Climate and vegetation dynamics of the northern Apennines (Italy) during the late Pleistocene and Holocene

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Abstract

This study reconstructs the regional vegetation and climate dynamics between the upper Late Pleistocene and Holocene around Pian del Lago, a coastal mountain marshland located at 831 m asl in western Liguria (NW-Italy), based on the pollen analysis of a 13 m-long sediment core. The record provided a unique opportunity to study a poorly documented period in northern Italy and across many parts of southwestern Europe. We propose an event stratigraphy based upon the identification of seven interstadials (NAI-7 to NAI-1) spanning the upper Late Pleistocene. The correlation with other terrestrial records in Italy, and with Mediterranean marine sequences and the

Greenland ice cores, permitted a coherent reconstruction of main environmental changes from >~*43,000* cal. BP. Significantly, the pollen record indicates the persistence of a mesophilous mountain vegetation cover, mainly composed of *Quercus* (deciduous and evergreen), *Abies*, *Fagus* and *Alnus* over the whole time period recorded. At the Last Glacial Maximum (LGM) and during the Late Würm Lateglacial, despite the presence of steppic vegetation composed of *Artemisia*, woodlands dominated by *Pinus*, with *Abies*, *Picea*, *Fagus*, *Alnus* and *Betula* are present. This forest composition provides an important insight into the history of *Picea* in southern Europe and Late Pleistocene refugia for mesophilous species. During the Early Holocene, *Pinus* is first replaced by *Abies* and then by deciduous *Quercus* and mixed temperate species as the dominant forest component. Both arboreal and herbaceous anthropogenic pollen indicators only make their appearance during the Late Holocene, attesting to the increasing importance of human activities .

Keywords

North-western Italy, Late Pleistocene, Holocene, Pollen Analysis, Micro-charcoal Analysis

1. Introduction

During the last few decades, several palynological studies have documented the Holocene environmental dynamics of the northern Apennines, NW Italy (e.g. Bellini et al., 2009a; Bertoldi et al., 2007; Branch, 2004, 2013; Branch and Marini, 2013; Branch and Morandi, 2015; Branch et al., 2014; Cruise, 1990a, 1990b; Cruise and Maggi, 2000; Cruise et al., 2009; Guido et al., 2003, 2004a, 2009, 2013; Lowe, 1992; Maggi, 2000; Morandi and Branch, 2018; Watson, 1996), including coastal areas (Arobba et al., 2018; Bellini et al., 2009b; Guido et al., 2004b, 2004c; Mariotti Lippi et al., 2004; 2007; Montanari et al., 1998; Montanari et al., 2014; Piccazzo et al., 1994). Very little is known about the upper Late Pleistocene (~50,000-11,700 cal. BP), however, with the majority of records only covering the Late Würm Lateglacial (~14,800-11,700 cal. BP), (e.g. Branch 2004; Branch and Morandi, 2015; Lowe, 1992; Lowe and Watson, 1993; Vescovi et al., 2010a, 2010b;

Watson, 1996). The only sites with a chronology covering the whole period in NW Italy are Lago di Massaciuccoli (Menozzi et al., 2002), Berceto (Bertoldi et al., 2007) and Ivrea (Arobba et al., 1997; Gianotti et al., 2008; 2015). Additional information for this time frame has been obtained from archaeological studies (mainly coastal caves), but these sedimentary archives are generally unsuitable for regional palaeoenvironmental reconstructions (see Kaniewski et al., 2005) (Fig. 1).

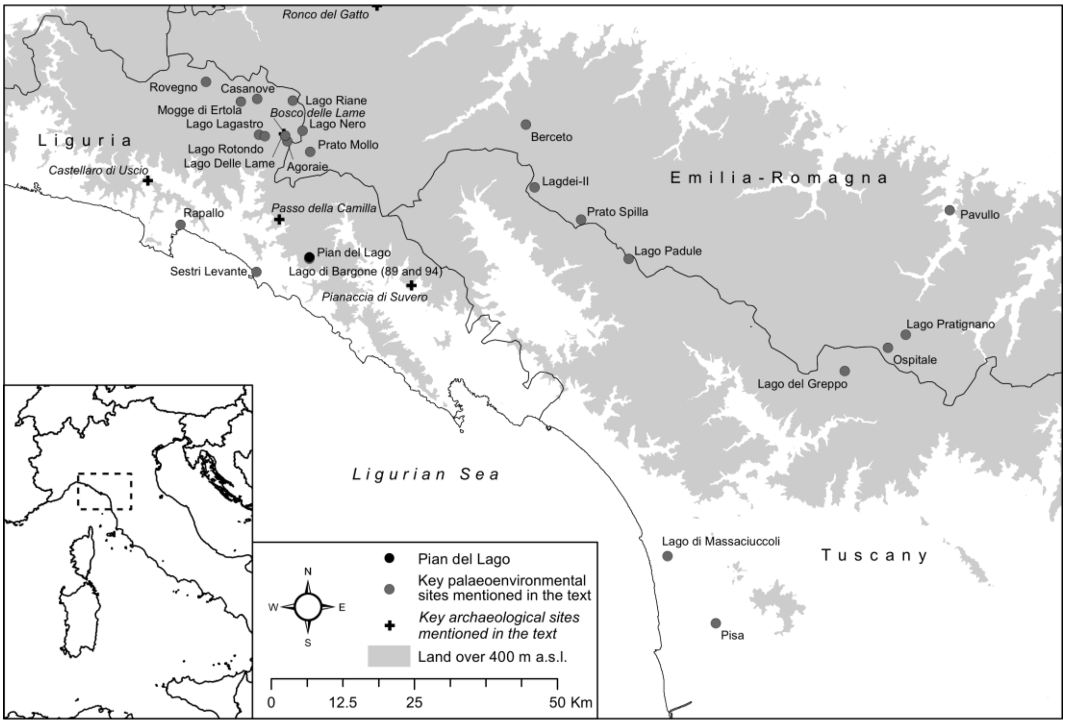

Fig. 1: Location of Pian del Lago and key Late Pleistocene and Holocene palaeoenvironmental records from the northern Apennines mentioned in the text

This new study from Pian del Lago provided a unique opportunity to fill this chrono-stratigraphic gap for NW Italy (cf. Magri, 2010; Magri et al., 2015) enabling: (1) reconstruction of the main vegetation dynamics of the area during the upper Late Pleistocene and the Holocene (~43,000-8000 cal. BP); (2) significantly improved understanding of the response of the northern Apennines to known periods of abrupt climate change towards the end of the last glaciation; (3) greater appreciation of the environmental and climatic setting for major developments in the human history of southwestern Europe and the Mediterranean.

