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Climate of the Past

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

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Abstract. A high-resolution pollen record from Lago 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 organic material. 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 beech 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 thermophyllous 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 Lago 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 corresponds 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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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 through 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, nevertheless, 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; Favaretto et al., 2008; Magny et al., 2006a, 2007b, 2009; Combourieu Nebout et al., 2009; Pross et al., 2009; Fletcher et al., 2010). 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 southeastern 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 Grande 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, which are separated by 450 km, provide a forest development asynchronism of ca. 4000 yr.

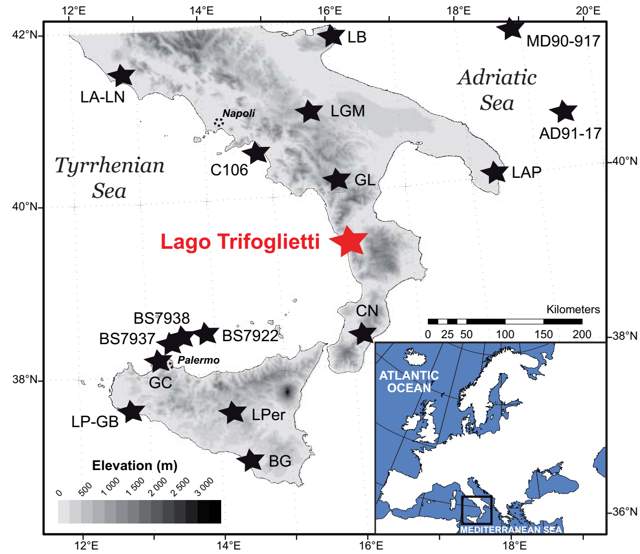

Fig. 1. Location of study site and other sites considered in the text: Lago Albano and Nemi (Ariztegui et al., 2000 and references therein), Lago Battaglia (Caroli and Caldara, 2007), Lago Alimini Piccolo (Di Rita and Magri, 2009), Lago Grande di Monticchio (Allen et al., 2002), C106 (Di Donato et al., 2008), Grotta di Latronico (Colonese et al., 2010), Canolo Nuovo (Schneider, 1985), Lago di Pergusa (Sadori and Narcisi, 2001), Biviere di Gela (Noti et al., 2009), Grotta di Carburangeli (Frisia et al., 2006), Gorgo Basso (Tinner et al., 2009), Lago Preola (Magny et al., 2011b; Calò et al., 2012), AD91-17 (Sangiorgi et al., 2003), BS7938 (Sbaffi et al., 2004), MD90-917 (Siani et al., 2012).

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 Lago Trifoglietti by a short pollen study published by Murgia et al. (1984), we have carried out new investigations there (1) to establish a new Holocene vegetation record in an

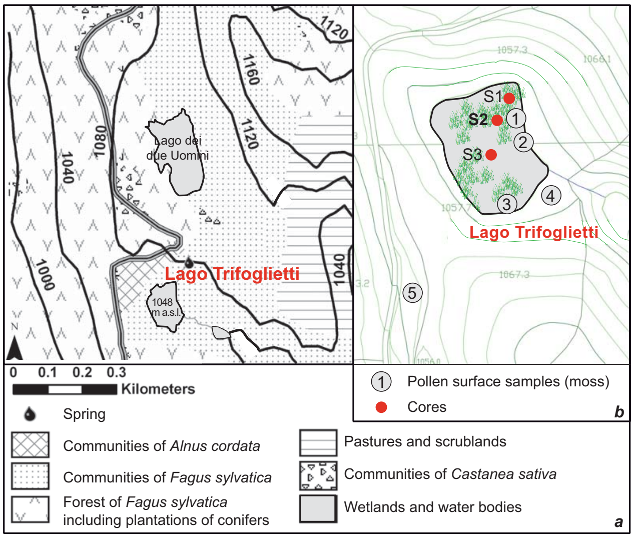

Fig. 2. (a) Actual vegetation map; **(b)** coring sites, surface samples and relevés localisation.

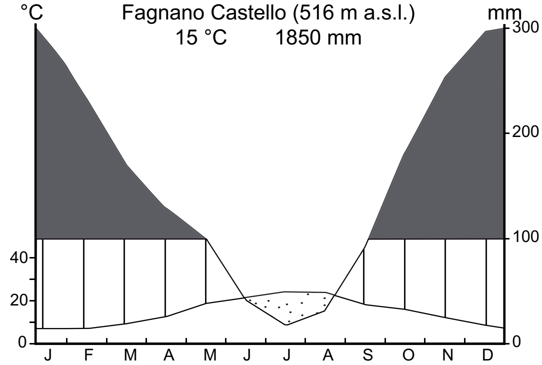

Fig. 3. Ombrothermic diagram of the meteorological station of Fagnano Castello, about 3 km away from Lago Trifoglietti. This station is on the eastern side of the mountain range, and the record ran for 42 yr (1921–1968; Ciancio, 1971).

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

Lago 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), Lago Trifoglietti is part of a natural high-altitude lucustrine system inhabited by endemic amphibians (Sperone et al., 2007). 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 (Sperone et al., 2007). 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 (ARSSA, 2003), 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 depression created behind the landslide body, but subsequent infilling with material from mountain runoff progressively gave them a rounded shape.

