint effects of drier climate and lake-basin infilling. Schneider (1985) also reported hydrological change (perhaps associated with temperature change) in the Canolo Nuovo site (945 m a.s.l.; Fig. 1) reflected by a *Quercus ilex* expansion and a fen development with *Alnus*, *Osmunda regalis* and *Sparganium* around 5000 uncal. BP (i.e. ca. 5800 cal. BP). In the Tyrrhenian Sea, the typical present-day foraminiferal association recognised in the core BS7922 testifies to the onset of deep winter water convection and vertical mixing starting at 6 ka which characterise the modern Tyrrhenian Sea (Fig. 1; Sbaffi et al., 2001). Since this date, the long-term salinity trend in the Adriatic Sea has been stable, despite higher frequency changes (Siani et al., 2012). It may therefore suggest that stabilised marine circulation around the Southern Italian peninsula coevals with onland stable hydrological pattern in Southern Italy. It has been related to effects of Neoglaciation in the Mediterranean, North Atlantic and Arctic areas since ca. 5700 cal. BP (Marchal et al., 2002; Miller et al., 2010; Giraudi et al., 2011).

5.2 Centennial-scale environmental and climatic changes

The data collected at Trifoglietti also illustrate high-frequency climate variability during the Holocene in the Southern Italy.

5.2.1 Early Holocene

Two sharp drops in AP centred at ca. 9800 and 9200 cal. BP (Fig. 9e) correspond to beech forest openings and increases in aquatic taxa, coincided with decreases in Pann (Fig. 9f). Taking into account radiocarbon-age uncertainty, these events may be related to the well-known cold Boreal oscillations recognised at higher latitudes (Fleitmann et al., 2007; Yu et al., 2010; Magny et al., 2001). In other terrestrial archives, an AP decrease is recorded at Monticchio at ca. 9800 cal. BP, while at Valle di Castiglione the AP record shows lower values at ca. 9300–9200 cal. BP (Di Rita et al., 2012; Fig. 9a). In the Tyrrhenian Sea, core BS7938 (Fig. 1) gives evidence of two peaks in cold foraminiferal species (particularly *Neogloboquadrina pachyderma*, right coiling) at ca. 9800 and 9000 cal. BP (Sbaffi et al., 2004).

From ca. 8200 to 7500 cal. BP, an AP_{wa} reduction marks changes in climate conditions at Trifoglietti (Fig. 9e). More arid conditions recorded in Pann (Δ150 mm, Fig. 9f) may have reduced fir and beech woods, favouring the expansion of marsh plants and the deposition of dark peat characteristic of shallower water. Around 8200 cal. BP, a general cooling associated with the 8.2 kyr event was recorded in the Mediterranean region (e.g. Bordon et al., 2009; Pross et al., 2009; Sadori et al., 2011). As observed in the Eastern Mediterranean (Dormoy et al., 2009), this 8.2 kyr event is also associated with dryer climate conditions but spans only ca. 200 yr (Pross et al., 2009). Therefore, no vegetation change spanning several centuries has been observed in other pollen records (e.g. Sadori and Narcisi, 2001; Allen et al., 2002). At Lake Preola, Magny et al. (2011b) observed a moisture decrease phase from 8300 to 6900 in the central core LPBC and two phases at 8400–8200 and 7400 cal. BP in the littoral core LPA, which may be compared with the two successive cool and dry events recorded at ca. 8200 and 7500 cal. BP in oxygen-isotope records from speleothems in Northern Sicily (Frisia et al., 2006). As discussed by Rohling et al. (2002), the interruption of Sapropel 1 during the 8.2 kyr event (Ariztegui et al., 2000) probably corresponded to a strengthening of the winter Siberian High responsible for cooler and drier climatic conditions with more frequent polar/continental outbreaks over the Eastern Mediterranean. Around the Italian Peninsula, marine sequences from the Adriatic and Tyrrhenian Seas also reveal a bi-phased Sapropel 1 interrupted from ca. 8000 to 7500 cal. BP (Ariztegui et al., 2000), marked by changes in faunal, organic and isotopic contents. According to Sangiorgi et al. (2003), surface waters in the Adriatic Sea (as reflected by core AD91-17; Fig. 1) were relatively unaffected by lowered temperatures, but winter winds were responsible for the sapropel interruption and associated water mixing, and re-oxygenation. On the basis of SST records from core BS7938 in the Tyrrhenian Sea, Sbaffi et al. (2004) reported a short cooling episode (labelled SCE5 event) of about 2–2.5 °C from ca. 8200 to 7500 cal. BP. Ariztegui et al. (2000), using terrestrial (i.e. Lakes Albano and Nemi in Central Italy; Fig. 1) and marine data (i.e. core MC82-12 in the Tyrrhenian Sea) came to the conclusion that both continental and marine realms underwent a reduction in precipitation and/or fluvial inflow from ca. 8200 to 7500 cal. BP. During the time of the sapropel interruption, the impact of more frequent outbreaks of Siberian dry winter air masses in the Eastern Mediterranean may have extended toward South Italian Peninsula.

From ca. 6800 to ca. 6500 cal. BP, the AP_{wa} record shows a decrease which cannot be explained by changes in annual rainfall characterised by an increase at that time. Despite indication of SST cooling inferred from foraminiferal assemblages in core AD91-17 (Sangiorgi et al., 2003) and MD90-917 (Siani et al., 2012) in the Adriatic Sea, this decline of AP probably reflects a locally more developed human impact as shown by slight increases in anthropogenic indicators and *Cerealia* (Fig. 8).

5.2.2 Mid and late Holocene

Near the final stage of the full overgrowth of the lake-basin, the Trifoglietti site becomes more sensitive to short-term minor variations in humidity. Thus, superimposed over the general trend towards shallow water, three successive phases of shallower water are identified (ca. 6100–5200, ca. 4300–3500 and ca. 2500–1800 cal. BP), and three phases of deeper water (ca. 5200–4300, ca. 3500–2500 and after ca. 1800 cal. BP).