2. Geographical and environmental setting

Pian del Lago is located near the village of Bargone, Casarza Ligure (Genova), Western Liguria, north-western Italy, at around 830 m a.s.l. and less than 3 km away from the coast (Fig.1 and Fig.2). The watershed ridge, marking the boundary of the catchment, reaches fairly high altitudes, considering the proximity of the sea: M. Roccagrande (971 m) and M. Tregin (870 m) on the western side, M. Alpe (1093 m), M. Zenone (1055 m) and M. Pu (1001 m) on the eastern side. These mountains are mainly of ophiolitic nature, but there are also sediments (e.g. jasper with manganese) that covered the submarine effusions. This explains the presence, since prehistoric times, of copper, iron and manganese mines in the surrounding area.

The climate of the area is sub-Mediterranean. Data from Castiglione Chiavarese weather station (300 m a.s.l.) indicate a mean annual temperature of 13°-14°C, with a maximum in summer (mean above 22°C) and a minimum in winter (6-8 °C). The mean annual precipitation is 1300 mm, while the average monthly rainfall distribution shows a maximum in November (160 mm) and a minimum in July (less than 50 mm). Before specific palaeoenvironmental studies were made, the origin of the swamp was attributed to periglacial phenomena, which would be consistent with other northern Apennines wetlands (cf. Cruise, 1990a). Faccini et al. (2009) have instead recognized deep-seated gravitational slope deformations (DSGSD), which is a geomorphological feature characterising other Ligurian landscapes. The palaeoenvironmental research presented here confirms that this phenomenon is older than ~*43,000* years.

The wetland contains lacustrine sediments, with thickness varying from a few metres to about 13.30 m. Despite to the altitude and proximity to the coast that cause a relatively mild humid climate, this is a mountain site comparable to other upland wetlands studied by pollen analysis in the massif of M. Beigua, western Ligurian coast (Guido et al., 2004a). The area surrounding the plateau is mainly treeless, except for the local reforestation with *Pinus nigra*. At slightly lower elevations meso-thermophilic deciduous forests of *Quercus cerris* L. (Turkey-oak), *Q. pubescens* Willd. (white oak), *Q. ilex* L. (holm oak), *Ostrya carpinifolia* Scop. (hop-hornbeam) and abandoned orchards of *Castanea sativa* Miller (sweet chestnut) are widespread. Presently, the area is included in the European ecological network Natura 2000, designed to protect the most endangered habitats and species, and it belongs to the Site of Community Interest (SIC IT1342806 M. Verruga - M. Zenone – M. Roccagrande - M. Pu).

Fig. 2: Photographs of Pian del Lago during the field investigations
(top – west facing; bottom – east facing) (in color online)

The plateau hosting the small wetland is partially occupied by grassland, formerly a pastureland, which is more and more invaded by a post-cultural scrubland dominated by *Buxus sempervirens* L. and heathland with *Calluna vulgaris* (L.) Hull, *Erica carnea* L., *E. arborea* L., *Pteridium aquilinum* (L.) Kuhn etc. The mire includes hygro-hydrophilous vegetation, i.e. sedges populations (*Carex* cfr. *caespitosa* L., *C. distans* L., *C. flava* L., *C. pallescens* L., *C. panicea* L., *C. stellulata* Good., *C.*

tumidicarpa Anderss.), stands of bulrushes (*Juncus articulatus* L., *J. effusus* L., *J. fontanesii* J. Gay, *J. tenageja* Ehrh.), *Typha latifolia* L. and *Molinia caerulea* (L.) Moench (Fig. 2).

3. Field and laboratory methods

One of the several cores sampled during the field campaign was studied for bio-stratigraphical analyses. This core (S1) is 1330 cm long and 10 cm in diameter and was recovered using a rotary drilling rig. Sub-samples for pollen and microcharcoal analysis were extracted every 5 or 10 cm, although sub-sampling was occasionally impossible due to the presence of stones or coarse sediment. In total, 100 levels have provided statistically valid pollen counts. Approximately 2 cm^3 of sediment were processed according to standard palynological treatments (Moore et al., 1991). With only some exceptions, a minimum of 300 pollen grains were counted (aquatic and spore taxa were excluded from the pollen sum). Pollen identification was completed to the lowest taxonomic level possible using reference materials and pollen atlases held at the University of Genoa (Punt, 1976; Punt and Blackmore, 1991; Punt and Clarke, 1980, 1981, 1984; Punt et al., 1988, 1995; Reille, 1992-1998). Pollen percentages and microcharcoal influx (particles cm^{-2} yr^{-1}) were calculated, and the results plotted using TILIA and TILIA.GRAPH version 2.1.1 (Grimm, 1993). Local pollen-assemblage zones (LPAZs) were identified using stratigraphically constrained cluster analysis (Grimm, 1987).

Chronological control for the sequence was provided by a Bayesian age-depth model based on 10 conventional AMS ^{14}C dating (Stuiver and Polach, 1977) and on 3 Uranium series dates (Table 1). The AMS ^{14}C samples were dated at CEDAD, University of Salento (Italy). All radiocarbon samples were prepared using standard acid-alkali-acid pre-treatment and were quoted in accordance with international standards (Stuiver and Kra, 1986). The radiocarbon ages were calibrated to the calendar timescale and a Bayesian age-depth model was generated using the R package (R Core Team, 2016) Bacon v.2.3.4 (Blaauw and Christen, 2011) and the IntCal13 radiocarbon calibration curve (Reimer et al., 2013). The Bacon software package creates flexible age-depth models utilising an autoregressive gamma process and is typically robust to the presence of outlying dates since these are modelled using a student-t distribution with wide tails (Christen and Pérez, 2009). 95% confidence intervals and weighted mean age estimates at 1 cm intervals along the core were generated through several million Markov chain Monte Carlo iterations (Blaauw and Christen, 2011).

