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Vegetation and fire history of the Euganean Hills (Colli Euganei) as recorded by Lateglacial and Holocene sedimentary series from Lago della Costa (northeastern Italy)

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Abstract
We reconstruct the vegetational and fire history of the Colli Euganei and northeastern Po Plain from *c.* 16 500 cal. BP to the present using AMS-dated sedimentary pollen, microscopic and macroscopic charcoal records. Our study site, Lago della Costa, is the only natural water basin with an undisturbed late-Quaternary sediment accumulation in the northeastern Po Plain. Mixed coniferous-deciduous forests occurred since at latest 14 500 cal. BP. Gradual expansion of e.g. *Alnus glutinosa* and *Carpinus betulus* is documented after *c.* 11 000 cal. BP. A further expansion of *Abies alba* and *Alnus* at 9200 cal. BP coincided with a population buildup of these species in the Insubrian region *c.* 200 km northwest of our site. A further increase of *Alnus* about 6400 cal. BP was accompanied by an expansion of *Castanea sativa* and *Juglans regia* as well as meadow and field plants. This vegetational change was contemporaneous with a huge increase of regional and local fire activity. Our data suggest that fire disturbance favoured strong and moderate re-sprouters, e.g. *Alnus*, *Carpinus* and *Castanea*, whereas fire-sensitive taxa, e.g. *Tilia* and *Abies* were disadvantaged. The close link between crops, weeds and fire activity suggests human impact as the main source of changes in Neolithic vegetation and fire regime. To our knowledge these are the oldest palaeobotanical data suggesting the cultivation of *Castanea* and *Juglans* in Europe and elsewhere. Our pollen and charcoal records document the subsequent cultivation of *Castanea*, *Juglans*, *Olea* and Cerealia t. during the Bronze Age (4150–2750 cal. BP). Subsequently, intensification of land use continued during the Iron and Roman Age and Medieval times. In contrast with other northern Italian sites vegetation around our site was always rather open with a substantial proportion covered by grassland. We explain this peculiarity of the site by its location near river banks and floodlands.

Keywords
Castanea, charcoal, Colli Euganei, *Juglans,* palaeoecology, Po Plain, pollen

Introduction

Few palaeovegetational records are available from the Euganean Hills (Colli Euganei) region and the eastern Po Plain (e.g. Lona, 1957; Neviani 1961; Paganelli, 1996a,b; Paganelli and Miola, 1991; Paganelli *et al*., 1988). Most of them are poorly dated. Therefore knowledge about postglacial vegetational dynamics of the northeastern Po Plain is scanty. This gap is crucial, for the Colli Euganei region is considered to be an important refugial area of thermophilous tree species during the last glacial maximum (LGM; e.g. Krebs *et al*., 2004; Paganelli and Miola, 1991). The Euganean Hills are a hotspot for plant biodiversity. Nowadays, they lie in a transitional position between the (evergreen) Mediterranean and (deciduous) temperate biomes that has also been denominated Euganean-Insubrian zone (Adamovic, 1933). Previous studies in this region suggest early expansions of thermophilous trees such as *Castanea sativa* (Lona, 1957; Paganelli, 1961; Paganelli *et al*., 1988). These are anomalous if compared with neighbouring sites south of the Alps (Gobet *et al*., 2000; Schneider and Tobolski, 1985; Valsecchi *et al*., 2006). On the basis of radiocarbon-dated peat sequences a local survival of *Castanea sativa* during the LGM has been proposed (Paganelli and Miola, 1991) that would explain the early expansion of this tree species.

Though almost nothing is known about the fire history of the Po Plain, recent studies have shown that fire has decisively influenced the vegetation dynamics in the nearby southern Alps in Italy and Switzerland (e.g. Conedera *et al*., 1996: Delarze *et al*., 1992; Gobet *et al*., 2000; Keller *et al*., 2002; Tinner *et al*., 1999). These studies show that during the mid and late Holocene the lowlands of the southern Alps partly developed fire-adapted ecosystems favouring disturbance species such as *Calluna vulgaris* and *Pteridium aquilinum*.

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Our new study has several goals. The primary goal is to reconstruct the vegetation and fire history of the site by means of pollen, microscopic and macroscopic charcoal analyses. Special attention is paid to interactions between vegetation and the fire regime. Although fire disturbance is considered as intrinsic in the Mediterranean and temperate ecosystems, the fire regimes during the Holocene were strongly modified by human activity, for instance to gain open land for agriculture by burning forests (Clark *et al*., 1989; Colombaroli *et al*., 2007; Tinner *et al*., 1999; Vannière *et al*., 2008). We secondly address the role of man for long-term fire-regime changes at our site by using the indicator-species approach for human impact (Behre, 1981). This procedure allows us to identify land-use phases by considering the abundance of pollen of crops and weeds. Furthermore, we quantify the long-term charcoal accumulation anomalies along the temporal scale by means of inferred fire frequency (IFF), fire-return interval (FRI) and mean fire interval (MFI), estimated according to events interpreted as local fire episodes. In a third step, we briefly address potential linkages between climate, vegetation, human impact and the fire regime.

Study area and study site

The Euganean Hills consist of about 100 individual hills, which are very distinct owing to their shapes (cones, ridges etc.) and different elevations. They cover an elliptical area of *c*. 22 000 ha, extending for about 65 km from their southern to their northern border (Figure 1). The hills are of submarine volcanic origin that formed during two phases that occurred *c*. 45 million and *c*. 35 million years ago. Between the volcanic deposits are calcareous and clayey marine sediments ('marne euganee'). The hilly region is located *c*. 50–60 km south of the maximum extent of the last Alpine glaciation (Orombelli *et al*., 2004). The site has a Cfa climate type (Köppen, 1923: i.e. a warm temperate rainy climate with warmest month > 22°C, coldest month between –3° and 18°C and more than four months > 10°C). This special kind of warm-rainy climate is widespread in southeastern China, Japan and the southeastern North America, but rare elsewhere in Europe (Spiess, 1994). Annual precipitation is about 720 mm at low altitudes near Lago della Costa (Monselice and Este) and 870 mm at Monte Venda (601 m a.s.l.), the highest point of the Euganean Hills. Annual mean temperature is about 13.0°C in Monselice and 10.8°C at higher altitudes of Monte Venda, respectively. The most important tree species in the Colli Euganei are *Quercus petraea, Q. pubescens, Q. ilex, Castanea sativa, Fraxinus ornus, Carpinus betulus, Acer pseudoplatanus, A. campestre, Fagus sylvatica, Sorbus torminalis* and non-native *Robinia pseudoacacia*. Because of the numerous narrow and deep valleys and the steep hills, different microclimatic conditions influence the vegetation. Mediterranean vegetation with evergreen species occurs on south-facing slopes with warmer and drier climatic conditions, whereas temperate deciduous vegetation is important on cooler and moister north-facing aspects. Mediterranean communities on the driest spots comprise species such as *Quercus ilex*, *Fraxinus ornus*, *Arbutus unedo*, *Erica arborea, Cistus salvifolius, Pistacia terebinthus* and *Ruscus aculeatus.* Soils can co-determine the occurrence of different vegetational communities. For instance, mixed *Castanea sativa* and *Quercus* woods grow on soils developed in volcanic rocks, whereas *Ostrya carpinifolia-Quercus pubescens* stands with admixed *Fraxinus ornus, Carpinus betulus, Fagus sylvatica, Q. ilex, Q. cerris, Acer campestre* and *Robinia pseudoacacia* prevail on calcareous sedimentary substrate. (Del Favero, 2001). To preserve this high biodiversity (e.g. the endemic Italian plant species *Haplophyllum patavinum*), the Euganean Hills have been declared a regional preserve area ('Parco Regionale') since 1989. For more information about the regional setting and the flora of the Colli Euganei, see Antonietti (1962), Mazzetti (2002) and Selmin (2005).

The study site, Lago della Costa near Arquà Petrarca (45°16′13″N, 11°44′35″E) is a small lake (3 ha) situated at the southeastern border of the Euganean Hills at 7 m a.s.l. The lake has no surface inlet, but it has several subaqueous thermal springs, probably originating from ancient rainwater of the Small Dolomites (Pasubio, Recoaro) and the Vicentino-Trentini plateaus (Piccoli *et al*., 1976, 1981). At the southern border of the lake is an artificial small outlet. During the last glaciation the lake used to be larger than today, as evidenced by drillings made for another study (Kaltenrieder *et al*., 2004, 2009).

Materials and methods

Coring

The parallel sediment cores (AP1 and AP3) were taken in 2001 from the northern part of the lake at 1.52 m water depth with a modified Streif- Livingstone piston corer (Wright *et al*., 1984). The cores were cross-correlated by matching distractive lithologic contacts and sedimentary layers. The sediment core for this study, AP1, was cored with a tube diameter of 8 cm from 0 to 9 m depth and with a tube diameter of 4.8 cm from 9 to 13 m depth.

Dating

AMS (Accelerated Mass Spectrometry) ^{14}C ages were obtained at the Institute of Physics of University of Erlangen-Nürnberg (Germany) and at the Poznan Radiocarbon Laboratory (Poland). Terrestrial plant macrofossils were used for dating (Table 1). The ^{14}C ages were converted to calibrated ages (years cal. BP) with the program Calib version 5.0.1 (Reimer *et al*., 2004; Stuiver and Reimer, 1993). The depth–age model used non-linear weighted regression within the framework of generalized additive models (Figure 2). This approach has the advantage of providing 95% age confidence intervals that take into account the errors of radiocarbon measurement, radiocarbon calibration, and the developed age–depth relationship (Heegaard *et al*., 2005).