At Trifoglietti nowadays, a spring 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 can reach more than 1800 mm yr^{-1} (Fig. 3), though a relatively short dry period develops in summer (Ciancio, 1971). 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*, *Helichrysum italicum*, *Sarothamnus scoparius* and *Alnus cordata* trees, develops in the more open *Fagus* forests.

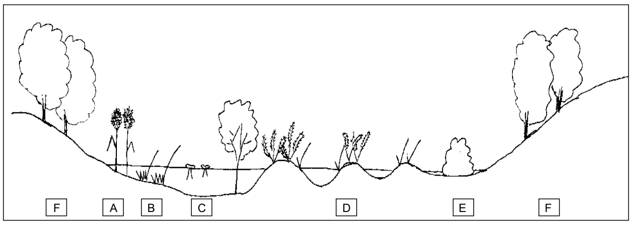

Fig. 4. Transect of actual vegetation around Lago Trifoglietti. A: *Sparganium erectum*; B: *Carex vesicaria*; C: *Potamogeton natans*, *P. nodosus* and *Alnus cordata* trees; D: *Carex paniculata*, *Osmunda regalis*; E: *Carex pendula*, *Mentha aquatica*, *Rubus ulmifolius*; F: *Fagus*.

A schematic transect of present-day vegetation is presented in Fig. 4. The lake vegetation comprises of 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 *Carex paniculata* swamp (D). This tall sedge grows in spaced tussocks protruding from the water surface, the living plant progressively builds 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 fibres accumulate in the ground, which tends to dry up, the sedge is, therefore, 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 sedge bed 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 centre (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 anthropogenic rise in water depth, however, is not compatible with the alder's ecological needs. The importance of Lago Trifoglietti depends on the presence of the endemic amphibians and on endangered aquatic and hygrophilous habitats in the Mediterranean area (Sperone et al., 2007). 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*.

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 north-east edge. Segments were extracted on site, wrapped in plastic, transported to the University of Franche-Comté and stored at 4 °C.

The cores were split 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 (de 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; de 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 organic material (Table 1). The radiocarbon ages have been calibrated in yr cal BP by using Calib 6.0 software (Stuiver and Reimer, 1993) based on calibration curve IntCal09 (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 $\pm$ 50 BP and 9940 $\pm$ 60 BP). The age-depth model (Fig. 5) is constructed using a mixed-effect regression model according to the procedure standardised by Heegaard et al. (2005).

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

Sample ID	Lab. code	Material	AMS ^{14}C Age BP	Depth MC (cm)	cal yr BP (2σ)
S4-A1	POZ-33804	Wood-Charcoal	125 ± 30	87	0–270
S4-A2	POZ-33806	Wood-Charcoal	2675 ± 35	172	2740–2850
S4-A3	POZ-33807	Wood-Charcoal	3970 ± 40	295	4290–4530
S4-A4	POZ-33808	Wood-Charcoal	4890 ± 35	371	5580–5710
S4-A5	POZ-33809	Wood-Charcoal	6660 ± 50	497	7430–7610
S4-A6	POZ-33810	Wood-Charcoal	7920 ± 50	571	8600–8980
S4-A7	POZ-33811	Wood-Charcoal	8600 ± 50	685	9490–9680
S4-A8	POZ-33812	Wood-Charcoal	9335 ± 60	761	10290–10710
S4-A9	POZ-33813	Wood-Charcoal	9630 ± 60	806	10 760–11 190
S4-B9	POZ-41168	Wood-Charcoal	9850 ± 50	843	11 190–11 388
S4-B9	POZ-33876	Wood-Charcoal	9940 ± 60	843	11 220–11 690

3.3 Pollen analysis

3.3.1 Surface samples

Studying the relationship between pollen rain and actual vegetation is essential for the interpretation of fossil pollen spectra. The pollen rain depends primarily on the internal parameters of the plant (production potential and dispersion) and external factors (topography and climate). Barthelemy and Jolly (1989) consider that the most important factor is the topography: the wind that rises along the slope, carrying the pollen that falls to the ground where the slope is interrupted by a shelf. The deposit is then behind the edge of the shelf into the basin (Brugiapaglia et al., 1998). At Trifoglietti, the filter effect operated by the dense forest vegetation that surrounds the lake is also taken into account. In order to interpret the fossil diagram, five moss samples were collected (Fig. 2b) and treated both chemically (NaOH, HCl, HF, acetolysis) and physically (sieving 300 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 pollen diagram of selected taxa from 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 $\times$ 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 pollen diagram of selected taxa 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*/*P. 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: 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