Lab code (dates marked * excluded from age model)	**Depth (cm)**	**Material**	**δ13C (‰)**	**^{14}C age (BP)**	**U/Th age (BP)**	**Calibrated age range cal BP (95.4% confidence)**
LTL3092A	100	Clay	-27.0	534 ± 45		650-500
LTL4200A	180	Peat	-27.5	3483 ± 50		3890-3630
LTL4201A	290	Peat	-25.3	8892 ± 60		10,200-9770
LTL4202A	380	Silty clay	-28.1	9625 ± 75		11,200-10,740
U-series1	400	Diatomite			13,840 ± 750	14,220-13,200
U-series2	432	Diatomite			21,260 ± 320	21,580-20,930
U-series3	464	Diatomite			21,550 ± 370	21,920-21,170
LTL12573A	471	Clay	-29.0	29,917 ± 150		34,310-33,710
*LTL4365A	529	Clay	-27.1	32,755 ± 300		37,900-36,060
*LTL4203B	530	Clay	-26.5	33,081 ± 280		38,220-36,420
*LTL4203A	530	Clay	-26.3	34,214 ± 500		40,000-37,320
LTL4204A	730	Sandy clay	-30.1	29,687 ± 170		35,430-34,860
LTL3093A	960	Clay	-32.0	31,122 ± 300		36,030-34,760
LTL12574A	1110	Clay	-29.9	31,458 ± 200		35,840-34,860
LTL1536A	1281	Peat	-35.5	40,844 ± 650		45,560-43,240

Table 1. Results of the radiocarbon and U-series dating

U-Series dating of amorphous opal silica is well established (Ivanovich and Harmon 1992; Neymark and Paces, 2000; Neymark et al., 2000, 2002). For minerals precipitated from aqueous solutions, U-series dating can provide precise chronologies if samples have high U/Th ratios and have remained closed to post-depositional mobility of U-series nuclides (e.g., Ludwig and Paces, 2002; Neymark and Paces, 2013). Three samples from diatom-rich units were analysed by XRD to quantify the mineralogy prior to age determinations (Sprynskyy et al., 2010; Table 2). Most of the samples are composed of amorphous opal silica (27-67%) and quartz (17-42%) with vermiculite, nimite and clinochrysotile, which are the weathering products of iron-rich, nickel-rich and hydrous phases from Serpentinite bedrock, respectively making up the remainder. As a result of the composition, the sub-samples were separated by density with fractions < 2.1 g/cm^3, < 2.3 g/cm^3 and a heavy fraction > 2.8 g/cm^3 together with a whole sample to create isochrons from the sub-fractions for analysis by mass spectrometry and gamma spectroscopy. For the gamma spectroscopy, samples and fractions were counted on a Harwell Instruments, Broad Energy BE5030 high purity germanium coaxial photon detector at the University of Reading (UK). External reproducibility was checked using international standards (Yokoyama and Nguyen, 1980). For the mass spectrometry, multiple, small sub-samples (100-500 mg) were extracted from the diatom-rich units and sub-fractions for determination of the $^{234}U/^{238}U$, $^{235}U/^{238}U$ and $^{230}Th/^{232}Th$ ratios by means of a Thermo-fisher iCAPQ Inductively Coupled Plasma Mass Spectrometer. External reproducibility was checked using international standards (NIST SRM 3164, 4355 and 4357) and by monitoring the (235/238) ratios in the samples to be within the naturally abundant ratio (137.5). U/Th concentrations were also determined via mass spectrometry using the same instrument. Age determinations were calculating following the methodology of Ludwig and Paces (2002). Isochrons were constructed for samples to check the integrity of the ages and correlated errors were reduced by calculating isochron ages in Isoplot v4.15 (Ludwig, 2008) and IsoplotR (Vermeesch, 2018).

	Diatomite	Sediment fraction			Serpentinite alteration products		
Sample Depth (cm)	Diatomite (opal silica)	Quartz	Albite (low)	Muscovite	Vermiculite	Clinochrysotile	Nimite
400-401	26.8	42.0	4.3	1.3	16.5	5.4	3.7
432-433	56.7	23.0	2.1	1.0	10.8	3.7	2.7
464-465	67.0	16.9	1.8	0.9	8.8	2.8	2.0

Table 2: Proportions (%) of minerals present in samples analysed for U-Series dating

4. Results

4.1 Sedimentary History and Geochronology

The results of the U-series and AMS ^{14}C dating are provided in Table 1. Although the age modelling approach utilised by the Bacon package is generally robust to the presence of outlying dates, it was not possible to obtain a stable age model that acceptably fitted all the dates. This was taken to indicate the presence of spurious dates in the sequence probably due to the re-deposition of older organics within the basin given the lithological evidence for erosion events in parts of the record (i.e. ingress of coarse sediments and boulders into the basin). LTL4365A, LTL4203A and LTL4203B, which were identified as potential outliers by initial models, were therefore considered to be erroneously old and excluded from subsequent analysis. The resulting age depth plot is presented in Fig. 3.