Loss-on-ignition (LOI)

Loss-on-ignition (LOI) analyses were carried out on 1 cm^3 subsamples of sediment at 10 cm intervals following Heiri *et al.* (2001), i.e. 4 h of combustion at 550°C for the estimate of organic matter content and 2 h of combustion at 950°C for the estimate of carbonate content (Figure 3).

Pollen analysis

Pollen preparation followed standard procedures for glycerine samples (Moore *et al*., 1991). *Lycopodium* tablets (Stockmarr,

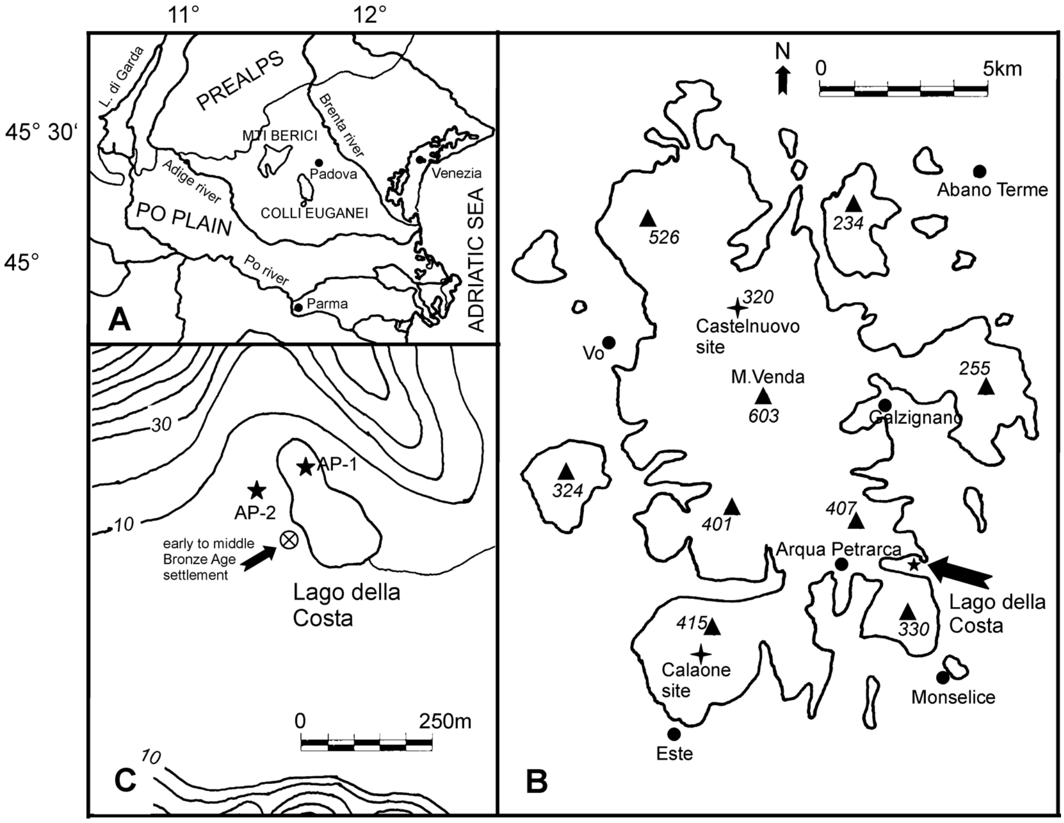


Figure 1. Maps showing the location of the study site. (A) Overview of the region around the Colli Euganei; (B) Colli Euganei with the study site Lago della Costa; (C) location of the sediment cores AP1 and AP2

Table 1. ^{14}C dates of Lago della Costa (core AP1)

Lab number	Core	Depth (cm)	Material	^{14}C dates, yr BP, conv. uncal.	Cal. BP 95% confidence limits[a]	Age in diagram cal. BP (P = AD 1950)[b]
Erl-4809	AP-1	32–38	charcoal, dicot.leaf	325±60	159–504	218
Poz-12374	AP-1	150–152	deciduous periderm	845±30	688–895	834
(Erl-4810	AP-1	320–326	charcoal, periderm	4946±50	5590–5876)	
Poz-12363	AP-1	332–358	deciduous periderm, wood	3525±30	3705–883	3781
Poz-19119	AP-1	526–570	wood, periderm, terrestrial seed parts	4960±40	5624–5732	5668
(Poz-12375	AP-1	730–732	*Cornus mas* seed	3425±35	3579–3826)	
(Erl-4811	AP-1	768–772	charcoal	7325±65	8005–8318)	
Erl-4812	AP-1	768–772	deciduous periderm, wood, *Alnus* fruit	5465±70	6019–6406	6343
Poz-12376	AP-1	802–804	deciduous twig	5830±40	6505–6738	6546
Poz-12377	AP-1	984–988	*Quercus* budscales, wood, periderm, dicot. leaf	7740±50	8420–8596	8525
Erl-4813	AP-1	1036–1040	charcoal, wood, periderm	8368±70	9141–9525	9281
Erl-4814	AP-1	1190–1194	charcoal, coniferous periderm, *Betula* fruit	10778±90	12637–12921	12838
Poz-12378	AP-1	1290–1298	deciduous and coniferous periderm, wood, *Betula* fruit	14270±70	16619–17480	16935

[a]Calibration of radiocarbon dates: Calib 5.0.1 (Reimer *et al*., 2004; Stuiver and Reimer, 1993).
[b]Heegaard *et al.* (2005).

1971) were added to sediment samples of 1 cm^3 before preparation for estimation of pollen and charcoal concentrations. A minimum of 600 pollen grains, excluding aquatic pollen and spores, were counted at each level. Pollen grains were identified using keys (e.g. Moore *et al*., 1991; Punt and Blackmore, 1976), pollen atlases (e.g. Reille, 1992, 1998) and the reference collection of the Institute of Plant Sciences, University of Bern. Pollen and microscopic charcoal diagrams were drawn with TILIA 1.12 and TiliaGraph. The results are presented as TgView 2.0.2 pollen diagrams (Grimm, 1992). The pollen diagrams were subdivided into local pollen assemblage zones (LPAZ) by using the zonation method of optimal partitioning (Birks and Gordon, 1985) as implemented in the program ZONE, version 1.2, written by Steve Juggins. To determine the number of statistically significant zones

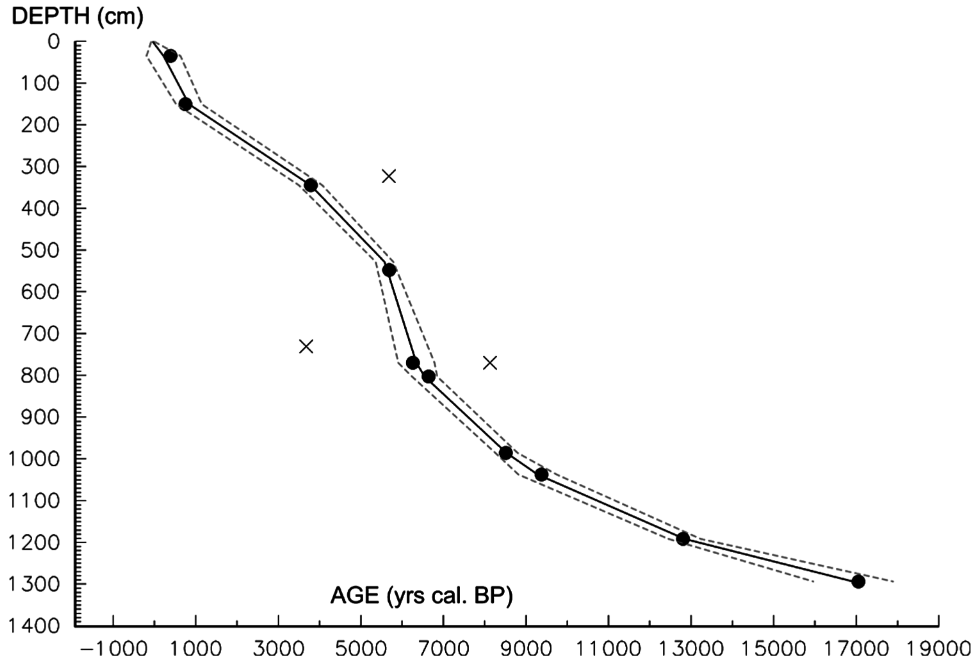


Figure 2. The depth–age model of AP1 (x-axis: age in yr cal. BP; y-axis: sediment depth in cm) is based on linear interpolation between ten AMS ^{14}C ages of terrestrial plant macrofossils (solid circles). Crosses show rejected ages. The ^{14}C ages were converted to calibrated years (yr cal. BP) with the program Calib version 5.0.1 (Reimer *et al.*, 2004; Stuiver and Reimer, 1993). The depth–age model was based on linear interpolation of the R-Stat values of calibrated ^{14}C ages (Heegaard *et al.*, 2005)

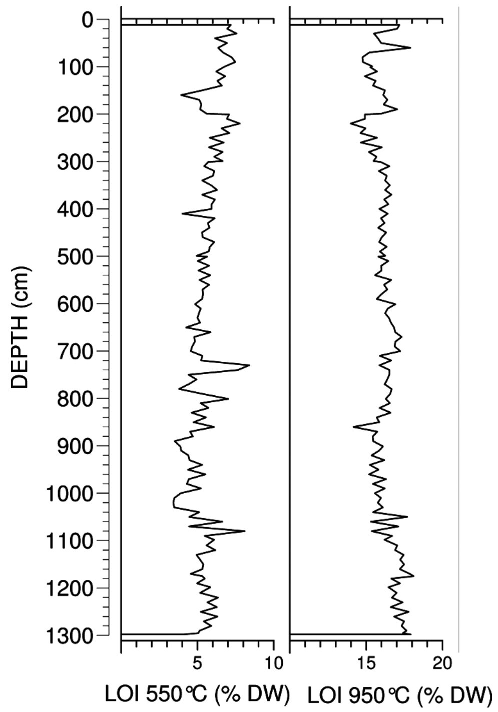


Figure 3. Profiles of loss-on-ignition (LOI) data expressed as percentage of dry weight (DW) measured in the AP1 sediment core at 10 cm intervals

in diagrams, we used the broken-stick model (Bennett, 1996; Birks, 1998). Pollen analysis was done by Petra Kaltenrieder.