From ca. 6100 to ca. 5200 cal. BP, the first shallow water phase corresponds to alder expansion reflecting evolution towards the terminal phase of lake infilling, but the regression of fir to the benefit of beech also suggests a dry episode, as supported by the ca. 100 mm annual precipitation decrease inferred by quantitative climate reconstruction (Fig. 9f; Peyron et al., 2012). Alder development is also reported at Canolo Nuovo at ca. 5000 uncal. BP (i.e. ca. 5800 cal. BP; Schneider, 1985). This time interval is also characterised by a cooling associated with the short cold event (SCE4) reported in marine cores from the Tyrrhenian (annual SST; BS7937; Sbaffi et al., 2004) and Adriatic Seas (alkenone SST; AD91-17; Sangiorgi et al., 2003). Magny (2004) and Magny et al. (2012) have already discussed the possible impact in Europe of a cold event related with a Rapid Climate Change (RCC) between 6000 and 5000 cal. BP defined by Mayewski et al. (2004). Local declination of these RCC may thus have affected the rain regime in the Alps where successive episodes of higher lake level between 5550 and 5300 cal. yr BP are observed at Lake Constance, coinciding with glacier advance (Magny and Haas, 2004). The dry and cool climate oscillation observed in Southern Italy contrasts with higher lake levels reconstructed in Central and Northern Italy (Magny et al., 2007a, 2012), and wet and cool conditions from 6000 to 5400 cal. BP reported in the Eastern Mediterranean by Finné et al. (2011).

From ca. 5200 to 4300 cal. BP, a more humid phase is inferred from deeper water reconstructed at Trifoglietti. This is supported by an increase in annual precipitation (Fig. 9c, f, C106, Di Donato et al., 2008; Peyron et al., 2012). This phase also coincides with a reduction in forest cover at Trifoglietti, which is probably a bias in AP_{wa} percentages.

A shallow water phase is recorded from ca. 4300 to ca. 3500 cal. BP. It suggests drier climate conditions that may be equivalent to a fall in lake-level dated to 4500–4000 cal. BP in Lake Preola (Sicily; Magny et al., 2011b), while an abrupt rise in lake level is observed in Central and Northern Italy (Magny et al., 2007a, 2012). According to Magny et al. (2011a), the orbitally-induced reorganisation of atmospheric circulation led to a southward migration of westerlies bringing more humidity to latitudes higher than 40° N, whereas opposite drier conditions developed in the South-Central Mediterranean. At Trifoglietti, this dry episode was particularly accentuated from 4000 to 3600 cal. BP if we consider the water-depth record (Fig. 9d), and around 4400 cal. BP if we refer to the Pann record (Fig. 9f). Such dry climate oscillation around 4400–4000 cal. BP has been recognised from previous studies in the Central and Eastern Mediterranean (Di Rita and Magri, 2009; Noti et al., 2009; Tinner et al., 2009; Finné et al., 2011). At higher latitudes, it coincided with the beginning of the Neoglacial

(Giraudi et al., 2011), marked by a glacier readvance in the Gran Sasso massif in Central Italy.

From ca. 3500 to ca. 2600 cal. BP, a phase of deeper water is associated with a reduction in alder carr. This more humid phase corresponds to peaks in annual precipitation (Fig. 9f; Peyron et al., 2012) that favoured beech/fir forest restoration (despite relative instability). The drop in AP_{wa} is linked to frequent occurrences of *Rumex, Chenopodiaceae* and *Plantago* which suggest pastoral activities in the surrounding forests. The 3500–2600 cal. BP time interval coincided with decreasing temperature at Monticchio (MTCO; Allen et al., 2002) as well as with increasing precipitation as inferred from the pollen record of the marine core C106 (Fig. 9c; Di Donato et al., 2008). From core BS7938 in the Tyrrhenian Sea, Sbaffi et al. (2004) reported a cooling in annual SST (by ca. 2.5–3.5 °C) and suggested it may be equivalent to a short cooling episode (event SCE2). The alkenone SST record from core AD91-17 (Sangiorgi et al., 2003) also suggests cooler conditions in the Adriatic Sea. This cool oscillation is also recorded in the Aegean Sea where changes in the foraminifera species document polar air outbreaks over the North-Eastern Mediterranean (Rohling et al., 2002).

Taking into account radiocarbon-age uncertainty, the drying phase observed at Trifoglietti around 2500–1800 cal. BP from both water-depth and annual precipitation records (Fig. 9d, f) may be an equivalent to the well-known cooling phase identified around 2700–2500 cal. BP at the Subboreal-Sublatlantic transition (van Geel et al., 2000), well marked by glacier advances in the Alps (Deline and Orombelli, 2005; Ivy-Ochs et al., 2009). The drier conditions recognised at Trifoglietti contrast with the phase of higher lake levels observed at higher latitudes in Central and Northern Italy (Magny et al., 2007a, 2012).

After ca. 1800 cal. BP, the Trifoglietti water-depth record (Fig. 9d) appears to be relatively stable, probably due to the nearly complete overgrowth of the lake basin making it less sensitive to further variation in humidity which might have been associated with more recent climate oscillations such as the Little Ice Age.