A multi-method approach of the Trifoglietti pollen sequence is applied in order to provide robust quantitative estimates of the Holocene climate and to better assess reconstruction error. We have chosen two "standard" methods based on different ecological concepts: the Modern Analogues Technique (MAT, Guiot, 1990), and the Weighted Average Partial Least Squares regression (WAPLS, ter Braak and Juggins, 1993). These methods are usually applied to reconstruct climate changes in Mediterranean area during the Lateglacial or the Holocene (e.g., Davis and Brewer, 2009; Dormoy et al., 2009; Di Donato et al., 2008; Joannin et al., 2011, 2012; Peyron et al., 2011; Combourieu Nebout et al., 2012). The WAPLS NMDS/GAM is a true transfer function based on a calibration between environmental variables and modern pollen assemblages whereas the MAT does not require real calibration. This method is based on a comparison of past assemblages to modern pollen assemblages and used a modern pollen dataset that contains more than 3500 modern spectra (Dormoy et al., 2009) and in which surface sample spectra from Lago Trifoglietti surroundings, from Mount Altesina (close to Lake Pergusa, Sicily) and Lake Preola (Sicily) have been included. Annual precipitations (MAT Pann, WAPLS Pann) have been reconstructed and represented in Fig. 9f. Winter and summer precipitations are also reconstructed and discussed in the paper of Peyron et al. (2012) which propose a climatic reconstruction based on a multi-method approach (MAT, WA, WAPLS, NMDS/GAM) on four Italian pollen records (Lakes Ledro, Accesa, Trifoglietti, Pergusa). More details on the methods and their application to Trifoglietti's pollen record are given in this paper. Note that *Alnus* is excluded in the climate reconstructions performed with both the MAT and the WAPLS and that the values of precipitation calculated for the surface samples taken close to the Trifoglietti site have been corrected according to the ombrothermic diagram of the closest meteorological station (1850 mm).

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 to 843 cm: gyttja layer,
- from 843 to 805 cm: silt layer,
- from 805 to 700 cm: mixed gyttja and silt layer,

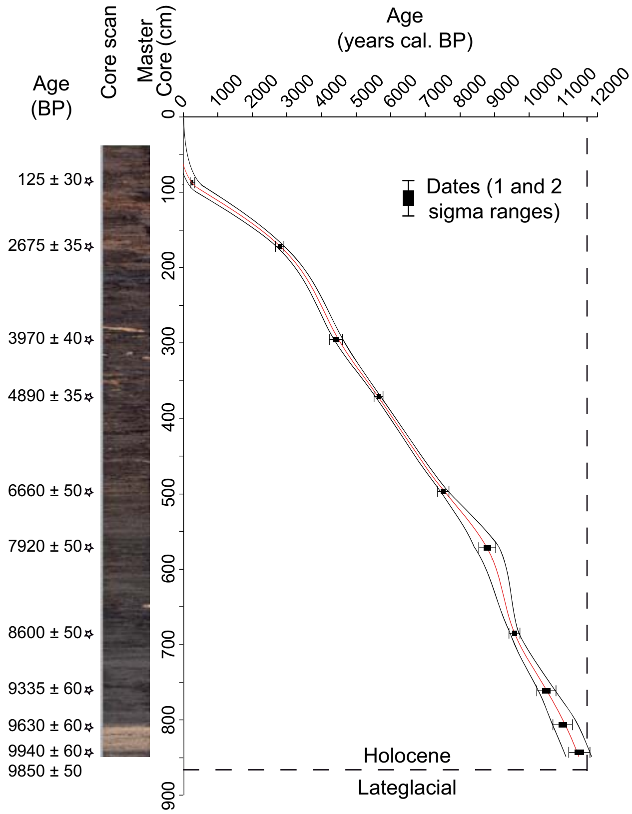

Fig. 5. Lithology and age-depth model of mastercore based on radiocarbon calibrated ages (AMS, see Table 1).

- 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, 213–200 and 100–97 cm) and gyttja/silt layers (162–152, 122–117 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. In this last level, strong MS values are not explained as no volcanic minerals have been found.

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. The rate decreases upwards. The average temporal resolution is estimated at ca. 70 yr/sample for the entire Holocene and attains a maximum of 37 yr/sample 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.

Lago Trifoglietti pollen rain broadly mimics the corresponding types of vegetation: in fact the filter effect, therefore, determines that the regional pollen rain is poorly recorded, while a good assessment of the local vegetation is well demonstrated by the results obtained in the diagram (Fig. 6). On the whole, the *Pinus* abundance recorded in open land (3 %) is in better accordance with reality than in *Fagus* wood (1 %). Pollen grains of *Quercus robur* tp., *Olea* and *Castanea* are produced by plants absent (almost absent in the case of *Castanea*) 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* percentages (10–30 %) are 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 Lago 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. Although *Quercus robur* tp. and *Fagus* 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 likely to have remained above the timberline at this time, surrounded by oro-Mediterranean meadows. The decrease of AP percentages could be due either to a lowering of the tree limit or to a poor pollen productivity of the temperate trees as a consequence of the cooling. Oaks and *Fagus* 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 Cichorioideae, 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 the local establishment of a mountain forest ecosystem dominated by *Fagus* and *Abies* trees. High values of AP suggest that the site is now below the timberline. *Abies* percentages also increase progressively to ca. 20 % and always remain lower than those of *Fagus*. Nevertheless, regular occurrences of *Abies* stomata ensure that the trees grew alongside *Fagus* in the lake's immediate surroundings. Considering the poor dispersal of *Abies* pollen grains (Mazier, 2006), this conifer was probably as abundant as *Fagus*. The present *Fagus* (beech) forest is directly inherited from the remote early Holocene, thus, furnishing a rare example of beech 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 Madonie Mountains in Sicily, are the relics of a 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,

Table 2. Relevé of vegetation from the peat/lake numbered 1 to 3, and from the surrounding forest of *Fagus* (4) and maquis with *Alnus cordata* (5). Codification of surface sample cover is as follows: 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