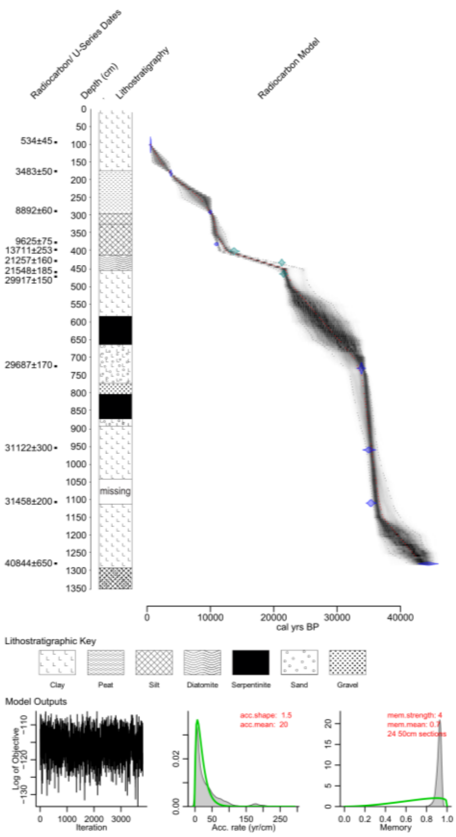

Fig. 3: Lithostratigraphy and age-depth model of Pian del Lago, Northern Apennines, Italy (in color online)

The age model indicates a highly variable accumulation rate at Pian del Lago over the past ~40,000 years, ranging from less than 10 yr cm^{-1} (during ~*36,580-33,850* cal. BP at 1099-750 cm) to over 180 yr cm^{-1} (during ~*21,670–12,490* cal. BP at 449-400 cm), with a mean accumulation rate of ~36 yr cm^{-1}. The average 95% confidence level was 3300 years, but uncertainties vary considerably throughout the sequence, ranging from only 218 years at the top of the sequence, to a maximum of 7671 years at 600 cm.

A simplified lithostratigraphy for Pian del Lago (core S1) is presented in Table 3. A predominately organic silt/clay with gravel (> ~*43,490* cal. BP) is overlain by clay and sandy clay deposition from > ~*43,490* to ~*34,790* cal. BP. This was followed by the erosion and deposition of Serpentinite and then gravel (~*34,790* to ~*34,020* cal. BP), indicating significant destabilisation of slopes surrounding the basin. A further period of Serpentinite deposition occurs from ~*30,750-26,880* cal. BP overlying a unit of sandy clay (~*34,020-30,750* cal. BP). Thereafter, mineral rich fine-grained sediments are deposited from ~*26,880 to* ~*9970* cal. BP (clay and silt), interrupted only by the formation of diatomite between ~*21,850-14,360* cal. BP. Diatomite formation at Pian del Lago may be attributed to successive algal blooms associated with the influx of freshwater into the basin, possibly enriched with minerals due to weathering of surrounding rocks. Although clay and silt deposition persisted into the Early Holocene, suggesting the presence of an unstable land surface surrounding the basin, from ~*9970* to *3205* cal. BP peat formation occurred, indicating increased organic sedimentation and improved stability. From ~*3205* cal. BP to the present day renewed clay deposition may be strongly associated with a reduction in woodland cover and human impact on the local environment.

Depth (cm)	Lithostratigraphy (Unit)	Modelled Age Range (cal. BP)
170-0	Clay	*~3205-<565*
290-170	Peat	*~9970-3205*
320-290	Silt	*~10,640-9970*
410-320	Silty clay	*~14,360-10,640*
450-410	Diatomite	*~21,850-14,360*
580-450	Clay	*~26,880-21,850*
660-580	Serpentinite rock	*~30,750-26,880*
770-660	Sandy clay	*~34,020-30,750*
800-770	Gravel	*~34,260-34,020*
870-800	Serpentinite rock	*~34,790-34,260*
890-870	Sandy clay	*~34,940-34,790*
1040-890	Clay	*~36,090-34,940*
1110-1040	Missing	*~36,715-36,090*
1290-1110	Clay	*> ~43,490-36,715*
1350-1290	Organic (peat) silt, clay and gravel	*> ~43,490*

Table 3: Simplified lithostratigraphy for Pian del Lago (core S1)

4.2 Vegetation History

During LPAZ PdL-1a (> *~43,400* cal. BP; 1330-1290 cm), woodlands are dominated by *Abies* (17%) and *Fagus* (13.5%) (Fig. 4a,b,c,d). These were succeeded by *Pinus* (11%) and deciduous *Quercus* (25%) (Figure 4). Through the zone *Quercus ilex* (2.4%), *Alnus* (2.3%), *Carpinus* (1.9%), *Ulmus* (1.2%), *Sorbus* (1.2%), *Tilia* (1%) and Ericaceae (1%) form mixed forests. The local wetland is colonized by Poaceae (16%) and Cyperaceae (5%), forming a sedge-grass swamp. Microcharcoal values (~1500 fragments cm^{-2} yr^{-1}) are not very high compared to the long-term mean, suggesting that during this period fire is not a very important disturbance factor.