5.3 Human impact history

Archaeological studies in Calabria have revealed a great number of Neolithic villages (e.g. Santuario della Madonna Cave, 40–70 m a.s.l., Scarciglia et al., 2009), but at Trifoglietti anthropogenic indicators are absent or ambiguous for that time interval. Local mountain forests may have filtered the signalling of regional disturbances, but surprisingly oak and ostrya pollen signals from altitudinal zones favourable to Neolithic agriculture do not show pertinent changes. This suggests that the surfaces submitted to slash and burn activity, were probably too small to modify regional pollen influx at Trifoglietti, and/or that the steep slopes between the site and the sea were unfavourable to settlement. Therefore, the palaeoenvironemental record established at Trifoglietti appears to show only weak effects of human impact and it may offer useful information about general climatic conditions prevailing during the Neolithic expansion in Southern Italy. Berger and Guilaine (2009) raised the question of a possible relation between the 8.2 kyr event and a delay in the Neolithic expansion in the Mediterranean basin. The first Neolithic settlement in South-Western Italy was recognised at the Grotta di Latronico (Fig. 1) and dated to ca. 7700–7500 cal. BP (Colonese et al., 2010), i.e. during a phase characterised at Trifoglietti by drier climate conditions (Fig. 9). However, further investigations and more radiocarbon dates are needed in order to better constrain the chronology of both Neolithic expansion and Holocene climate changes in Southern Italy, and for a better understanding of possible relationships between climatic and cultural changes.

Since ca. 4000 cal. BP, AP_{wa} has steadily recorded forest reduction that can be related to the combined effects of (1) the mid- to late Holocene climate drying and (2) the increasing impact of growing populations. Clear disturbances in forest ecosystems are observed (drop in pollen percentages of *Abies* and *Fagus*, but also of deciduous oaks). However, the forest reduction probably concerned mostly the collinean (oak decrease) and Mediterranean belts (sclerophylous taxa development). Broadly synchronous deforestation has been indicated in several pollen sequences from Southern Italy and interpreted by Di Rita and Magri (2009) as an aridity crisis combined with progressive increasing human impact, marked by 1) during the middle Bronze age, the use of fire to clear land for agricultures and grazing (*Pteridium* spores), 2) in Roman times, the exploitation of *Abies* for timber, and 3) since the Middle Ages, the cultivation of *Castanea, Juglans* and *Olea*.

Pollen-based vegetation poorly records cereals, which can be wild cereal growing in Southern Apeninnes (Schneider, 1985), and also of anthopogenic indicators with the exception of those indicating pastoral activities in forests. The distal signal of antropogenic impact remains extremely faint as shown by the still high AP_{wa} percentages, while beech forest remains dominant around the lake.

6 Conclusions

The high-resolution pollen-record of Lake Trifoglietti provides new insights into paleoenvironmental and palaeoclimatic changes which may have characterised the Holocene period in the Southern Italy:

- The history of Holocene vegetation cover shows that an important and relatively stable forest, directly inherited from the early Holocene, was able to survive throughout that entire period in the form of a puzzlingly dense beech forest. This therefore constitutes a rare example of a woodstand which has survived climate changes for more than 11 000 yr and suggests that changes in temperature and precipitation in the growing season at Trifoglietti never attained a magnitude sufficient to alter the high competitivity of a thick beech forest.

- It supports a southward delay in the thermophilous forest expansion dated to ca. 13 500 cal. BP at Monticchio, ca. 11 000 cal. BP at Trifoglietti, and finally ca. 9800 cal. BP in Sicily.

- The pollen record of Trifoglietti shows only poor imprints of agricultural activity and anthopogenic indicators, apart from those indicating pastoral activities beneath forest cover. The strongest human impact in the Trifoglietti surroundings is the selective exploitation of fir.

- Using (1) a specific ratio between hygrophilous and terrestrial taxa, and (2) the Modern Analogue Technique, the pollen data collected at Lake Trifoglietti led to the establishment of two palaeoclimatic records based on changes in (1) lake depth and (2) annual precipitation. This allows recognition of both millennial-scale trends and centennial-scale oscillations which may have characterised the Holocene in the Southern Italy. Thus, on a millennial scale, the records suggest increasing moisture from ca. 11 000 to ca. 9400 cal. BP, a maximum of humidity from ca. 9400 to ca. 6200 cal. BP, before a general trend towards drier climate conditions that prevail up to the present. Superimposed on these millennial-scale trends, several successive centennial-scale oscillations appear to have punctuated the entire Holocene as described below. Identification of a cold dry event around 11 300 cal. BP, responsible for a marked decline in timberline altitude and possibly equivalent to the PBO, must be confirmed by further investigations to verify both chronology and magnitude. Two cold and possibly drier Boreal oscillations developed at ca. 9800 and 9200 cal. BP. The 8.2 kyr event corresponded at Trifoglietti to the onset of cooler and drier climatic conditions which persisted until ca. 7500 cal. BP. Finally, the second half of the Holocene was characterised by dry phases at ca. 6100–5200, 4400–3500, and 2500–1800 cal. BP, alternating with more humid phases at ca. 5200–4400 and ca. 3500–2500 cal. BP. Considered as a whole, these millennial-scale trends and centennial-scale climatic oscillations support contrasting patterns of palaeohydrological changes recognised between the North- and South-Central Mediterranean.

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Table 1. AMS–radiocarbon dates with 2σ range of calibration from Lake Trifoglietti's S2A and S2B cores.