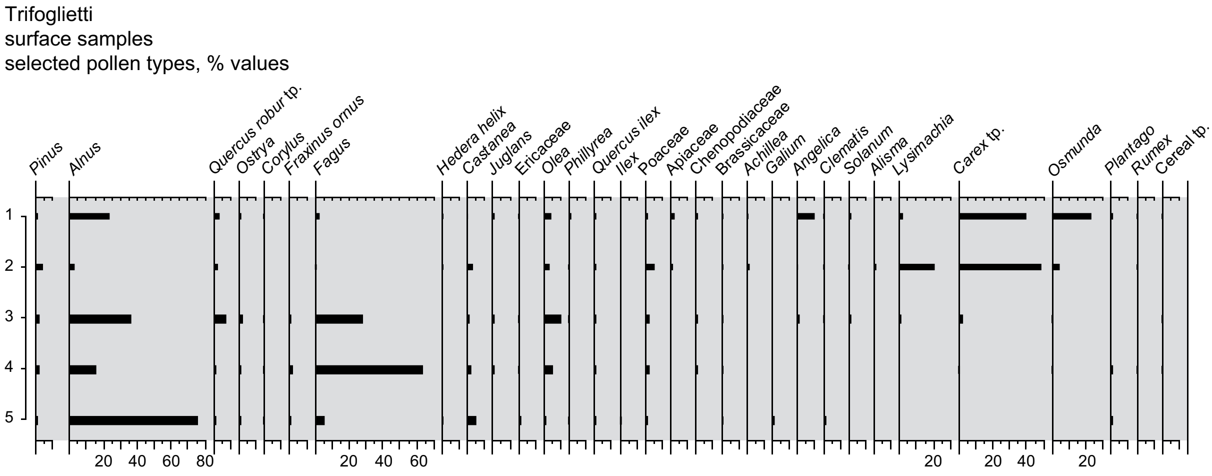

Fig. 6. Pollen diagram of five surface samples (see location map, Fig. 2b).

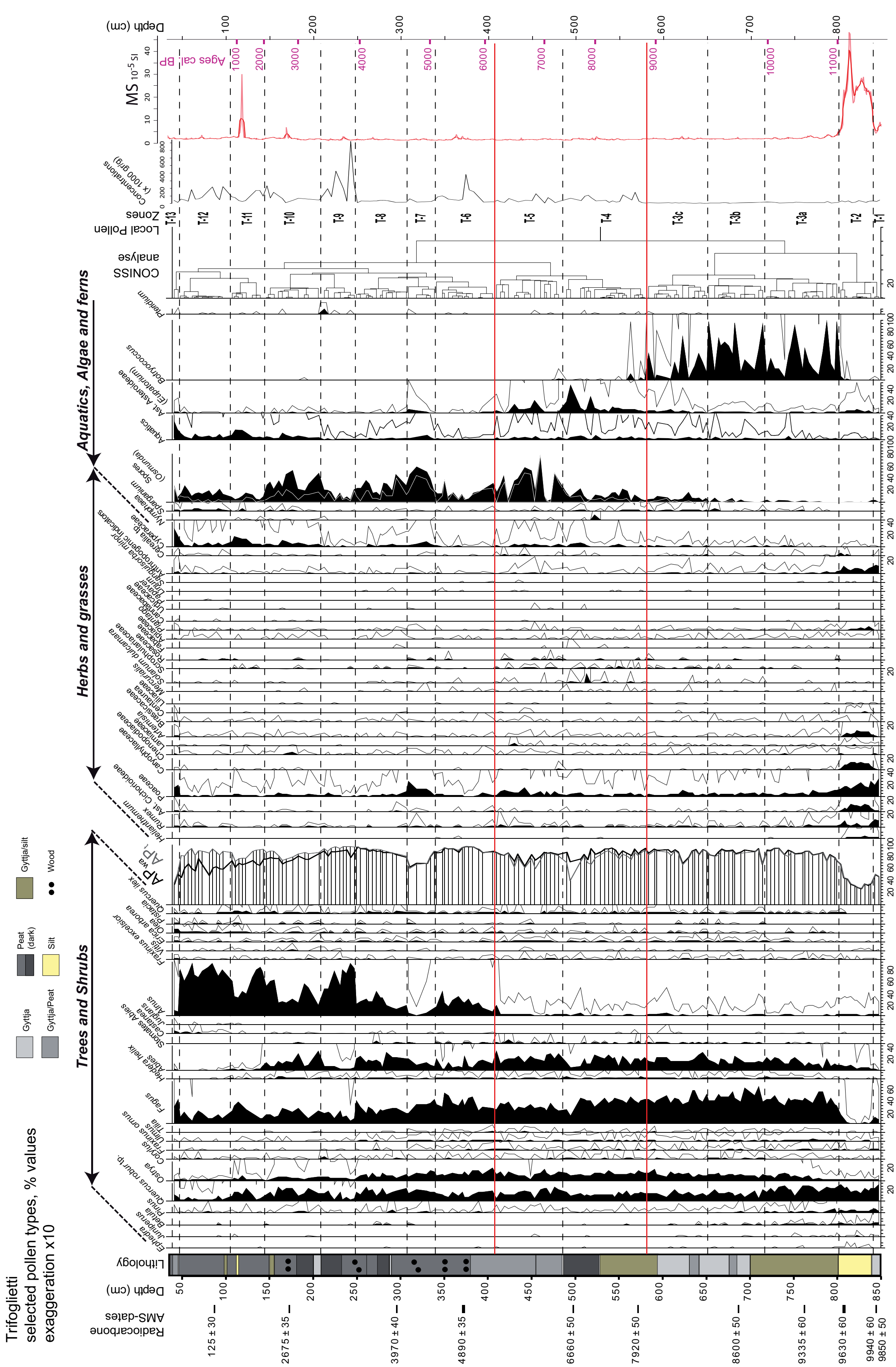

Fig. 7. Pollen diagram represented according to depth showing percentages of main pollen taxa. Pollen zones are based on CONISS. 10* exaggerations of the pollen curves are also shown. Total concentration of pollen grains and Magnetic susceptibility are represented on the right.