Microscopic charcoal analysis

Microscopic charcoal particles longer than 10 µm (or area >75 µm^2) were counted in pollen slides following Tinner and Hu (2003) and Finsinger and Tinner (2005). Charcoal number concentration (particles/cm^3) and influx (particles/cm^2 per yr) were estimated with the same approach as for pollen (Stockmarr, 1971). Mean sampling resolution for pollen and microscopic charcoal was 10 cm, corresponding to a mean temporal resolution of 131 ± 98 yr between the samples (mean ± SD). For the Holocene (from 11 868 cal. BP to present), the mean temporal resolution was 103 ± 59 yr between the samples (mean ± SD). Unfortunately, it is not possible to estimate quantitatively the regional fire frequencies without continuous sampling and without a calibration set comparing modern regional fire frequencies and the microscopic charcoal influx in surface sediments (Tinner *et al*., 1998). Microscopic charcoal analysis was made by Simone Hofstetter and Petra Kaltenrieder.

Macroscopic charcoal analysis

For the analysis of macroscopic charcoal, the core of AP1 was subsampled in 2 cm slices with a standard volume of 20 cm^3. The contiguous subsamples were washed through a 0.2 mm mesh screen. Only particles with ≤0.5 mm were considered for analysis. Charcoal areas were estimated by fine-grid graph paper under a microscope. Macroscopic charcoal analysis was made by Giovanni Procacci.

Correlation analysis

We calculated correlation coefficients to investigate whether microscopic charcoal and pollen are significantly related to each other, and we applied a *t*-test to determine whether the correlation coefficients *r* are significantly different from 0 ($r \neq 0$, $\alpha = 5\%$, two-sided, Bahrenberg *et al*., 1985). The period selected for correlation analyses was 9330–4420 cal. BP, equivalent to the local pollen assemblage zones (LPAZ) APL-2 and APL-3 (Figures 4 and 5; for cultural epochs see Table 2).

Macroscopic charcoal inferred fire frequency

Macroscopic charcoal concentrations (CHAC) were treated with the decomposition method, initially described by Long *et al.* (1998). Raw data were re-sampled to interpolate them to a constant time interval of 40 yr, which corresponds to the lowest sediment-accumulation rate in the whole sequence. Then CHAC values were divided by this deposition time of the binned interval to obtain charcoal influx or charcoal accumulation rate (CHAR; mm^2/cm^2 per yr). Subsequently CHAR data were logarithmically transformed to stabilize signal variance (log(CHAR+1)). To eliminate the slowly varying component or background signal of the charcoal record, influx values were smoothed with a robust locally weighted regression type (Robust Loess function) with a 1000-yr time window that best fit the low-frequency variation (see Figure 7). Background charcoal influx (BCHAR) might be caused by several sedimentary processes on charcoal (e.g. the deposition of reworked particles from littoral sediment, Whitlock and Millspaugh, 1996). Alternatively it may also be linked to fuel availability and characteristics (Marlon *et al*., 2006) or regional fire activity (Whitlock and Larsen, 2001). However, the difference between charcoal influx and the background component defines the peak component (Clark *et al*., 1996). It is usually represented by two populations of values: the lower ones are interpreted as analytical noise and the positive highest ones above the threshold values (TV) are assumed to express fire episodes in the local or microregional area around the lake. Statistical distribution analysis was used to decompose the peak-component frequency distribution and to choose the threshold value (TV; see Figure 8). A Gaussian mixture model (Software CLUSTER by Bouman, 1997; see also Gavin *et al*., 2006) allows individualizing three mean populations of values in the histogram plot. Inferred Fire Frequency (IFF) results from this time-series analysis of the peaks component. The FRI (fire return interval) and MFI (mean fire interval) are estimated as the number of years between two episodes and between the first and the last fire episode divided by the number of intervals between all the fire episodes, respectively.