Sample ID	Lab. code	Material	AMS 14C Age BP	Depth MC (cm)	cal. yr BP (2σ)
S4-A1	POZ-33804	Wood-Peat-Charcoal	125 ± 30	87	0–270
S4-A2	POZ-33806	Wood-Peat-Charcoal	2675 ± 35	172	2740–2850
S4-A3	POZ-33807	Wood-Peat-Charcoal	3970 ± 40	295	4290–4530
S4-A4	POZ-33808	Wood-Peat-Charcoal	4890 ± 35	371	5580–5710
S4-A5	POZ-33809	Wood-Peat-Charcoal	6660 ± 50	497	7430–7610
S4-A6	POZ-33810	Wood-Peat-Charcoal	7920 ± 50	571	8600–8980
S4-A7	POZ-33811	Wood-Peat-Charcoal	8600 ± 50	685	9490–9680
S4-A8	POZ-33812	Wood-Peat-Charcoal	9335 ± 60	761	10 290–10 710
S4-A9	POZ-33813	Wood-Peat-Charcoal	9630 ± 60	806	10 760–11 190
S4-B9	POZ-41168	Wood-Peat-Charcoal	9850 ± 50	843	11 190–11 388
S4-B9	POZ-33876	Wood-Peat-Charcoal	9940 ± 60	843	11 220–11 690

Table 2. Relevé of vegetation from the peat/lake numbered 1 to 3, and from the surronding forest of *Fagus* (4) and maquis with *Alnus cordata* (5). Codification of surface sample cover is as following: 5 = 100 %–80 %; 4 = 80 %–60 %; 3 = 60 %–40 %; 2 = 40 %–20 %; 1 = 20 %–1 %; + =< 1 %.

	1 *Carex paniculata* vegetation	2 *Carex paniculata* vegetation	3 Transition lake vegetation to *Fagus slvatica* wood	4 *Fagus sylvatica* wood	5 Transition maquis to *Alnus cordata* wood
Surface m^2	5	5	5	20	50
Herbaceous layer cover	100	100	90	100	100
Depht of water cm	60	50	10		
Carex paniculata	5	5			
Osmunda regalis	2	3	1		
Angelica sylvestris	1	1			
Lysimachia vulgaris	+	1			
Eupatorium cannabinum	+	1			
Oxalis acetosella	+	1			
Rubus hirtus	+	+			
Lycopus europaeus	+	+	+		
Solanum dulcamara	+				
Alnus cordata	+				1
Athyrium filix-foemina	+		+		
Lonicera sp.	+				
Holcus lanatus		+			
Arisarum proboscideum		+			
Carex distans		1			
Mentha aquatica		+	1		
Carex acutiformis			2		
Rubus ulmifolius			2		
Carex pendula			1		
Fagus sylvatica			1	5	
Vinca minor				4	
Cyclamen hederifolium				2	
Polysticum aculeatum				1	
Pinus nigra subsp. laricio				+	
Erica arborea					3
Cistus salvifolius					2
Helichrysum italicum					2
Sarothamnus scoparius					2
Clematis vitalba					1

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Table 3. Inventory of local pollen zones with depth and estimated ages, main taxa, total of arboreal pollen (AP), common and rare pollen types and palynomorphs used for hygrophilous vegetation. Note that two ratios AP$_t$ and AP$_{wa}$ are used (arboreal pollen without *Alnus* (AP$_{wa}$) has been calculated by excluding main hygrophilous taxa (Aquatics and *Eupatorium*) of the NAP).

LPAZ	Depth (cm) Age (yr cal. BP)	Main taxa observed	Total of Arboreal Pollen %	Common pollen types (CPT) Rare pollen types (RPT)	Palynomorphs
T-13	46–40 *33–0*	*Fagus*	AP$_t$ 60 AP$_{wa}$ 40	CPT: *Deciduous Quercus*, *Ostrya*, *Castanea*, *Alnus*, *Olea*, *Poaceae*, *Cyperaceae* RPT: *Abies*, *Juglans*, *Fraxinus excelsior*, *Erica arborea*, *Pistacia*, *Quercus ilex*, *Rumex*, Ast. *Asteroideae*	*Osmunda* and aquatics development
T-12	106–46 *800–33*	*Fagus-Alnus*	AP$_t$ 88–98 AP$_{wa}$ 50–78	CPT: *Deciduous Quercus*, *Ostrya*, *Olea*, *Cyperaceae* RPT: *Corylus*, *Castanea*, *Juglans*, *Pistacia*, *Quercus ilex*, *Rumex*, *Poaceae*	*Osmunda* and aquatics reduction
T-11	144–106 *2100–800*	*Fagus-deciduous Quercus-Alnus*	AP$_t$ 88–98 AP$_{wa}$ 68–80	CPT: *Ostrya*, *Quercus ilex*, *Poaceae*, *Cyperaceae* RPT: *Hedera helix*, *Abies*, *Olea*, Ast. *Asteroideae*	*Osmunda* and aquatics development
T-10	210–144 *3500–2100*	*Fagus-deciduous Quercus-Abies-Alnus*	AP$_t$ 75–95 AP$_{wa}$ 67–88	CPT: *Ostrya*, *Hedera helix*, *Poaceae*, *Cyperaceae* RPT: *Pinus*, *Olea*, *Quercus ilex*, Ast. *Asteroideae*	*Osmunda* and aquatics development
T-9	246–210 *3950–3500*	*Fagus-Alnus*	AP$_t$ 90–98 AP$_{wa}$ 81–90	CPT: *Ostrya*, *deciduous Quercus*, *Abies*, *Poaceae* RPT: *Hedera helix*, *Olea*, *Quercus ilex Cyperaceae*, Ast. *Asteroideae*	*Osmunda* reduction, rare aquatics and *Pteridium*
T-8	308–246 *4650–3950*	*Fagus-deciduous Quercus-Abies-Alnus*	AP$_t$ 80–95	CPT: *Ostrya*, *Alnus*, *Poaceae*, *Cyperaceae* RPT: *Betula*, *Hedera helix*, *Erica arborea*, *Quercus ilex*, Ast. *Asteroideae*	*Osmunda* and aquatics reduction
T-7	338–308 *5100–4650*	*Fagus-deciduous Quercus-Abies*	AP$_t$ 65–80	CPT: *Ostrya*, *Alnus*, *Poaceae*, *Cyperaceae* RPT: *Ulmus*, *Hedera helix*, *Olea*, *Quercus ilex*, *Rumex*, Ast. *Asteroideae*	*Osmunda* and aquatics development
T-6	408–338 *6150–5100*	*Fagus-deciduous Quercus-Alnus-Ostrya*	AP$_t$ 85–98	CPT: *Abies*, *Hedera helix* RPT: *Pinus*, *Ulmus*, *Olea*, *Quercus ilex*, *Rumex*, *Poaceae*, *Cyperaceae*, Ast. *Asteroideae*	*Osmunda* and aquatics reduction
T-5	484–408 *7300–6150*	*Fagus-deciduous Quercus-Abies-Ostrya*	AP$_t$ 65–92	CPT: *Hedera helix*, *Alnus*, *Fraxinus excelsior*, *Quercus ilex*, *Rumex*, *Poaceae*, *Cyperaceae*, Ast. *Asteroideae* RPT: *Fraxinus ornus*, *Tilia*, *Corylus*, *Olea*, *Lamiaceae*, *Scrophulariaceae*, *Rosaceae*, *Cerealia* tp.	*Osmunda* and aquatics
T-4	654–580 *9400–8900*	*Fagus-deciduous Quercus-Abies-Ostrya*	AP$_t$ 40–93 AP$_{wa}$ 71–93	CPT: *Ulmus*, *Corylus*, *Fraxinus ornus*, *Hedera helix*, *Quercus ilex*, *Poaceae*, *Solanum dulcamara*, *Scrophulariaceae*, Ast. *Asteroideae* RPT: *Erica arborea*, *Rumex*, *Rosaceae*	*Osmunda* and aquatics development