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
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	

indicating that the oak belt must have been closer on the mountain slope. In spite of the vicinity of the Mediterranean belt, sclerophyllous 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. 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 *Abies*/*Fagus* 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 *Fagus* 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 *Fagus* 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) *Abies* becomes more abundant than *Fagus*.

In zone T-6 (ca. 6150–5100 cal BP), the regression of *Abies* to the benefit of *Fagus* also suggests a dry episode. Zone T-7 (ca. 5100–4650 cal BP) is mainly characterised by an apparent reduction in mountain trees, but this is partly influenced by the auto-correlation between taxa percentages due to the high percent of aquatic plants and *Osmunda*. However, after stabilisation of *Fagus* and *Abies* in T-8, T-9 marks the beginning of forest regression at ca. 4000 cal BP. This change is probably due to generalised forest opening by Bronze Age populations, though anthropogenic indicators are almost absent; a minor increase 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 *Fagus*/*Abies* 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 and/or to climate change. 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 mesophyllous underwood development is favoured by high atmospheric moisture (Blasi et al., 2006). The quasi-disappearance of *Hedera*, however, seems more concomitant with that of *Abies* and, therefore, underscores lower moisture or pastoral activities within the woods. In the upper part of T-11 also begins the continuous occurrences of *Castanea* and *Juglans*. Rare but regular *Castanea* pollen grains are identified throughout 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* (colonies) are recorded, typical of an open lake with deep water (Testa et al., 2001) 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 Asteroideae 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 *Abies* to the benefit of *Fagus* 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 Lago 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