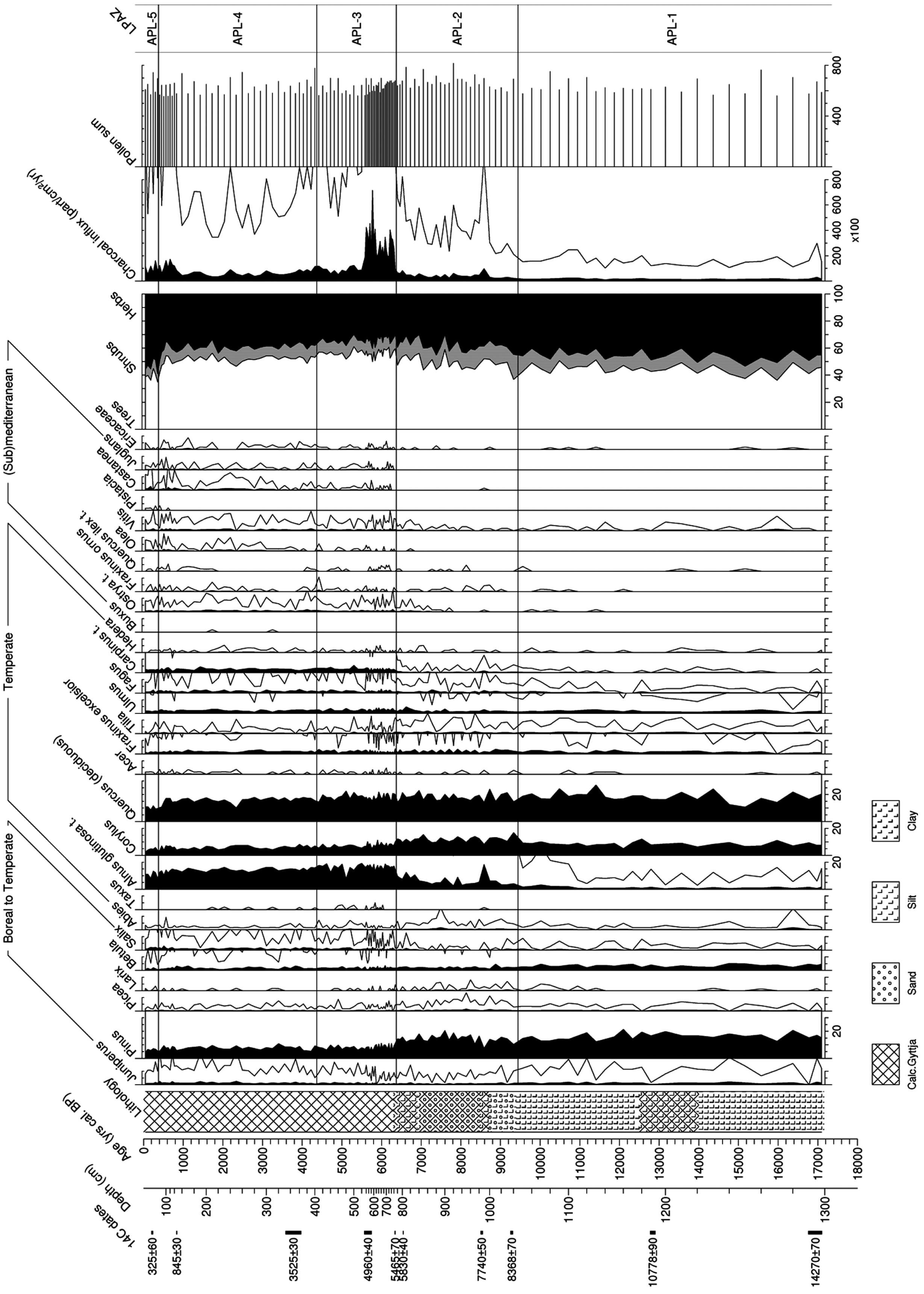
Results and interpretation

Chronology and sediment description

According to our depth–age model, ten of the 13 radiocarbon dates provided realistic age estimates (Table 1). The date obtained on a *Cornus mas* seed was obviously too young; perhaps the seed was transported down-core while coring, though attention to this problem was paid by using only terrestrial macrofossils from the centre of the core. Conversely, two samples of millimetre-sized charcoal particles provided too old ages. Charcoal pieces of this size may provide too old ages, a problem that is known from systematic comparison of terrestrial-macrofossil dates (Conedera *et al*., 2009; Oswald *et al*., 2005). To address such dating uncertainties, the dates obtained on millimetre-sized charcoal material were compared with a date from uncharred terrestrial plant remains (deciduous periderm, wood and one *Alnus* fruit) at the same sediment depth (768–772 cm, Table 1). This new date is in line with the other dates (Table 1) and thus we conclude that it is reliable. The consistent chain of (uncharred or only partly charred) Holocene dates (Figure 2) also proves that the fossils (e.g. pollen) were not re-worked. However, results on the littoral core as well as previous pollen studies from adjacent areas (see vegetation history) suggest that the date 14 270 ± 70 ^{14}C yr BP (*c*. 17 000 cal. BP) might be too old by *c*. 1000–2500 years. The material for this oldest date was recovered in silty layers, possibly indicating that substantial erosional processes might have brought into the sediment older re-worked macrofossils. The chosen depth–age model suggests that sediments accumulated slowly in the deeper part (*c*. 17 000–*c*. 10 000 cal. BP) and faster from *c*. 10 000 cal. BP to present (Figures 2 and 4). The sediments are silt and clay from 1300 to 1220 cm (17 095–13 962 cal. BP), silty calcareous gyttja from 1220 to 1176 cm (13 962–12 500 cal. BP), silt and clay from 1176 to 1044 cm (12 500–9400 cal. BP), silty sand from 1044 to 995 cm (9400–8650 cal. BP), silty or partly sandy calcareous gyttja from 995 to 766 cm (8650–6300 cal. BP) and calcareous gyttja from 766 to 12 cm (6300 cal. BP–present) (Figure 4). Throughout the whole sequence the deposits are rich in minerogenic material, with only modest carbonate and organic contents (Figure 3), the latter especially from the early to the late Holocene, depicting a continuous slightly increasing trend.

Pollen inferred vegetation history and charcoal-inferred fire history

The pollen diagram was subdivided into five statistically significant local pollen assemblage zones (LPAZ), APL-1 to APL-5 (Figure 4). The basic microscopic and macroscopic charcoal results are presented in the corresponding pollen zones. We assume that microscopic charcoal is a proxy for regional fires (20–100 km radius around the site), whereas macroscopic charcoal may indicate the occurrence of local fires (Carcaillet *et al*., 2001; Clark, 1988; Higuera *et al*., 2007; MacDonald *et al*., 1991; Peters and Higuera, 2007; Tinner *et al*., 1998; Whitlock and Larsen, 2001).


LPAZ
APL-5
APL-4
APL-3
APL-2
APL-1
Pollen sum
Charcoal influx (part/cm²/yr)
x100
Herbs
Shrubs
Trees
(Sub)mediterranean
Temperate
Boreal to Temperate
Ericaceae
Juglans
Castanea
Pistacia
Vitis
Olea
Quercus ilex t.
Fraxinus ornus
Ostrya t.
Buxus
Hedera
Carpinus t.
Fagus
Ulmus
Fraxinus excelsior
Tilia
Acer
Quercus (deciduous)
Corylus
Alnus glutinosa t.
Taxus
Abies
Salix
Betula
Larix
Picea
Pinus
Juniperus
Lithology
Age (yrs cal. BP)
Depth (cm)
14C dates
325±60
845±30
3525±30
4960±40
5465±70
5830±40
7740±50
8368±70
10778±90
14270±70
Clay
Silt
Sand
Calc.Gyttja

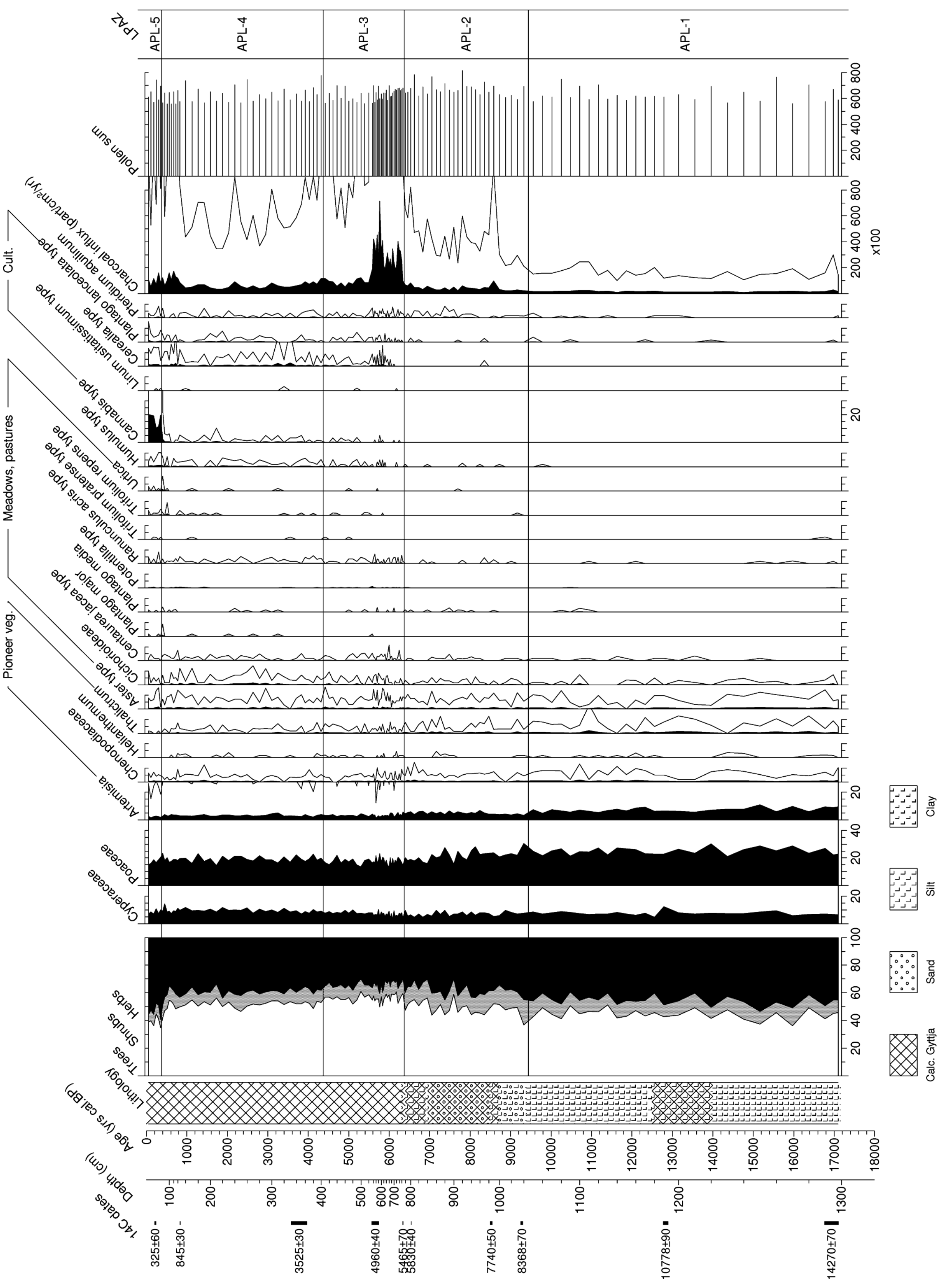


Figure 4. Pollen percentage (selected types) and microscopic charcoal influx (particles/cm^2 per yr) diagram of AP1. Open curves show 10× exaggerations. The pollen diagram was subdivided into local pollen assemblage zones (LPAZ) by the zonation method of optimal partitioning (Birks and Gordon, 1985) as implemented in the program ZONE, version 1.2, written by Steve Juggins. To determine the number of statistically significant zones in the diagram, we used the broken-stick model (Bennett, 1996; Birks, 1998)

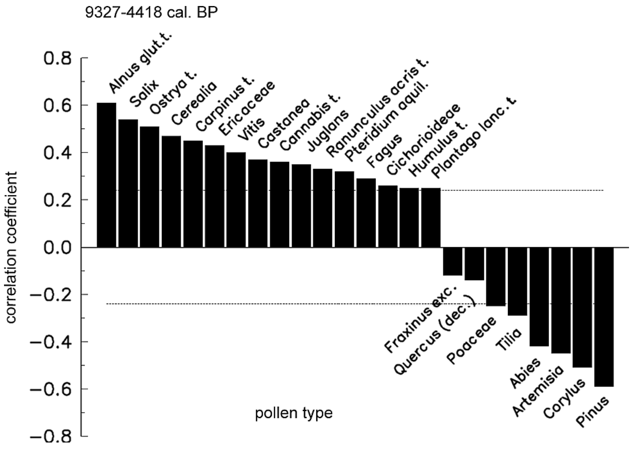


Figure 5. Correlograms showing correlation coefficients between microscopic charcoal influx and selected pollen types between 9327 and 4418 cal. BP. Correlation coefficients outside the lines are significant at $P = 0.05$