* please give definition for italic figures.

Table 3. Continued

LPAZ	Depth (cm) Age (yr cal. BP)	Main taxa observed	Total of Arboreal Pollen %	Common pollen types (CPT) Rare pollen types (RPT)	Palynomorphs
T-3c	654–580 *9400–8900*			CPT: *Hedera helix*, *Alnus*, *Erica arborea*, *Poaceae* RPT: *Betula*, *Ulmus*, *Castanea*, *Olea*, *Rumex*, *Scrophulariaceae*, *Cyperaceae*, Ast. *Asteroideae*	
T-3b	720–654 *10 000–9400*			CPT: *Betula*, *Corylus*, *Ulmus*, *Erica arborea*, *Hedera helix*, *Poaceae* RPT: *Pistacia*, *Rumex*, *Cyperaceae*, Ast. *Asteroideae*	
T-3a	804–720 *11 000–10 000*			CPT: *Ulmus*, *Betula*, *Pinus*, *Hedera helix*, *Poaceae*, *Rumex* RPT: *Fraxinus ornus*, *Quercus ilex*	
T-3	804–580 *11 000–8900*	*Fagus-deciduous Quercus-Abies-Ostrya*	AP_t 80–95		*Botryococcus* (algae) is strongly developed despite a marked variability
T-2	842–804 *11 400–11 000*	*deciduous Quercus-Poaceae-Caryophyllaceae-Artemisia*	AP_t 25–40	CPT: *Betula*, *Pinus*, *Abies*, *Helianthemum*, *Rumex*, Ast. *Cichorioideae*, *Chenopodiaceae*, *Plantago*, Ast. *Asteroideae* RPT: *Juniperus*, *Ulmus*, *Alnus*, *Centaurea*, *Lamiaceae*	
T-1	850–842 *Before 11 400*	*deciduous Quercus-Fagus-Poaceae*	AP_t 50–55	CPT: *Betula*, *Pinus*, *Alnus*, *Helianthemum*, *Rumex*, Ast. *Cichorioideae*, *Chenopodiaceae* RPT: *Abies*, *Fraxinus ornus*, *Artemisia*, *Plantago*, Ast. *Asteroideae*	

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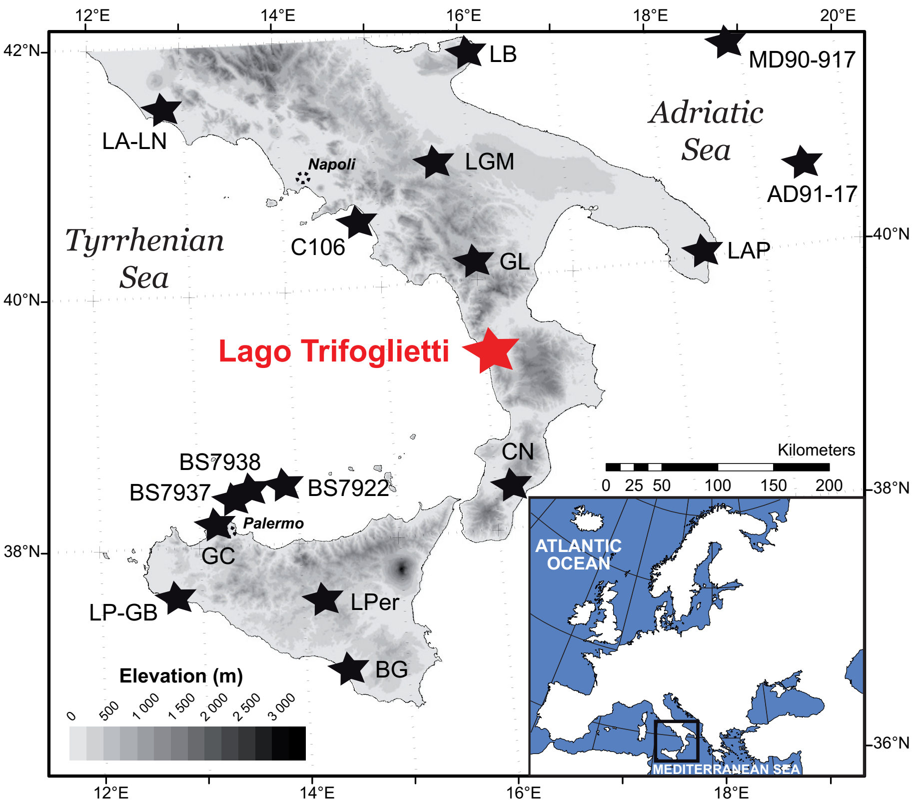