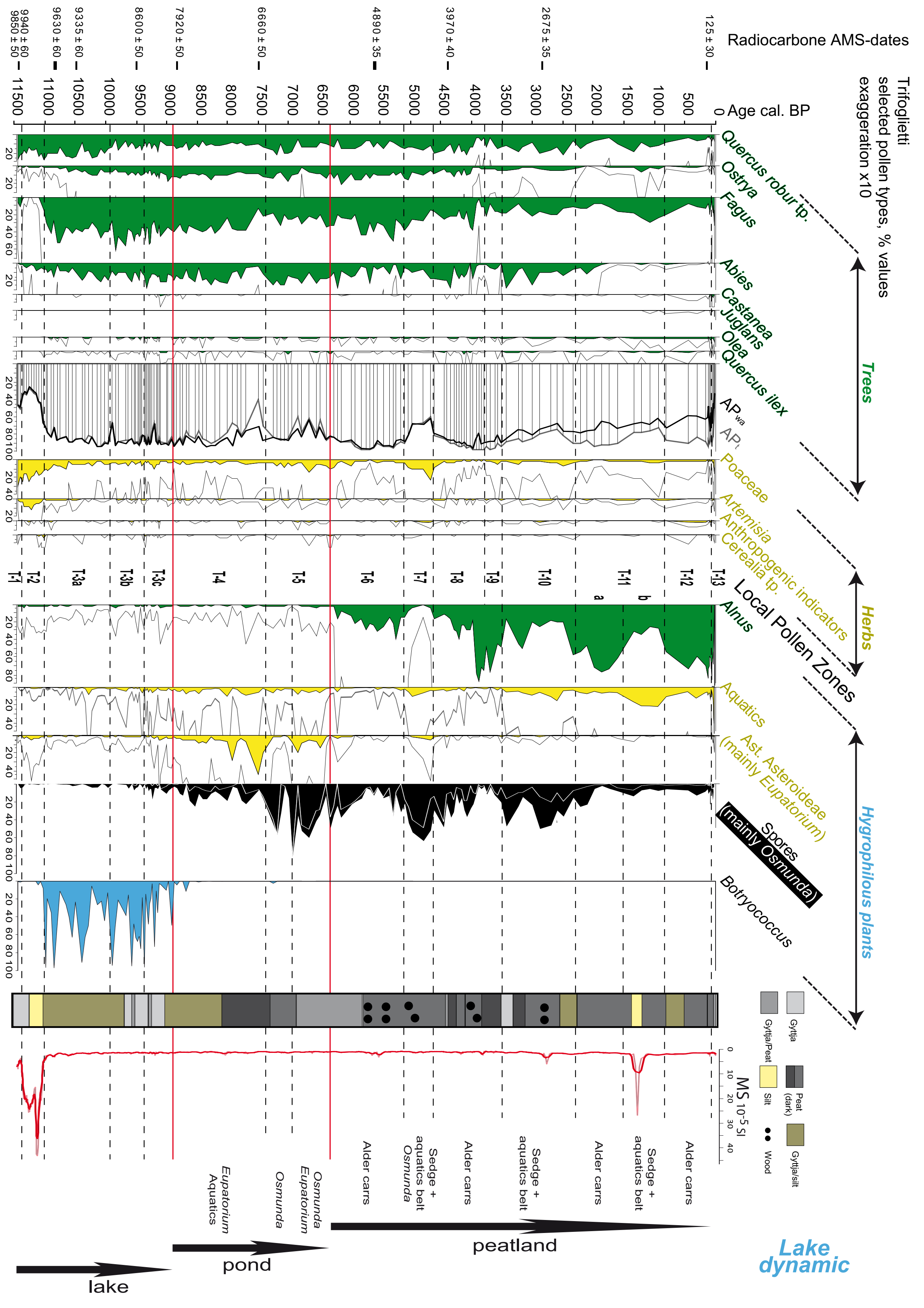

Fig. 8. Main pollen taxa, lithology and Magnetic Susceptibility represented in age (calibrated BP). On the right, local vegetation is divided into phases that correspond to lake-depth dynamic.

marked by alder decline to the benefit of aquatic plants and *Osmunda*. Within T-11 (ca. 2100–800 cal BP), two sub-zones can be distinguished 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. According to Landi and Angliolini (2010), riparian alder-woods (*Alnus glutinosa*) and alder swamps have similar ecological characteristics and are associated to *Osmunda regalis* in Tuscany (Italy). Moreover, the *Osmundo-Alnion* phytocoenoses can be identified by their generally oligotrophic nature and presence in watercourses that do not dry up in summer, in contact with the water table or near springs. In the case of Lago Trifoglietti, this association is observed in the modern surface sample 1 (Fig. 6), however, when looking at the fossil record, abundant variations of *Alnus* and *Osmunda* are opposed. This suggests slight differences in ecological requirements of these two taxa.

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*. First order clustering obtained from CONISS analysis clearly separates samples where algae (*Botryococcus*) and more terrestrial taxa (spores and *Alnus*) are dominant (Fig. 7). 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 which combining the two previously defined ratios, is generated in order to infer environmental evolution; this uses a logarithmic representation illustrated in Fig. 9d.

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 (more particularly during summer) as evidenced in central Italy and in Sicily (Ariztegui et al., 2000; Sadori et al., 2004; Giraudi et al., 2011; Magny et al., 2007a, 2011a,b).

4.2.5 Pollen-based quantitative reconstruction of precipitation

The quality of the MAT reconstruction appears acceptable for all the Holocene: the adopted threshold is 61.99, and only 2 samples between ca. 7950 and ca. 7500 yr cal BP have been removed because the number of analogues selected was too low. For all other samples, 8 modern analogues have been selected for the climate reconstruction. The modern analogs selected are located in Italy (samples close to Lago Trifoglietti), Alps, and Pyrenean areas, except for the period between ca. 11 500 to ca. 11 200 cal BP. This strong precipitation anomaly is driven by a switch from regional to extra-regional analogues, from Italy to high-elevation East regions (Greece, Turkey). The dissimilarity coefficients are, however, acceptable in this part of the reconstruction, as for the entire sequence.

To test the MAT results and to obtain a more reliable climate reconstruction, results provided by the WAPLS have been added. These results are in accordance with the annual precipitation based on the MAT. Annual precipitations reconstructed at Trifoglietti are around 900–1000 mm (1100 mm for the first part of the Holocene, when *Fagus* percentages are particularly high) and the error bar is close to 1200 mm (it can reach 1800 mm, not shown in the Fig. 9 for clarity). The quality of the reconstruction is acceptable, but the precipitations can appear underestimated taking into account the extremely high modern values (1850 mm). This underestimation may be related to the fact that this station is located at lower altitude (516 m a.s.l.) and is facing east (while Trifoglietti is facing west). Despite these uncertainties, when the climatic parameters – temperature or precipitation – are very low or high, all the methods often fail to reproduce such pattern (Combourieu Nebout et al., 2009). Therefore, it is preferable to discuss in terms of trend instead of raw values. The climate trend reconstructed at Lago Trifoglietti during the Holocene is consistent with closest sites such as Lake Preola in Sicily (see Peyron et al., 2012) and with the estimates obtained for a marine core located in the Gulf of Salerno (Fig. 9c) by Di Donato et al. (2008). These curves also seem in agreement with the fact that at present the natural populations of Mediterranean *Abies* live in areas where mean annual precipitations are above 1000 mm.

From ca. 11 500 to ca. 11 200 cal BP (Fig. 9f, see also Peyron et al., 2012), MAT annual precipitation reconstructed at Trifoglietti illustrates a marked drying phase (500 mm yr^{-1}).

The abrupt *Fagus* re-development at ca. 11 200 cal BP suggests a rapid increase in annual rainfall (Δ 200 mm). This increase then continued progressively from ca. 10 700 to ca. 8700 cal BP (Δ 250 mm) which favoured *Abies* expansion. WAPLS Pann show similar variations and trends although range of values appears smoothed compared with MAT Pann (Δ 300 mm between ca. 11 200 and ca. 8700 cal BP).

Both precipitation reconstruction show a long-term progressive drying from ca. 9500 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. 9500 to 6000 cal BP), drying phases (with low *Abies* values) at around 11 300 cal BP, ca. 8200–7500 cal BP, and a marked drying around 4200 cal BP.