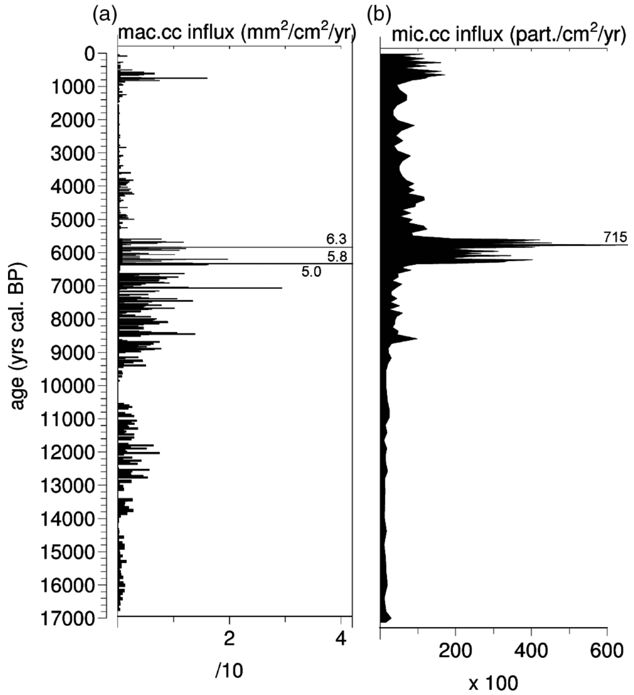


Figure 6. Comparison of macro- and microscopic charcoal influx in the sediment of AP1. Microscopic charcoal was counted in the pollen samples (every 10 cm), while macroscopic charcoal was analysed in contiguous samples of 2 cm thickness (sample vol. 20 cm^3) and measured by area only ≥ 0.5 mm^2. (a) macroscopic charcoal influx (mm^2/cm^2 per yr); (b) microscopic charcoal influx (particles/cm^2 per yr)

Table 2. Prehistoric and historic periods in Northern Italy

Age (yr cal. AD/BC)	Cultural epoch
100 BC–AD 375 (2050–1575 cal. BP)	Roman Period
800–100 BC (2750–2050 cal. BP)	Iron Age
2200–800 BC (4150–2750 cal. BP)	Bronze Age
3300–2200 BC (5250–4150 cal. BP)	Copper Age (Late Neolithic)
5500–3300 BC (7450–5250 cal. BP)	Neolithic
9250–5500 BC (11 200–7450 cal. BP)	Mesolithic
– 9250 BC (11 200 cal. BP)	Palaeolithic

Bagolini and Biagi (1990), de Marinis (1999), Malone (2003), Müller and Kaenel (1999)

The Lateglacial and early-Holocene sediments before 9400 cal. BP are represented by a rather long and homogenous pollen zone. The comparison of the pollen record of Lago della Costa with other records from the region suggests that the transition from open (non-arboreal pollen > 50%) to forested environments at the beginning of the Lateglacial is not recorded in the lacustrine sedimentary sequence of AP1. This marked vegetational shift occurred at 16 000–14 500 cal. BP in the lowlands south of the Alps (Vescovi *et al*., 2007). We therefore assume that the oldest date of 14 270 ± 70 ^{14}C yr BP (17 056 cal. BP) at a sediment depth of 1290–1298 cm is too old. This interpretation is supported by the littoral pollen sequence of AP2 (Kaltenrieder *et al*., 2009), which points to rather open environments and low *Quercus* (deciduous) values (<5%) at 30 000–*c*. 16 500 cal. BP.

Pollen of *Pinus*, *Picea*, *Abies* and *Larix* but also *Corylus*, as well as high percentages of *Quercus* deciduous (20%) and regular finds of pollen of other thermophilous deciduous trees such as *Fraxinus excelsior*, *Tilia, Ulmus, Fagus,* and *Carpinus* t., suggest the presence of mixed coniferous-deciduous forests in the region around Lago della Costa between *c*. 16 500–14 500 and 9400 cal. BP. Regular findings of *Vitis* and *Hedera* pollen throughout the zone APL-1 indicate the thermophilous character of these Euganean Hills forests during the Lateglacial and the early Holocene. Single pollen finds of (sub-) Mediterranean taxa such as *Ostrya* t., *Fraxinus ornus* and *Quercus ilex* also point to rather warm conditions. Especially in the case of *Fraxinus ornus*, an insect-pollinated tree, we can almost exclude long-distance transport from warmer regions in the southern Mediterranean. Pollen of light-demanding pioneer woody (*Juniperus, Betula*) and herbaceous taxa (*Artemisia*, Poaceae, Chenopodiaceae, *Thalictrum* and *Aster* t.) may reflect the drier, steppe vegetation of the adjacent Po Plain. Recent studies of surface samples from soils and sediments of Central Asian sites indicate that arboreal pollen values as low as 30–40% may already reflect densely forested areas that are surrounded by continental steppes (Beer *et al*., 2007). However, we cannot exclude that the steppe elements recorded in our diagram (e.g. *Artemisia*, Chenopodiaceae, *Thalictrum*) were also growing locally, for instance on the drier, south-facing slopes of the Euganean Hills.

Microscopic charcoal influx is low, not exceeding 3000 particles/cm^2 per yr (or 1.1 mm^2/cm^2 per yr; Tinner and Hu, 2003). Macroscopic charcoal influx (0.07 mm^2/cm^2 per yr) is relatively low before 9400 cal. BP, although, somewhat surprising, higher than in the pre-historical periods with moderate to high human impact (late Bronze Age, Iron Age and Roman period, *c*. 3600–1575 cal. BP; Table 2, Figure 6). These moderate charcoal influx levels probably reflect natural or quasi-natural regional and local fire activities under the environmental conditions of that time. It is conceivable that drier, more continental climatic conditions during the Lateglacial and early Holocene (e.g. Tinner and Ammann, 2001; Tinner and Kaltenrieder, 2005; Tinner *et al*., 1999) may have induced the higher local fire incidence recorded in the macroscopic charcoal influx.

Our pollen record shows that steppe and boreal elements (*Artemisia*, Chenopodiaceae, *Thalictrum*, *Juniperus*, *Betula*) declined at the beginning of the zone APL-2 (9400–6400 cal. BP).

They were replaced by thermophilous temperate and (sub-) Mediterranean woody taxa (moderate increase of pollen of *Corylus, Acer, Fraxinus excelsior, Tilia, Ulmus, Fagus, Carpinus* t. *Fraxinus ornus, Quercus ilex*). Abundant pollen of *Pinus* indicates that pines were still present, probably as the most important conifers in the deciduous woodlands. The slight rise in *Abies* pollen (*c*. 2%) presumably documents single trees or small stands growing in relatively moist microhabitats. Today *Abies alba* is absent in the forest vegetation of the Euganean Hills. Similarly, regular pollen finds of *Larix* suggest the presence of this heliophilous taxon with very poor pollen-dispersal capacity (Lang, 1994) in the hills. Single pollen of herbaceous taxa as *Plantago media* t., *Ranunculus acris* t., *Trifolium repens* t. and *Urtica* point to (slightly) expanding meadow habitats. A first (weak) cluster of pollen indicative of human activities is dated at *c*. 8400 cal. BP (6400 cal. BC) with a few pollen of *Humulus* t., *Plantago lanceolata* t. and the first pollen grain of Cerealia t. Their presence is followed by an increase of spores of *Pteridium aquilinum* at *c*. 8200 cal. BP and is preceded by a strong rise in microscopic (3.3 mm^2/cm^2 per yr; 9776 part/cm^2 per yr; Figure 6) and macroscopic charcoal influx (0.14 mm^2/cm^2 per yr). This finding may document late-Mesolithic land-use and fire activities, involving first attempts of local cereal crop production before the onset of the Neolithic at *c*. 5500 cal. BC (see discussions in e.g. Behre, 2007; Haas, 1996; Tinner *et al*., 2007).

Our pollen data show that the regional environments of Lago della Costa changed conspicuously at the onset of zone APL-3 (*c*. 6400–4400 cal. BP, *c*. 4400–2400 cal. BC). The decline of pollen of pioneer elements (*Artemisia*, Chenopodiaceae, *Thalictrum*) and boreal tree taxa (*Pinus, Picea, Larix*) as well as more thermophilous *Abies* and *Tilia* is partly associated with a marked increase of pollen of temperate (*Taxus*, *Alnus glutinosa* t., *Fagus* and *Carpinus* t.) and of (sub-) Mediterranean arboreal taxa (*Ostrya* t., *Quercus ilex* t., *Olea, Vitis, Castanea* and *Juglans*). Moreover, pollen of meadow taxa such as *Centaurea jacea* t., *Potentilla* t. and *Ranunculus acris* t. as well as cultural indicators as *Humulus* t., *Cannabis* t., Cerealia t. and *Plantago lanceolata* t. increased distinctly. Synchronously, macroscopic and microscopic charcoal reach the highest influx values throughout the entire postglacial period, with three extraordinary peaks in macroscopic charcoal (0.5, 0.58 and 0.63 mm^2/cm^2 per yr) at *c*. 6400 and 5800 cal. BP (*c*. 4400 and 3800 cal. BC), and with one extraordinary peak in microscopic charcoal (71506 part/cm^2 per yr or 21.0 mm^2/cm^2 per yr) at 5800 cal. BP (*c*. 3800 cal. BC).

Our pollen data suggest a rather abrupt shift from early- to mid-Holocene vegetational composition (zone APL-2) to modern (temperate and sub- Mediterranean) forest and woodland environments that was associated with a marked increase in weeds and cultivated plants. The vegetational shift was accompanied by a high increase of fire activity. Given the pollen and charcoal pattern (Figures 4–6) we assume that most of these changes can be explained by increasing anthropogenic activities during the Neolithic (Table 2). Especially, strong and moderate re-sprouters as *Alnus, Carpinus* t., *Castanea* and *Fagus* could have been favoured by (anthropogenic) fire disturbance, while fire-sensitive taxa such as *Tilia* and *Abies alba* could have been disadvantaged (Delarze *et al*., 1992; Tinner *et al*., 2000, 2005).