Fig. 1. Location of study site and other sites considered in the text: Lago Albano and Nemi (Ariztegui et al., 2000), Lago Battaglia and Lago Alimini Piccolo (Di Rita and Magri, 2009), Lago di Monticchio (Allen et al., 2002), C106 (Di Donato et al., 2008), Grotte di Latronico (Colonese et al., 2010), Canolo Nuovo (Schneider, 1984), Lago di Pergusa (Sadori and Narcissi, 2001), Biviere di Gela (Noti et al., 2009), Grotte di Carburangeli (Frisia et al., 2006), Gorgo Basso (Tinner et al., 2009), Lago Preola (Magny et al., 2011b), AD91-17 (Sangiorgi et al., 2003), BS7938 (Sbaffi et al., 2004), MD90-917 (Siani et al., 2012).

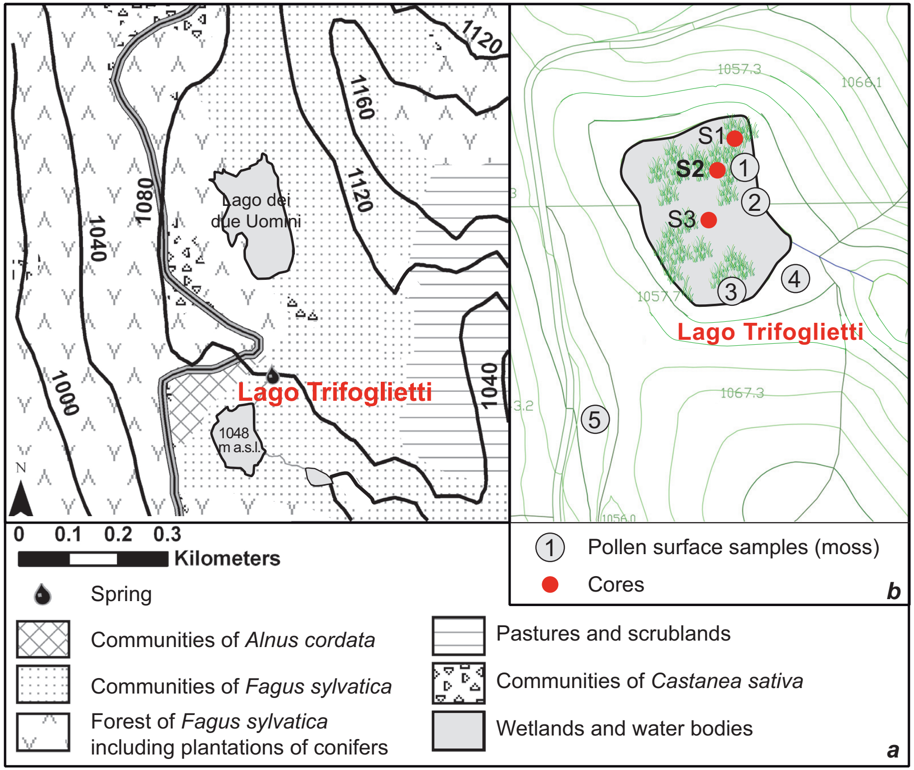

Fig. 2. (a) Actual vegetation map; **(b)** coring sites, surface samples and relevés localisation.

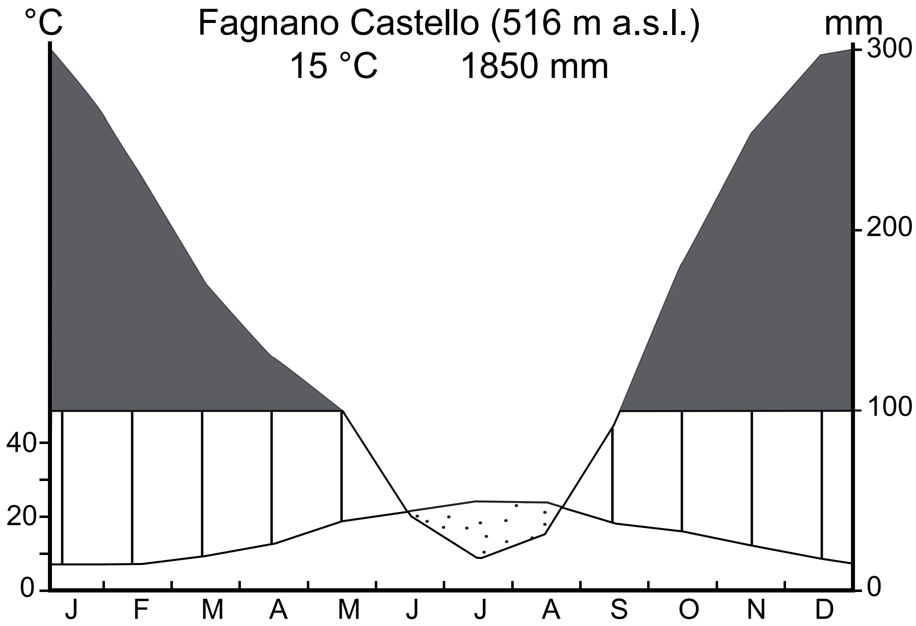

Fig. 3. Ombrothermic diagram of the meteorological station nearest to Fagnano Castello.