Since 1700 cal BP, and despite *Abies* disappearance as well as oak regression and AP_{wa} decrease, *Fagus* forest again attains the prevalence attested at the early Holocene and probably explains the final increase in the MAT Pann (Δ 300 mm). However, this increase is not corroborated by WAPLS Pann and 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 Battaglia, Caroli and Caldara, 2007; Lago Alimini Piccolo, Di Rita and Magri, 2009; Lago Grande di Monticchio, Allen et al., 2002; Lago di Pergusa, Sadori et al., 2008; Tavoliere Plain, Di Rita et al., 2011; Fig. 1), though most of these concern lowlands. Lago Trifoglietti, however, appears as a unique example of a well-dated pollen sequence 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 recognise long-term climate variations which have affected southern Italy since the early Holocene.

5.1.1 Early Holocene expansion of mesophyllous 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 reach 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 Lago Trifoglietti, the timberline reached at least the same altitude. Nevertheless, the status above the timberline 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 *Abies* 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; Calò et al., 2012) 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 timberline 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 to correlate 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 (Fletcher et al., 2010; Di Rita et al.,

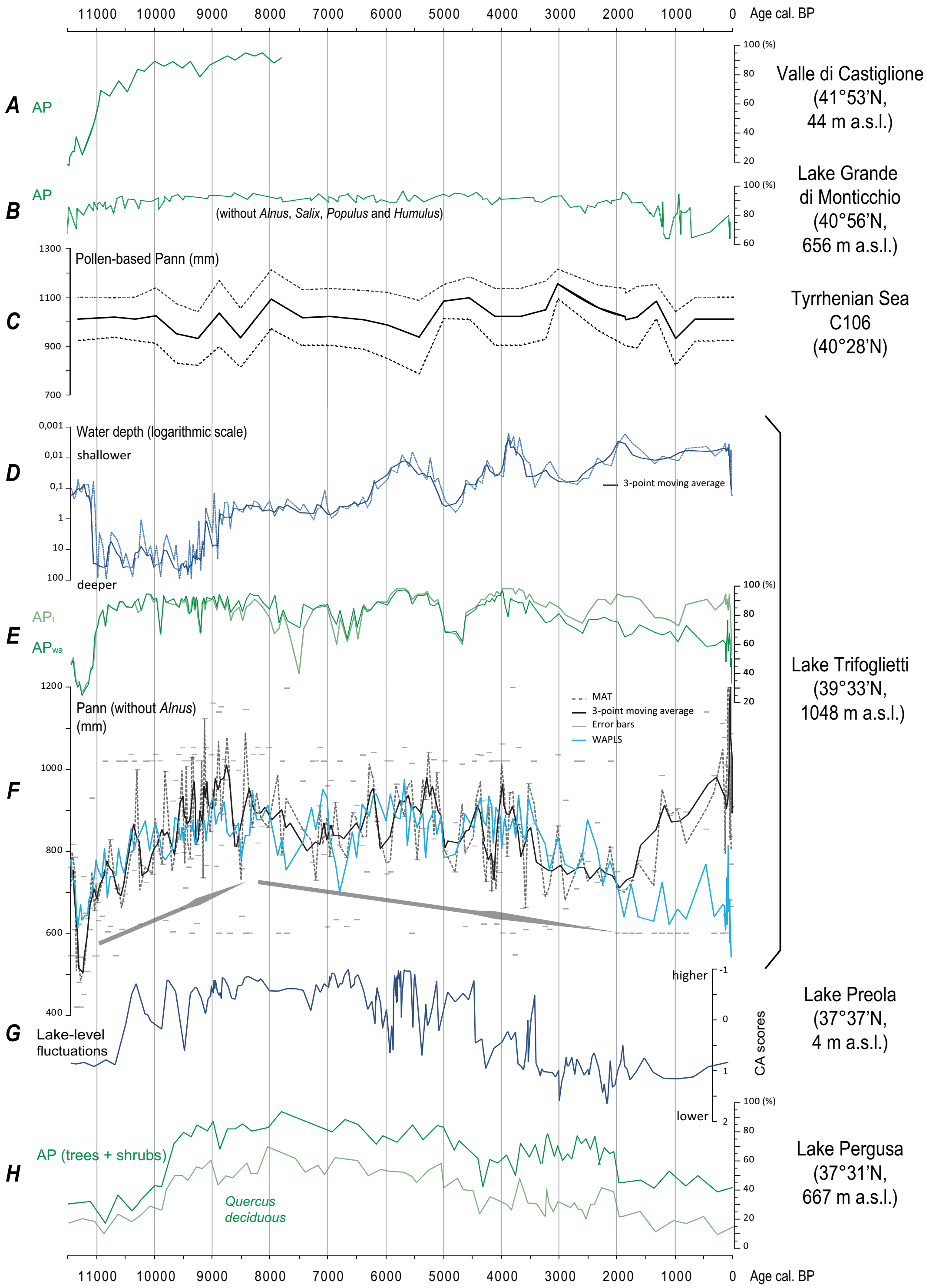

Fig. 9. Comparison of paleorecords from Valle di Castiglione (A; Di Rita et al., 2012), Lake Grande di Monticchio (B; AP changes; Allen et al., 2002), C106 marine core [C; pollen-based annual precipitation (Pann); Di Donato et al., 2008], Lago Trifoglietti [D, pollen-based water-depth; E, AP_t and AP_{wa} (Arboreal Pollen total or Without *Alnus*); F, pollen-based annual precipitation (Pann) using MAT and WAPLS methods], 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).