During LPAZ APL-4 (4300–400 cal. BP) constant pollen percentage values of most taxa of mixed oak forests, with some (sub-) Mediterranean elements and agricultural taxa (pasture and meadow taxa and cultural indicators such as *Centaurea jacea* t., *Ranunculus acris* t. and *Plantago lanceolata* t.) indicate no major vegetational changes in the forests or woodlands. However, increases of *Castanea*, *Juglans, Olea*, *Cannabis* t. and Cerealia t. pollen point to intensified land use in the area. Interestingly, macroscopic and microscopic charcoal influx decreases slightly at the beginning to rise again only at the end of this zone, though showing relatively high fluctuations.

In the youngest LPAZ of the core AP1, APL-5 (400 cal. BP to today) a marked decrease of total tree pollen, particularly *Alnus glutinosa* t. and *Quercus* deciduous, suggests that forested environments in the area were significantly reduced. Forest openings were related to intensification of land use, as inferred from the increases of pollen of *Cannabis* t., Cerealia t. and *Plantago lanceolata* t. Pollen of *Artemisia* decreases, possibly indicating a further reduction of uncultivated open-lands in the plain. Constant microscopic charcoal influx values (10 000 part/cm^2 per yr, *c*. 3.3 mm^2/cm^2 per yr) point to moderate regional fire activities, while according to the macroscopic charcoal record local fires declined (0–0.02 mm^2/cm^2 per yr).

Correlation analysis

Several pollen types are significantly correlated with microscopic charcoal influx between 9330 and 4420 cal. BP (Figure 5). The correlation coefficients are significantly positive for *Alnus glutinosa* t., *Salix, Ostrya* t., Cerealia, *Carpinus* t., *Ericaceae, Vitis, Castanea, Cannabis* t., *Juglans, Ranunculus acris* t., *Pteridium aquilinum, Fagus, Humulus* t. and *Plantago lanceolata* t., whereas Poaceae, *Tilia, Abies, Artemisia, Corylus* and *Pinus* show significant negative correlation coefficients.

Local fire history inferred from macroscopic charcoal

The macroscopic charcoal records were analysed in more detail to reconstruct important fire-regime parameters such as IFF (inferred fire frequency), MFI (mean fire interval) and FRI (fire return interval). Macroscopic charcoal influx can be subdivided into four frequency categories: (1) values equal to or close to zero (14 500–14 000, 10 500–9500, 3500–1000, 500–0 cal. BP), (2) low peak values with a background equal to or close to zero (16 700–14 500, 4300–3500, 1000–500 cal. BP), (3) high peak values with a background equal to or close to zero (6500–5500 cal. BP), and (4) high peak values with high background values (14 000–10 500, 9500–6500 cal. BP). From the ratios of CHAR to BCHAR ratios, the Gaussian mixture model helps to disentangle three overlapping subdistributions and to identify the upper limit of the main distribution (TV1=1.70), which may potentially be the upper limit of the variations related to analytical noise (see Figure 8). 57 residual peaks identified above this TV are interpreted as local (to regional) fire episodes. The upper limit of the second subdistribution (TV2=3.76) separates two populations of peaks. The second population (1.70< CHAR ratio <3.76) is represented by the highest peak values that appear during phases with high background signal. The third one (>3.76) is highly differentiated from the background and mainly corresponds to low and high peak values during phases with a nearly-zero background signal. The distributions of peaks along the sequence are evaluated by the smoothing sum of episodes in a 1000 yr moving time window (Figures 7 and 8).

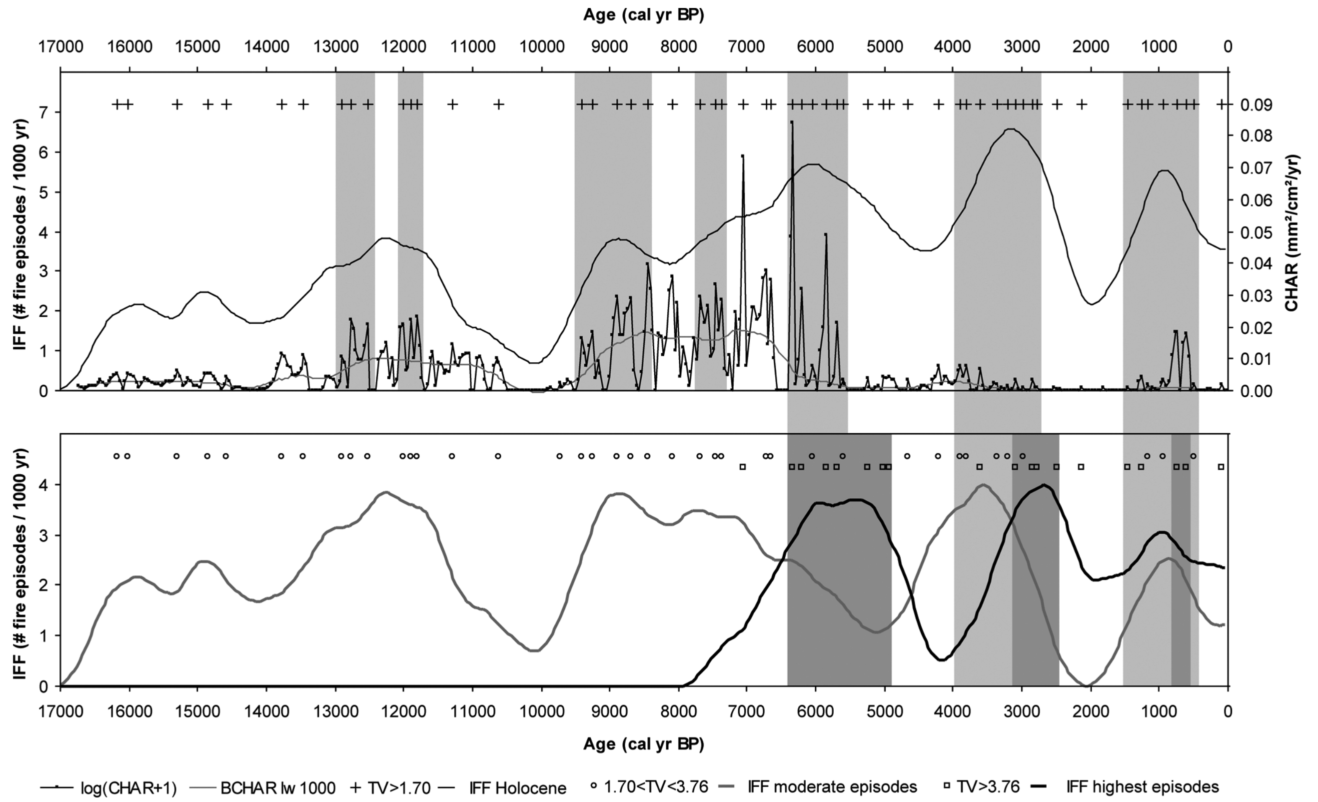


Figure 7. Macroscopic charcoal accumulation rate or influx (CHAR; resampled at 40 yr constant time interval) with background (BCHAR); locally weighted regression with a time window of 1000 yr) from Lago della Costa AP1 core. The + symbols represent identified charcoal episodes for a threshold value (TV) of 1.7. The open circle symbols represent identified charcoal episodes for values 1.7<TV<3.76. The open square symbols represent identified charcoal episodes for a threshold value (TV) of >3.76. Inferred Fire Frequencies (IFF) result from this time-series analysis of the peak component

Over the entire sequence IFF ranges between 0.7 and 6.5 episodes/1000 yr and the tendency is a progressive increase from the Lateglacial towards historic time. MFI for the entire Holocene is 287 yr, and FRI oscillates between 80 and 1200 yr. From this sequence six main phases are characterized by IFF >3.5 fire episodes per 1000 years, namely: 13 000–11 700, 9500–8500, 7800–7400, 6400–5600, 4000–2800 and 1500–500 cal. BP. If we consider the second and the third population of peaks separately, the sequence appears divided into two parts: before *c*. 7100 cal. BP IFF is low and fire episodes are represented by the second population of peak values, whereas after 7100 cal. BP, IFF is higher and fire episode values mainly belong to the third population of peaks. Before and after 7100 cal. BP, MFI is 383 and 218 yr, respectively, whereas FRI oscillates between 80–1200 yr and 80–680 yr. The highest peak-ratios document strong extra charcoal inputs probably related to exceptional fire episodes, which mainly appear during three phases: 6400–4900, 3100–2400 and 800–600 cal. BP.

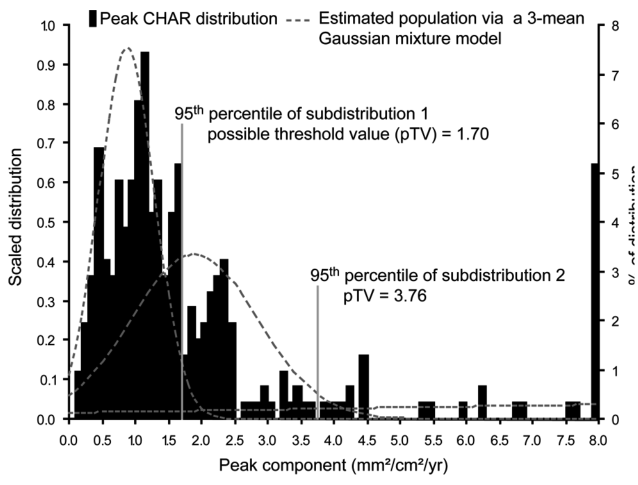


Figure 8. Frequency distribution of the CHAR residuals with fitted curves from a Gaussian mixing model (Software CLUSTER by Bouman, 1997; see also Gavin *et al*., 2006). The lowest population of values (95%) can be considered as analytical 'noise', and the positive highest ones above the threshold values (TV) are assumed to express fire episodes in the local or micro-regional area around the lake. The vertical grey lines show the threshold values (TV 1.7, 3.76) chosen to identify charcoal peaks most likely due to local fire episodes

Discussion and conclusions

Relevance of the study site

The small lake Lago della Costa is most probably the only preserved natural water basin with an undisturbed late-Quaternary sediment accumulation in the eastern edge of the Po Plain (own investigations and A. Miola, personal communication, 2006). The present landscape in the Colli Euganei region and surrounding Po Plain is a result of intensive land use over millennia. From AD 1556 onward many drainage channels were built to reclaim the paludified landscape at the southeastern border of the Euganean Hills. As a consequence most peatlands dried out and collapsed. Furthermore, in the hills the forests and woods were cut for meadows, pastures and other agricultural purposes.