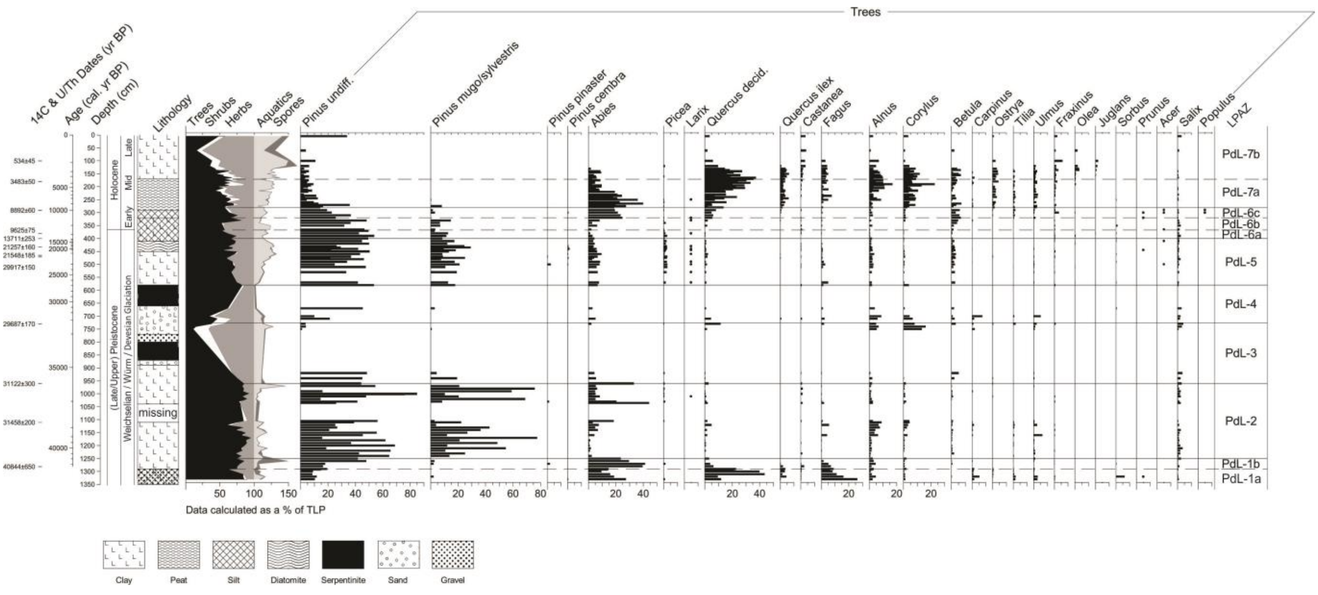

Fig. 4a. Pollen diagram from Pian del Lago, Northern Apennines, Italy: tree taxa

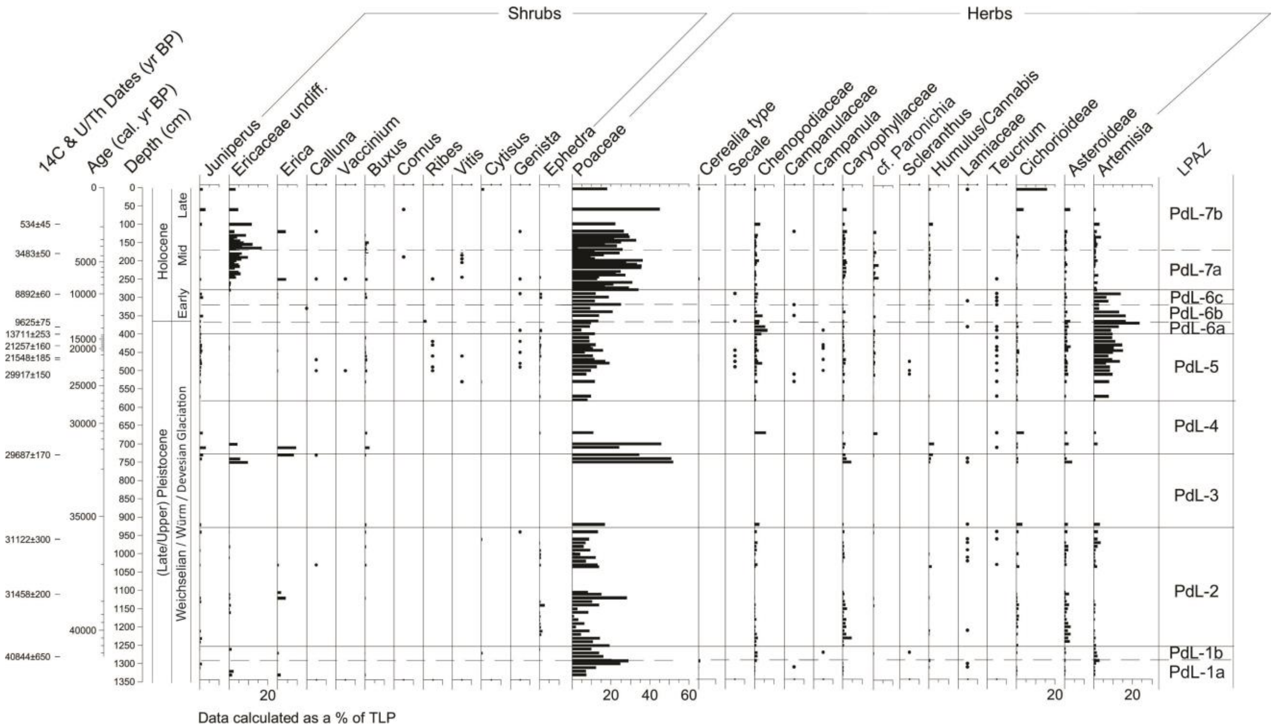

Fig. 4b. Pollen diagram from Pian del Lago: shrubs and herbs

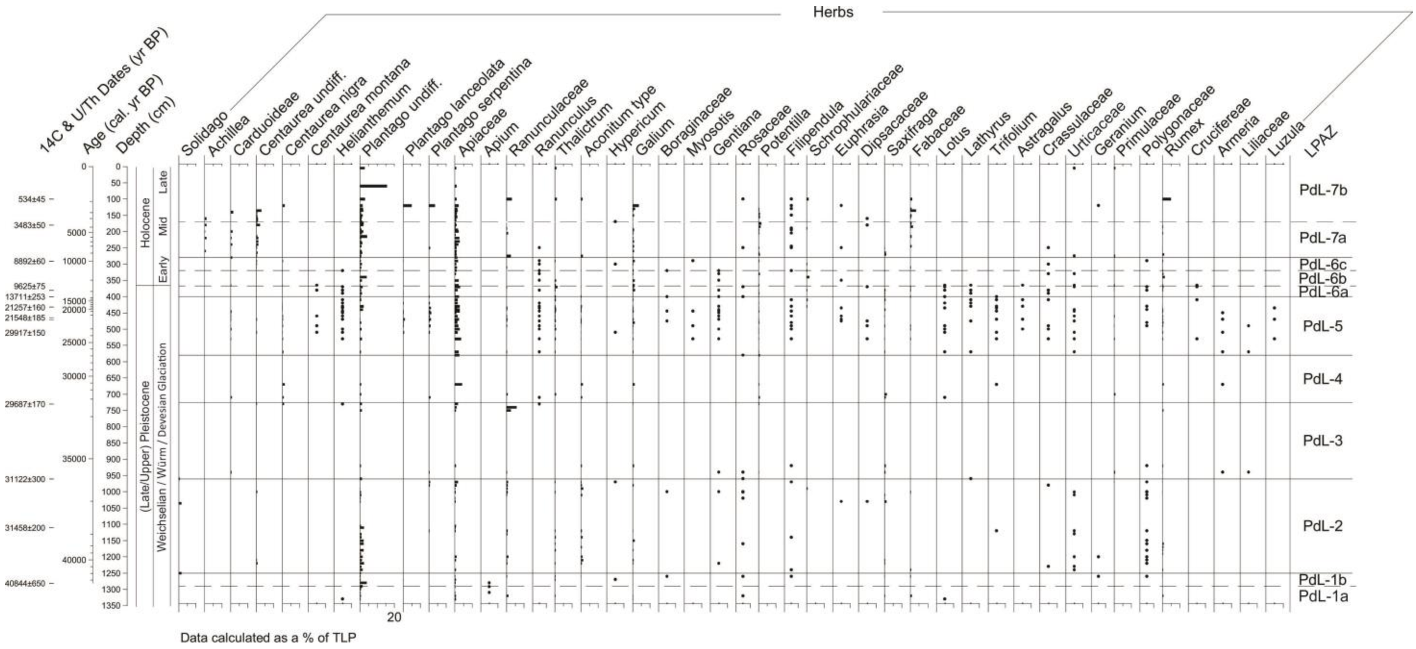

Fig.4c. Pollen diagram from Pian del Lago: herbs (continued)

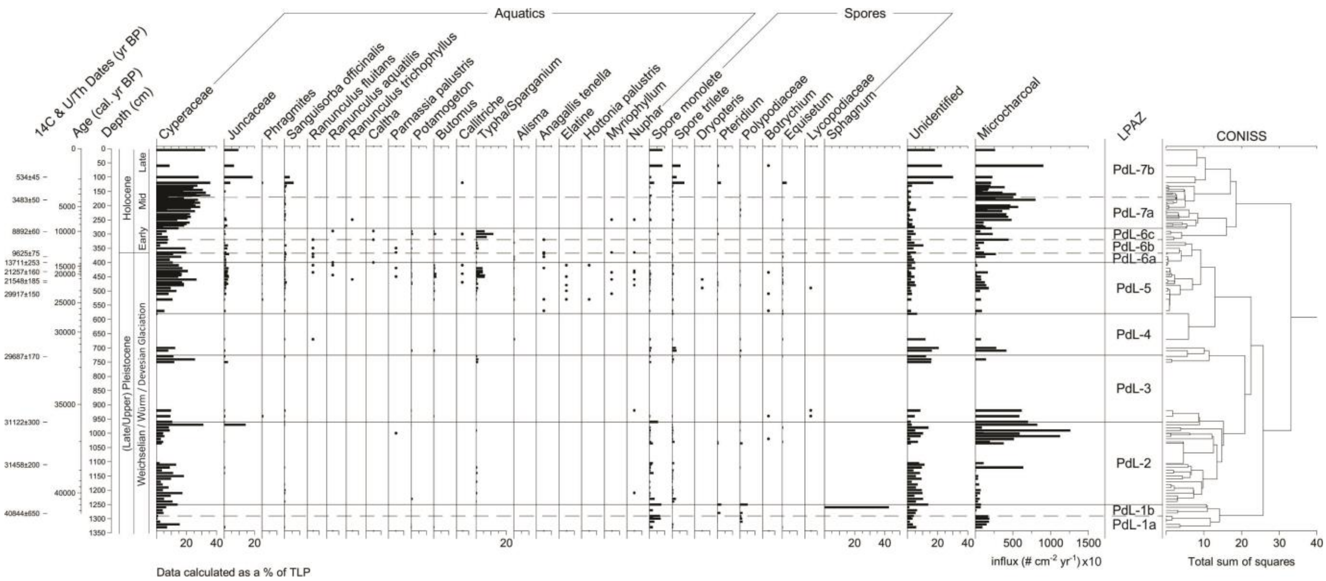

Fig.4d. Pollen diagram from Pian del Lago: aquatics, spores, microcharcoal

LPAZ PdL-1b (> *~43,400-41,940* cal. BP; 1290-1250 cm) is characterized by the expansion of coniferous woodlands dominated by *Abies* (31%) and *Pinus* (26%), and a decline of mesophilous broadleaved woodlands recorded in PdL-1a (deciduous *Quercus* 8%, *Fagus* 5.5%). High presence of Poaceae (15%) and Cyperaceae (4%) indicate the persistence of grass-sedge swamp, fringed by *Alnus* (3%), whilst the surprisingly high value of *Sphagnum* spores (43%) suggests the deposition of moss-rich organic sediment. During this phase microcharcoal values are very low (~200 fragments cm^{-2} yr^{-1}), indicating little influence of fire on ecosystem dynamics.

During LPAZ PdL-2 (*~41,940-35,470* cal. BP; 1250-960 cm), *Pinus* (including *mugo*/*sylvestris*) is dominant (69%) together with *Abies* (7% but with a peak >40%), as well as a diverse mixture of woodland and shrubland species comprising *Corylus* (1%), deciduous *Quercus* (0.7%), *Fagus* (0.6%), *Castanea* (0.6%), *Ulmus* (0.5%), Ericaceae (0.4%) and *Ephedra* (0.3%). *Alnus* (2.5%) and *Salix* (1.3%), together with Cyperaceae and Poaceae dominate the wetlands. Asteroideae, Caryophyllaceae, *Plantago*, *Artemisia*, Chenopodiaceae, Cichorioideae, Ranunculaceae, Apiaceae, Polygonaceae and *Solidago* are present. Microcharcoal values are low (~300 fragments cm^{-2} yr^{-1}) at the beginning and then increase, reaching a maximum value (>12,500 fragments cm^{-2} yr^{-1}) during the last part of this phase suggesting an important role of fire in shaping vegetation structure and composition.