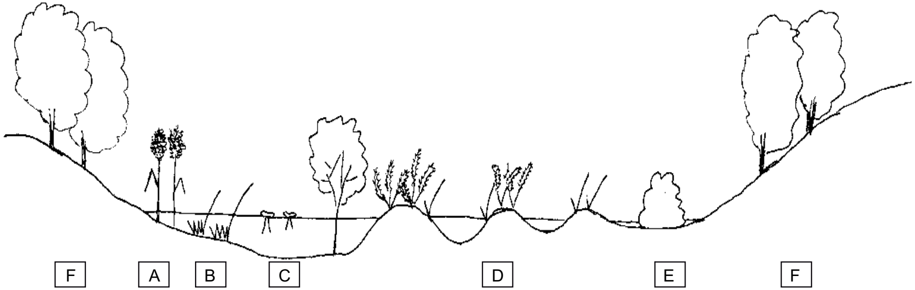

Fig. 4. Transect of actual vegetation around Lake Trifoglietti. A: *Sparganium erectum*; B: *Carex vesicaria*; C: *Potamogeton natans*, *P. nodosus* and *Alnus cordata* trees; D: *Carex paniculata*, *Osmunda regalis*; E: *Carex pendula*, *Mentha aquatica*, *Rubus ulmifolius*; F: *Fagus* wood.

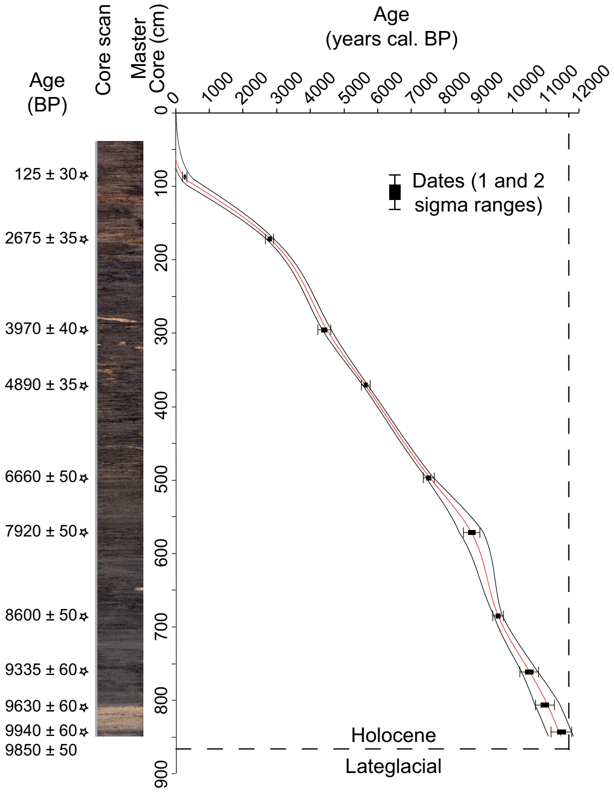

Fig. 5. Lithology and age-depth model of mastercore based on radiocarbon calibrated ages (AMS, see Table 1).

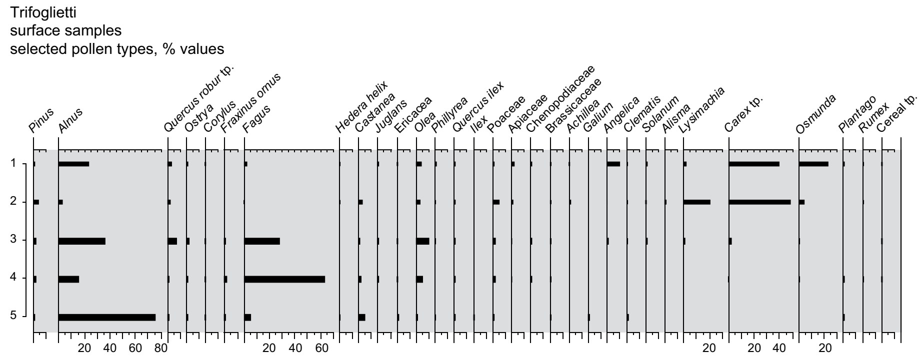

Fig. 6. Pollen diagram of five surface samples (see location map, Fig. 2b).

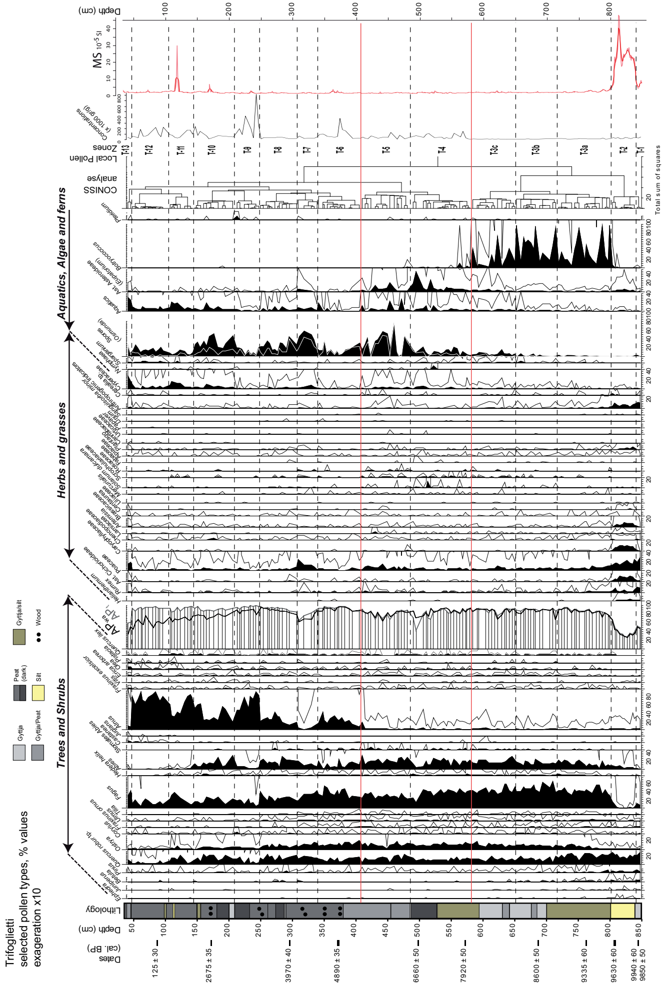

Fig. 7. Caption on next page.