By consulting historical records of the excavation activities (the business company responsible today is Societa Lago Costa d'Arqua s.r.l.) we were able to find a spot in the lake that had not been disturbed by the fango exploitation for therapy purposes during the past decades. The top of our sequence, especially the date at 325 ± 60 ^{14}C yr BP and the strong peak of *Cannabis* t. pollen (that is characteristic for almost all lacustrine sequences of the Alps and their northern and southern forelands, see e.g. Gobet *et al*., 2000; Tinner *et al*., 1998; van der Knaap *et al*., 2000), is an unequivocal proof of undisturbed sedimentary conditions up to the present.

Both empirical and simulation studies (e.g. Broström *et al.*, 2004; Conedera *et al*., 2006; Jacobson and Bradshaw, 1981; Sugita, 1994) demonstrate a correlation between the size of the lake and the relevant source area of pollen. On the basis of these studies the relevant source area for a small study site like Lago della Costa (3 ha) is assumed to comprise only a few hundred metres around the lake shore, and the corresponding total source area has a radius of 10–30 km around the lake. Thus the proportion of pollen transported from long distance is relatively small.

Vegetation, fire and climate interactions under quasi natural conditions

During the last glacial maximum (LGM) the Euganean Hills and surrounding Po Plain were not glaciated. Pollen sequences show that the Po Plain and the Berici Hills (Figure 1A; Wick, 2004) were situated in a steppe environment with some small *Pinus, Larix* and *Juniperus* woods. The pollen records from Lago della Costa (Lona, 1957 and Figure 1C: AP2; Kaltenrieder *et al*., 2009) and from peat sediment of Galzignano (Figure 1B; Miola and Gallio, 1998) and Fonteghe near Arquà Petrarca (Neviani, 1961) also indicate that during the LGM there was a predominance of cold-steppe vegetation, with the main herbaceous taxa Poaceae, *Artemisia* and Chenopodiaceae accompanied by the arboreal taxa *Pinus, Larix* and *Juniperus*. Surprisingly, pollen of thermophilous deciduous tree taxa (e.g. *Quercus, Tilia, Fagus, Fraxinus, Ulmus* and *Carpinus*) is regularly present in these LGM records. This assemblage led several authors to hypothesize that these taxa possibly survived the last LGM in favourable micro habitats (sheltered, humid sites) of the Euganean Hills (Kaltenrieder *et al*., 2004, 2009; Lona, 1957; Miola and Gallio, 1998; Neviani, 1961).

Between the LGM and the Bølling-Allerød interstadial (*c*. 19 000–14 500 cal. BP) temperatures increased gradually in and around the Alps, leading to the contraction of the Alpine ice sheet (Casadoro *et al*., 1976; Friedrich *et al*., 1999; Kromer *et al*., 1998; Lister, 1988; Niessen and Kelts, 1989). As a consequence of climatic warming and ice recession, the first forests were established at around 16 000 cal. BP in the southern Alps and their forelands. The climatic warming at the beginning of the Bølling-Allerød interstadial has been recorded in many areas of the Northern Hemisphere (e.g. *c*. 8–12°C in Greenland and 4–6°C in Europe at 14 700–14 500 cal. BP; Björck *et al*., 1998; Heiri and Millet, 2005; Lowe and Hoek, 2001; von Grafenstein *et al*., 1999) leading to pronounced changes in the biosphere. For the western part of the Po Plain, the δ^{18}O record of the sediment of Lago Piccolo di Avigliana suggests that the timing of this shift was *c*. 14 650 cal. BP (Finsinger *et al*., 2008). In the southern Alps and their forelands an abrupt change of woodland structure and density occurred at 14 800–14 300 cal. BP, probably in response to climatic change (Vescovi *et al*., 2007). It seems likely that similar vegetational processes occurred at Lago della Costa at 16 500–14 500 cal. BP; but because of chronological uncertainties we cannot address this topic accurately.

During the Younger Dryas, a climatic cooling of Northern Hemispheric extent from 12 600 to 11 500 cal. BP, air temperature decreased by *c*. 4°C in and around the northern Alps (Heiri and Millet, 2005; von Grafenstein *et al*., 1999, 2000). The environmental effects of the Younger Dryas are documented in several palaeoecological studies, including those from the neighbouring southern Alps (e.g. Lang, 1961; Pini, 2002; Schneider and Tobolski, 1985; Tinner *et al*., 1999; Vescovi *et al*., 2007). There the forest cover diminished across all vegetational belts, and herbaceous taxa re-expanded together with coniferous trees such as *Pinus cembra* and *Larix decidua*. After the Younger Dryas cooling, environments south of the Alps responded markedly to climatic warming of the early Holocene at *c*. 11 500 cal. BP (e.g. Vescovi *et al*., 2007; Wick, 1996).

In contrast to these records from the southern Alps and their forelands, vegetational conditions at Lago della Costa remained relatively stable until *c*. 9400 cal. BP. No unambiguous vegetational changes can be related to the Younger Dryas cooling and the onset of the Holocene. This lack of evidence at Lago della Costa is probably a result of various factors. The vegetation in the lowlands around the site had been rather open throughout the postglacial, probably as a consequence of river disturbance in the Po Plain (floodplains, gravel soils with alluvial sediments and peat layers: Miola *et al*., 2003, 2006). In agreement, postglacial arboreal pollen values at Lago della Costa (40–45%; Figure 4: APL-1) are far below those from adjacent regions such as the southern Alps or the Berici Hills. We assume that because of the natural openness of the woodlands, climatic-driven vegetational changes such as those induced by the Younger Dryas cooling are difficult to detect. Furthermore, the proximity to the refuges of the last glacial and the mild climatic conditions in the Euganean Hills may also have contributed to soften the imprint of vegetational responses to environmental and climatic changes. Nevertheless, gradual expansion trends as e.g. for *Alnus glutinosa* and *Carpinus* during the Holocene are clearly documented after *c*. 11 000 cal. BP. Probably because of landscape openness and low biomass availability, the fire impact was relatively low (Figures 6 and 7) until 9400 cal. BP.

Abies alba and *Alnus glutinosa* expanded at 9200 cal. BP, when they expanded also in the Insubrian region *c*. 150–200 km west of Lago della Costa (Tinner and Lotter, 2006; Tinner *et al*., 1999). This vegetational change has been interpreted as climatically driven (i.e. a shift towards more oceanic conditions, see Tinner and Lotter, 2006; Tinner *et al*., 1999), since it occurred during a cold-humid phase in and around the Alps (CE-2, 9500–9000 cal. BP, Haas *et al*., 1998). Similarly, the delayed Holocene expansion of *Abies* in the Adriatic region has been related to an increase of moisture availability as a consequence of the early-Holocene sea transgression over the northern Adriatic depression (Lambeck *et al*., 2004; Ravazzi *et al*., 2006). According to the macroscopic charcoal record, fire frequency started to increase 200 years before (i.e. at 9400 cal. BP) the expansions of *Abies alba* and *Alnus glutinosa* (IFF moderate episodes: CHAR ratio

<3.76: Figure 7). A similar increase at the same time has been observed in Tuscany, associated with low lake level (Vannière *et al*., 2008). At Lago della Costa, microscopic charcoal increased clearly around 9100 cal. BP, though regional fire activity certainly remained relatively moderate. From this time onwards, fire activity was higher than before at both local and regional scales (Figures 6 and 7). We hypothesize that this early increase of fire activity was primarily of natural origin, possibly linked to climatic change (CE-2, 9500–9000 cal. BP) and increasing biomass availability as a consequence of the expansion of denser and more oceanic forests at around 9200 cal. BP (Figure 4).

Our pollen record suggests that *Ostrya* communities established at about 8000 cal. BP in the Lago della Costa area, marking the onset (though on a lower level) of today's *Ostrya-Quercus* woods on calcareous substrate ('Ostryo-Quercetum', Del Favero, 2001). This early establishment of *Ostrya* communities was probably natural and comparable with that in the region of Lake Garda and eastwards to the Balkan Peninsula, where *Ostrya* t. pollen was already present at the beginning of the Holocene or even earlier (Beug 1964, 1965; Huntley and Birks, 1983; Willis, 1994).

Vegetation, fire and human impact

In the Palaeolithic and Mesolithic (before *c*. 5500 cal. BC; 7450 cal. BP) human impact at the study site was low, although early attempts at local introduction of agriculture may have already occurred during the late Mesolithic at *c*. 8400 cal. BP (e.g. first appearance of Cerealia t. pollen grains in the Lago della Costa record). However, this topic remains elusive in the absence of systematic archaeobotanical analyses (see discussions in Behre, 2007; Tinner *et al*., 2007). Given the lack of unambiguous evidence of land use, we assume natural or quasi-natural conditions prior to the onset of the Neolithic at *c*. 5500 cal. BC.