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; DiRita 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 by Chiarugi (1937) and by Reille (1992–1998) 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 weakly expressed in the Trifoglietti pollen record. This suggests that *Corylus* and its associated mesophyllous 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). Sclerophyllous 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. 9500 to 6000 cal BP and attain its maximum at ca. 8700 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; Zanchetta et al., 2007; Sadori et al., 2008; Leng et al., 2010; 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).

In this case, 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 8800 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 MD90-917 (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 9500 cal BP at Trifoglietti may have resulted from the combined effects of lake-basin infilling and a generally drier climate in the south-central Mediterranean. Considering its intermediate location between palaeohydrological records from central Italy and Sicily, the water-depth record of Lago 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 coeval with inland 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 and mid 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 (Magny et al., 2001; Rasmussen et al., 2007; Fleitmann et al., 2007; Yu et al., 2010; Fletcher et al., 2010). 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 (Δ 150 mm, Fig. 9f) and reduced fir and beech woods favoured 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; Fletcher et al., 2010; 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 carbone- and 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 at ca. 8200 cal BP (Siani et al., 2010) or from ca. 8000 to 7500 cal BP (Ariztegui et al., 2000), marked by changes in faunal, organic and isotopic contents. According to Siani et al. (2010, 2012), short-term SST cooling spell recoded in MD90-917 core is responsible for the resumption of deep-water formation and re-oxygenation phases in the South Adriatic basin at 8.2 ka during the S1 interruption. 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 reoxygenation. On the basis of SST records from core BS7938 in the Tyrrhenian Sea, Sbaffi et al. (2004) reported a short cooling episode (labeled 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 this time, the impact of more frequent outbreaks of Siberian dry winter air masses in the eastern Mediterranean may have extended toward south Italian Peninsula. In MD90-917, the SSTs drop of about 3 °C during the cold 8.2 ka event, is followed by a short-lived centennial lighter cooling (1 °C) between 7.8 and 7.5 ka at the time of sapropel S1b (Siani et al., 2012). It can, therefore, suggest that several short events added and/or mixed during the time interval 8200–7500 cal BP due to low temporal resolution and chronological uncertainties.

From ca. 7000 to ca. 6400 cal BP, the AP_{wa} and WAPLS Pann records show a decrease. In Basilicata, Piccarreta et al. (2011) observed an increase in flood frequency from ca. 7200 to 6300 cal BP (the strongest phase is up to ca. 6800 cal BP) which is related to colder and moister climate. This correlates with 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. At Trifoglietti, this decline of AP could reflect a locally more developed human impact as shown by slight increases in anthropogenic indicators and Cerealia (Fig. 8).

At Santuario della Madonna Cave, periods of human activity are interspersed in deposits which characterised the record of rapid oscillations in the moisture regime during the Late Neolithic (since 5th millennia BC; Scarciglia et al., 2009). However, this hypothesis needs to be tested by further investigation in a region (Calabria) marked by the scarcity of archeological findings and more particularly in the mountainous areas.

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, this corresponds to a ca. 100 mm summer precipitation decrease inferred by quantitative climate reconstruction (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 effect 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 wet and cool climate oscillation (wet winter but dry summer) observed in southern Italy contrasts with higher lake levels reconstructed in central and northern Italy (Magny et al., 2007a, 2012), and is in accordance with 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 increases in annual precipitation (Fig. 9c, C106, Di Donato et al., 2008) and summer precipitation (Peyron et al., 2012). This phase also coincides with a reduction in forest cover at Trifoglietti, which can also be affected by a bias in AP_{wa} percentages.

A shallow water phase is recorded from ca. 4300 to ca. 3500 cal BP. It suggests drier summer 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 4200 cal BP if we refer to the MAT 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 (Drysdale et al., 2006; Di Rita and Magri, 2009; Noti et al., 2009; Tinner et al., 2009; Finné et al., 2011; Roberts et al., 2011b). At higher latitudes, it coincided with the beginning of the Neoglacial (Giraudi et al., 2011; Zanchetta et al., 2012; Vannière et al., 2012), 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 favours beech/fir forest restoration (despite relative instability) and corresponds to peaks in annual precipitation (Fig. 9f; Peyron et al., 2012). 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 and 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 along the coast (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 palaeoenvironmental 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. At Trifoglietti, this is marked by (1) during the middle Bronze age, the use of fire to clear land for agricultures and grazing (*Pteridium* spores) and (2) since the Middle Ages, the cultivation of *Castanea*, *Juglans* and *Olea*. The exploitation of *Abies* for timber in Roman times is expected to caused the disappearance of *Abies*, however, climate change (marked by a drought at ca. 2000 cal BP) cannot be excluded (Allen et al., 2002).

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 Lago Trifoglietti provides new insights into palaeoenvironmental and palaeoclimatic changes which may have characterised the Holocene period in 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 dense beech forest. This, therefore, constitutes a rare example of a beech 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.

- The pollen analysis supports a southward delay in the thermophyllous forest expansion dated to ca. 13 500 cal BP at Monticchio, ca. 11000 cal BP at Trifoglietti, and finally ca. 9800 cal BP in Sicily. Persistence of arid conditions is expected to explain the increasing delay from northern to southern Italy.

- 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 Lago 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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