During LPAZ PdL-3 (~*35,470-33,250* cal. BP; 960-725 cm) there is an overall reduction in *Pinus* (~28%) and *Abies* (7.5%). Deciduous woodlands with *Corylus* (6.5%), *Alnus* (between 35% and 5%), Q*uercus* (2.6%), *Salix* (2.5%), *Betula* (1.7%), *Ulmus* (0.6%), *Carpinus* (0.45%), *Fagus* (0.35%) and *Tilia* (0.30%) are present. The overall reduction in woodland cover is indicated by the increased proportion of shrubland (mainly Ericaceae, 4%) and herbaceous (66%) taxa. Poaceae (almost 30%) significantly increase during the zone together with a diverse range of taxa including Caryophyllaceae, Ranunculaceae, Asteroideae, *Artemisia* and Cichorioideae. The wetland continues to be dominated by Cyperaceae (13%), together with *Typha* (0.5%). The zone has some samples with a very low pollen concentration (< 6000 grains/gram) with poor pollen preservation, and therefore there are concerns over the reliability of these data. Microcharcoal values remain quite high but decrease with respect to the last part of the previous phase, with values ~3400 fragments cm^{-2} yr^{-1}.

LPAZ PdL-4 (~*33,250-26,880* cal. BP; 725-580 cm) records an expansion of *Pinus* woodland (26%, including *Pinus mugo/sylvestris*) with a diverse range of other woody taxa, including *Alnus* (6%), *Corylus* (4%), *Carpinus* (3%), *Abies* (2.6%), *Salix* (2.1%), deciduous *Quercus* (1.7%), *Ulmus* (1.6%), *Betula* (1.5%) and *Fagus* (1.1%), as well as Ericaceae (4.6%), *Juniperus* (1.4%) and *Buxus* (1.1%). Nevertheless, herbaceous taxa reach 57% of the pollen values and are dominated by Poaceae (27%), as well as Chenopodiaceae (2%), Cichorioideae (1.7%), Apiaceae (1.4%), Asteroideae (1%) and *Artemisia* (1%). Once again, the wetland is dominated by Cyperaceae (7%). Microcharcoal influxes continue to decrease (values ~2500 fragments cm^{-2} yr^{-1}).

LPAZ PdL-5 (~*26,880-12,480* cal. BP; 580-400 cm) is characterized by the highest number of *taxa* (up to 55 TLP). *Pinus* (54%, including *Pinus mugo/sylvestris*) remains dominant, together with *Abies* (5.7%), *Betula* (1.9%), *Alnus* (1.7%), *Picea* (1.6%), *Fagus* (1%), *Salix* (0.7%) and deciduous *Quercus* (0.7%). Shrub taxa include *Juniperus* (0.5%), *Buxus* (0.4%) and *Ephedra* (0.23%). Despite the formation of diatomite in the upper part of the zone, the woodland cover remains broadly similar throughout. *Artemisia* values are notably higher than in previous zones (9%) and dominate the herbaceous layer together with Poaceae (11%) and small amounts of Apiaceae (2%), Chenopodiaceae (1.3%) and Asteroideae (1.2%). The wetland includes Cyperaceae, Juncaceae, *Typha*, *Sanguisorba officinalis*, *Phragmites*, *Butomus*, *Myriophyllum*, *Equisetum* and *Callitriche*. Microcharcoal values are characterised by a rapid decline during this phase (~600 fragments cm^{-2} yr^{-1}).

During LPAZ PdL-6a (~*12,480-11,600* cal. BP; 400-367 cm) *Pinus* (56%, including *Pinus mugo*/*sylvestris*) dominates, while *Abies* temporarily withdraws (2%) and *Picea* (1%) starts to decline. Deciduous woodlands are mainly composed of *Salix* (1%), *Alnus* (0.8%), *Betula* (0.4%) and *Fraxinus* (0.35%). Shrub taxa include *Ephedra* (0.4%) and *Juniperus* (0.3%). The herbaceous layer is dominated by *Artemisia* (14%), together with Poaceae (9%), Chenopodiaceae (4.5%), Apiaceae (1.7%) and Asteroideae (1.5%). On the wetland, Cyperaceae (12%) and Juncaceae (1.6%) are the main taxa. Microcharcoal values (~1000 fragments cm^{-2} yr^{-1}) increase during this period with respect to the previous phase.

LPAZ PdL-6b (~*11,600-10,760* cal. BP; 367-330 cm) is characterized by an increase in *Abies* (5%) and deciduous *Quercus* (1%), concomitant with the beginning of the *Pinus* decline (48%, including *Pinus mugo/sylvestris*). *Betula* (3%), *Picea* (0.4%), *Castanea* (0.35%), *Fraxinus* (0.3%), and *Juniperus* (1.5%) are also present. The most notable change in the herbaceous taxa is the decline in *Artemisia* (12%), Chenopodiaceae (2%) and Asteroideae (1.2%), although there is still a diverse range of taxa including Poaceae (14%), *Plantago* (1.3%) and Apiaceae (1%). The wetland includes *Salix* (1.4%) and *Alnus* (1%), with Cyperaceae (12%), Juncaceae (1.5%) and *Typha* (1%). During this phase microcharcoal values (~800 fragments cm^{-2} yr^{-1}) are characterised by a decline.

LPAZ PdL-6c (~*10,760-9550* cal. BP; 330-280 cm) is dominated by *Pinus* (27%, including *Pinus mugo/sylvestris), Abies* (22%) and deciduous *Quercus* (6%), together with *Betula* (5%), *Corylus* (1.3%), *Fraxinus* (1%) and *Tilia* (0.9%). *Juniperus* (0.8%), *Ephedra* (0.65%) and *Buxus* (0.5%) also occur. The herbaceous layer is mainly composed of Poaceae (17%), *Artemisia* (7.5%), Chenopodiaceae (1.2%) and Apiaceae (1.2%). On the wetland, *Alnus* (1.4%), *Salix* (0.4%), Cyperaceae (6.3%) and *Typha* (6%) are present. Microcharcoal values (~1800 fragments cm^{-2} yr^{-1}) increase during this period with respect to the previous phase.

LPAZ PdL-7 (~*9550* cal. BP to the present day; 290-0 cm) spans the remaining part of the Holocene. Due to detailed previous research on this part of the sequence (Cruise et al., 2009), the pollen stratigraphical changes have simply been divided into two major sub-zones to aid description and brief discussion of the main vegetation changes: LPAZ PdL-7a (~*9550-3765* cal. BP) and 7b (~*3765-0* cal. BP).