Intense land use started at *c*. 6300 cal. BP around Lago della Costa (increase of meadow and field plants, *Centaurea jacea* t., *Ranunculus acris* t., *Plantago lanceolata* t. and Cerealia t. Early land-use activities were linked to the use of fire, probably to gain place for fields (increase of fire frequencies, Figures 7 and 8 and positive correlation between charcoal and Cerealia t.; Figure 5). In the forested parts of the Colli Euganei increased fire disturbance probably favoured strong and moderate re-sprouters such as *Alnus, Carpinus* and *Castanea* or fire-adapted ferns such as *Pteridium aquilinum,* while fire-sensitive taxa such as *Tilia* and *Abies alba* could have been disadvantaged or even displaced (Figure 5; see also Delarze *et al*., 1992; Tinner *et al*., 2000). These long-term linkages between fire and vegetation are consistent with observations at other sites south of the Alps (e.g. Keller *et al*., 2002; Tinner *et al*., 1999).

The most striking finding of Lago della Costa is the early and regular appearance of *Castanea sativa* and *Juglans regia* about 6300 years ago. The pollen record (continuous pollen curves throughout the past 6300 years, reaching 1–2%) shows that these two fruit trees are a constituent of the vegetation of the Colli Euganei since at least Neolithic times (one finding of *Castanea sativa* is dated at *c*. 8800 cal. BP). The expansion of chestnut and walnut trees at 6400–6200 cal. BP was associated with the appearance or expansion of cultivated plants and weeds (e.g. Cerealia t., *Linum usitatissimum* t., *Plantago lanceolata* t., *Cannabis* t., *Ranunculus acris* t.) as well as a huge increase in regional fire activity. This unambiguously shows that the two trees were advantaged or perhaps even introduced for agricultural purposes. To our knowledge these are the oldest unambiguous pollen data showing evidence for a combined chestnut and walnut tree cultivation in Europe and elsewhere. Our interpretation that *Castanea sativa* and *Juglans regia* were cultivated in the Colli Euganei is based on the synchronous expansion of the two fruit trees and the strong correlation with agricultural activities (e.g. *Plantago lanceolata* t. and Cerealia t. pollen) and fire (charcoal, Figure 4). It appears unlikely that the two tree species were just promoted or favoured by humans. The two species have substantially different ecological preferences (e.g. *Juglans* prefers carbonatic and *Castanea* siliceous bedrocks, Gobet *et al*., 2000; Lauber and Wagner, 2007) and strategies. Moreover, there is no evidence that *Juglans regia* was present in the Colli Euganei before the Neolithic (no pollen grains found before), while *Castanea sativa* was probably already present before the onset of agriculture (occurrence of Glacial and Holocene pollen, Kaltenrieder *et al*., 2009). Younger evidences for cultivation of *Castanea* together with *Juglans* are documented in several regions in Anatolia, northeastern Greece and Croatia, dating back to *c*. 3700–3000 ^{14}C BP (*c*. 4000–3200 cal. BP; Bottema, 1974; Eastwood *et al*., 1999; Jahns and van den Bogaard, 1998; van Zeist and Bottema, 1991; Willis and Bennett, 1994). At two sites in southwestern Turkey, the pollen assemblages at that time resemble those at our site and are indicative of the so-called Beysehir Occupation Phase with an advanced form of agriculture, including fruit-tree cultivation. At these western Asian sites, the pollen percentages of *Juglans* and *Castanea* remain generally low at 1–2% (Bottema and Woldring, 1990; Eastwood *et al*., 1999; van Zeist *et al*., 1975). Mercuri *et al*. (2002) suggested that a Pre-Roman advanced agricultural economy existed in central Italy at around 3000 cal. BP, probably including the cultivation of *Castanea* and *Juglans* together with other crops. Although it is likely that besides *Castanea*, also *Juglans* survived the last Ice Age in Italy (Accorsi *et al*., 1989; Beer *et al*., 2008; Krebs *et al*., 2004; Paganelli and Miola, 1991), in most cases *Juglans* and *Castanea* spread together only with the Greek and Roman civilizations 1500–2500 cal. BP in the Italian peninsula (e.g., Colombaroli *et al*., 2007; Drescher-Schneider *et al*., 2007; Gobet *et al*., 2000; Tinner *et al*., 1999). However, in agreement with our data, recent studies show that nutshell fragments of *Juglans regia* were already present at early to middle Neolithic archaeological sites in Italy, northeast of the Euganean Hills (Rottoli and Castiglioni, 2009), suggesting harvesting or cultivation of the species elsewhere in Italy. Outside Italy, nuts of *Juglans regia* in Neolithic cultural layers in Germany and Switzerland (region of Lake Constance) were already reported by early authors (Bertsch, 1951). We assume that the early combined cultivation (which may include preferential treatment) of *Juglans* and *Castanea* at our site was only possible because of the mixed carbonatic and siliceous bedrocks, a situation which is rare elsewhere in southern Europe.

The archaeological record documents the presence of a settlement in the Colli Euganei during the early Neolithic. It was situated in the nearby Calaona valley near Baone (about 3 km north of Este; Figure 1B), at the southwestern border of the Euganean Hills, and it belonged to the so-called 'Cultura di Fiorano'. Towards the middle and late Neolithic new settlements belonging to the 'Cultura di Vasi a Bocca Quadrata' (Square Mouthed Pottery Culture) were built around Este. The most prominent settlement of the late

Neolithic was Castelnuovo di Teolo ('Cultura Chassey-Lagozza'; Figure 1B), on the rockface of Monte Pendice at 298 m a.s.l.

During the Bronze Age (*c*. 2200–800 cal. BC) land use became more intensive in the Po Plain (Castelletti *et al*., 2001). The central Po Plain was settled by many large villages named Terramara (Mercuri *et al*., 2006). In order to understand to what degree the land was used by prehistoric populations, it is important to perform pollen analysis directly on sediments from prehistoric settlements (on-site records). However, because of the absence of conditions that allowed pollen preservation, only a few of the various excavated prehistoric settlements were investigated by pollen analysis; they are situated in the area of Lago di Garda (e.g. Valsecchi *et al*., 2006) and the Po Plain (e.g. Accorsi *et al*., 1999; Mercuri *et al*., 2006; Ravazzi *et al*., 2004). These palaeobotanical and archaeological investigations provide evidences of strong forest (or woodland) clearings and vegetation changes around the big settlements (Terramara) by intensification of anthropogenic activities. In contrast to these regions apparently only a small settlement existed at the lakeshore of Lago della Costa during early and middle Bronze Age ('2000–1600 BC: Cultura di Polada'). The archaeological excavations between 1885 and 1906 (by F. Cordenons, A. Alfonsi) yielded different artefacts such as pottery, decorations, and tools made of clay, stone, deer bone and horns that were made for domestic use, cattle-breeding and hunting activities, but no pollen analysis was done. Our nearby pollen and charcoal record suggests ongoing land use with the cultivation of important crops such as *Castanea*, *Juglans, Olea*, *Cannabis* t. and Cerealia t. Fire was probably still used for agricultural purposes as e.g. documented by the strong local fire incidence at 3100–2400 cal. BP (1600–450 cal. BC) (Figure 7, IFF>3.76). During Medieval times intensification of land use included strong forest clearances and expansion of arable farming and pasturing. This final opening of vegetation was associated with high local and regional fire activity at 800–600 cal. BP (AD 1150–1350 yr; Figures 6 and 7) and led to the current vegetational situation in the Euganean Hills.

Considerations about the natural potential vegetation of the Colli Euganei

Natural plant communities are hardly recognizable anymore in our study area (Selmin, 2005), but the general opinion is that the natural vegetation of the Euganean Hills would be characterized by deciduous mixed forests with components of deciduous *Quercus, Fraxinus excelsior, Tilia, Ulmus, Acer* and *Fagus*. Only a marginal role would be played by *Castanea sativa, Ostrya carpinifolia* and *Carpinus betulus* (Antonietti, 1962). Evergreen broadleaved and (sub-) Mediterranean species would regularly occur on drier south-facing slopes (Selmin, 2005). Our study confirms these estimates, although it shows that *Abies alba* would probably occur naturally if not excluded by the long-term effects of land use and fire disturbance.

It is difficult to address the question whether the fruit trees *Castanea sativa* and *Juglans regia* were (naturally) present in the region prior to 6400 cal. BP. Although the occurrence of *Castanea* and *Juglans* pollen prior to Roman occupation is quite common in the eastern Po Plain (Accorsi *et al*., 1989; Paganelli and Miola, 1991), the temporal resolution and precision of those studies is rather low if compared with our new Lago della Costa record. However, Paganelli *et al*. (1988) found wood of *Castanea sativa* ^{14}C-dated to 4030 ± 80 yr BP in an open soil profile at S. Felice di Cologna Veneta (20 km to the west of the Euganean Hills). LGM finds of *Castanea sativa* pollen (Conedera *et al*., 2004; Kaltenrieder *et al*., 2004, 2009; Krebs *et al*., 2004; Paganelli and Miola, 1991) suggest that this species could have survived the ice age in the Euganean Hills. Additional investigations in the area will be needed to address this question more thoroughly.

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