Fig. 7. Pollen diagram represented according to depth showing percentages of main pollen taxa. Pollen zones are based on CONISS. 10* exaggerations of the pollen curves are also shown. Total concentration of pollen grains and magnetic susceptibility are represented on the right.

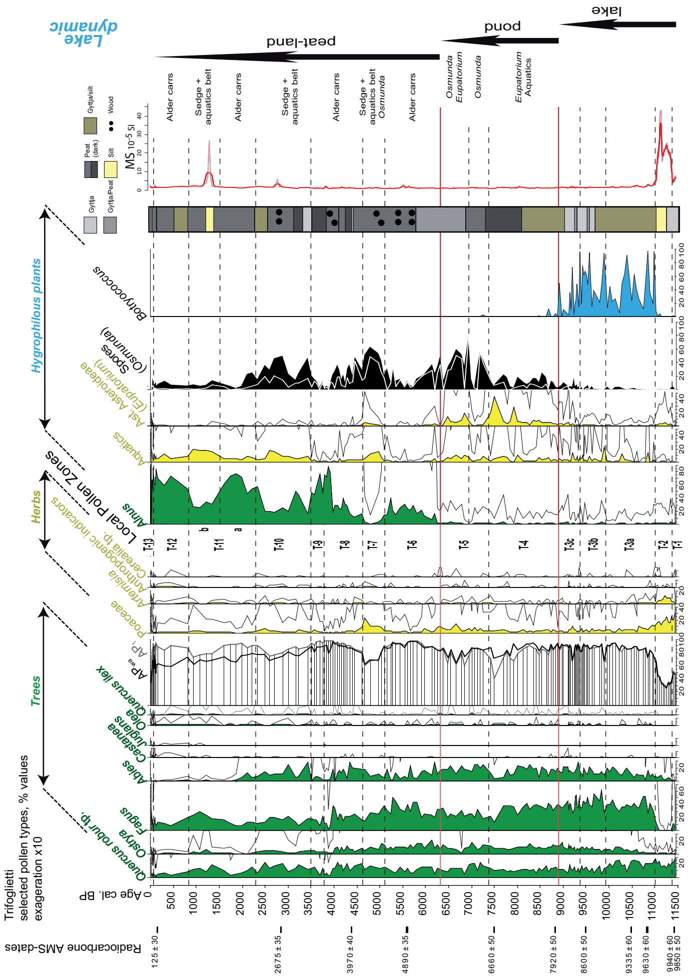

Fig. 8. Caption on next page.

Fig. 8. Main pollen taxa, lithology and magnetic susceptibility represented in age (calibrated BP). On the right, local vegetation is divided into phases that correspond to lake-depth dynamic.

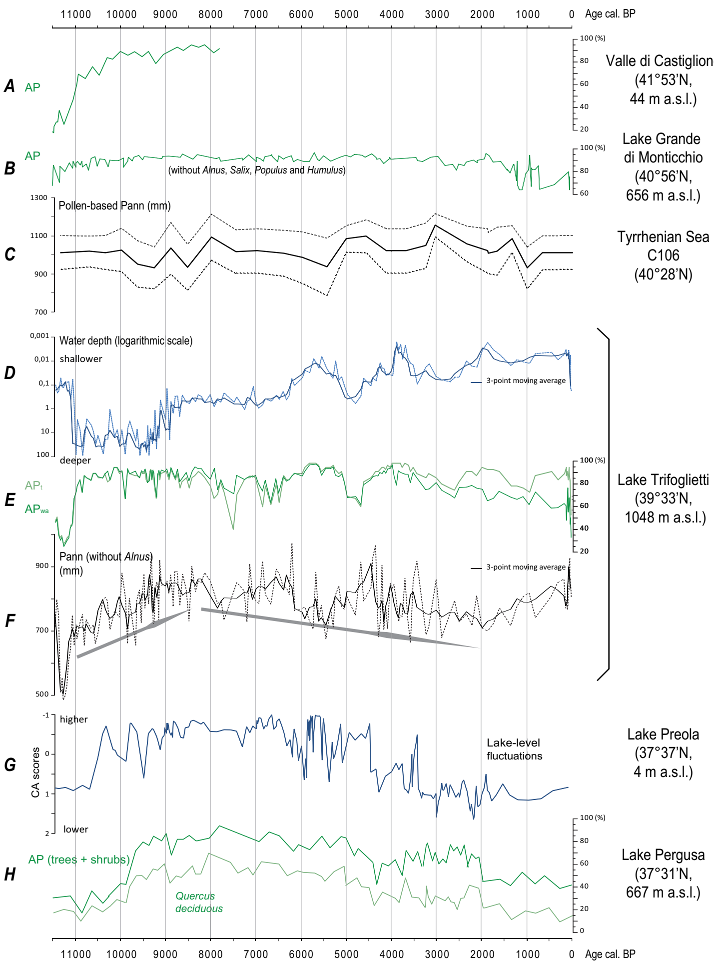

Fig. 9. Caption on next page.

Fig. 9. Comparison of paleorecords from Valle di Castiglione (A; Di Rita et al., 2012), Lake Di Monticchio (B; AP changes; Allen et al., 2002), C106 marine core (C; pollen-based annual precipitation (Pann); Di Donato et al., 2008), Lake Trifoglietti (D, pollen-based water-depth; E, AP_t and AP_{wa} (Arboreal Pollen total or Without *Alnus*); F, pollen-based annual precipitation (Pann)), Lake Preola (G; lake-level changes; Sicily, Magny et al., 2011b) and Lake Pergusa (H; AP changes and deciduous *Quercus*; Sicily, Sadori et al., 2011).