LPAZ PdL-7a (~*9550-3205* cal. BP, 290-170 cm): Before ~*6000* cal. BP *Abies* (24%) replaced *Pinus* (12%) as the dominant tree, and deciduous *Quercus* (11%), *Corylus* (6%), *Alnus* (3%), *Betula* (1.6%), *Ulmus* (1.2%), *Ostrya* (1.2%) and *Tilia* (0.7%) form a mixed temperate woodland, possibly with *Quercus ilex* (2.5%) and *Fagus* (1.7%), respectively at lower and higher altitudes. *Vitis* becomes more frequent. Ericaceae (2.4%) spread and occupy dry and poor soils. Amongst the herbs, Poaceae significantly increase from this zone onwards makes up most of the herbaceous pollen, along with Cyperaceae. *Artemisia* has a clear and definitive decline resulting in a higher diversity of other herbaceous taxa typical of more mesic grasslands (e.g. Caryophyllaceae, Chenopodiaceae, Fabaceae, Apiaceae, *Sanguisorba officinalis*, *Potentilla*, *Filipendula*, *Plantago*, *Centaurea*, *Cirsium* and *Achillea*). The increasing abundance of microcharcoal (~2400 fragments cm^{-2} yr^{-1}) may suggest sustained human impact on the environment (see 5.2).

LPAZ PdL-7b (~*3205-0* cal BP, 170-0 cm): During this final part of the sequence *Abies* values drop (2.9%) and *Pinus* continues to decrease (7%). *Fagus*, *Tilia* and *Carpinus* almost disappear from the area (both 0.2%). Despite a decline in deciduous *Quercus* (16.5%), broadleaves dominate the landscape. The appearance of *Castanea* (2%), *Olea* (1%) and *Juglans* (0.4%), which are important indicators of human activity throughout the Mediterranean, testifies their cultivation. Ericaceae remain abundant (7%). After reaching minimum values, corresponding to a spread of woodland cover, Poaceae (26%) increases again and, together with Cyperaceae (26%), Juncaceae (3.5%) and *Sanguisorba officinalis* (10%) dominate the herbaceous layer, probably reflecting hydrological changes in the basin catchment. Cichorioideae, *Plantago* and *Rumex* show isolated peaks and, together with Cerealia, Caryophyllaceae and *Centaurea*, represent indicators of human activity (Behre, 1981; Branch, 2004). The peak in fern spores together with an increase in microcharcoal (~3200 fragments cm^{-2} yr^{-1}) indicate an important role of fire in the vegetation succession, possibly due to periods of higher human activity. The abundance of unidentified pollen grains suggests caution in the interpretation of the upper part of the sequence.

5. Discussion

5.1 Upper Late Pleistocene

Our data from Pian del Lago indicate that the northern Apennines undoubtedly experienced periods of abrupt climatic and vegetation changes during the upper Late Pleistocene. The record is unique for this part of Italy and is one of the few terrestrial sedimentary deposits spanning the last glacial stage in southwestern Europe (see Allen and Huntley, 2000; Fletcher et al., 2010). It thus permits improved understanding of the spatial and temporal patterns of vegetation succession, and the possible causes of these changes. Although the radiocarbon dated pollen stratigraphy from Pian del Lago marshland does not have the geochronological precision of other central and southern Italian longer lake sequences, such as Lago Grande di Monticchio (Allen et al., 1999; Watts, 1985; Watts et al., 1996a,b) and Valle di Castiglione (Follieri et al., 1988), it does permit a broad correlation with these records, as well as with Mediterranean marine sequences (Cacho et al., 2001) and the Greenland ice core records (Rasmussen et al., 2014) (Fig. 5 and Fig. 6). Correlation with these sequences is dependent upon specific pinning points, most notably the termination of the Würm glacial stage at ~14,300 cal. BP, the onset of the Holocene at ~11,700 cal. BP, and the expansion of pollen of woody taxa reflecting ameliorating climatic conditions (see Fletcher et al., 2010; Pini et al., 2010; Magri et al., 2015).

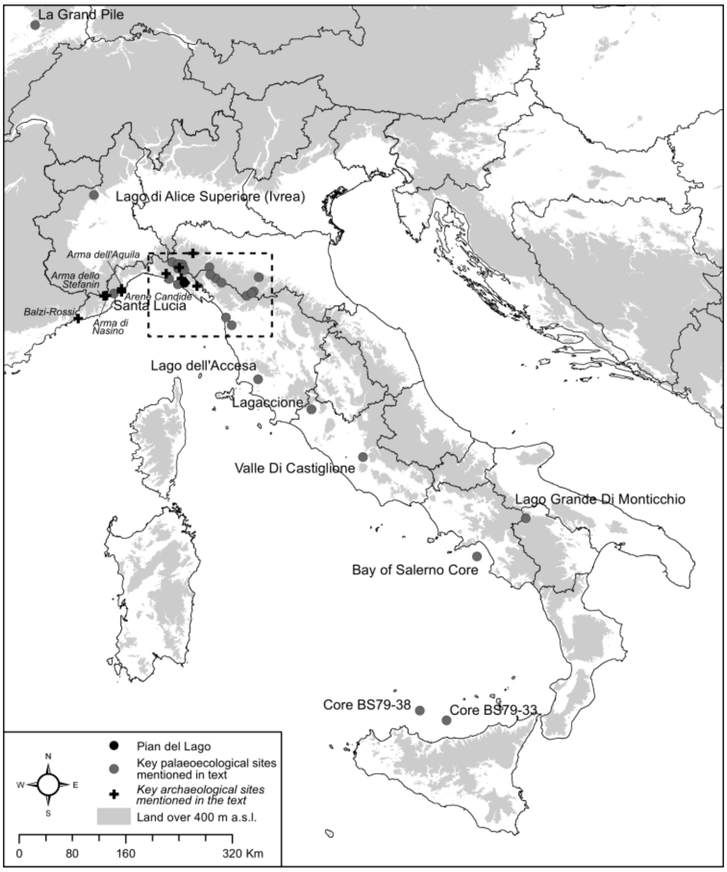

Fig. 5: Key Late Pleistocene and Holocene palaeoenvironmental and palaeoclimatic records from southwestern Europe mentioned in the text

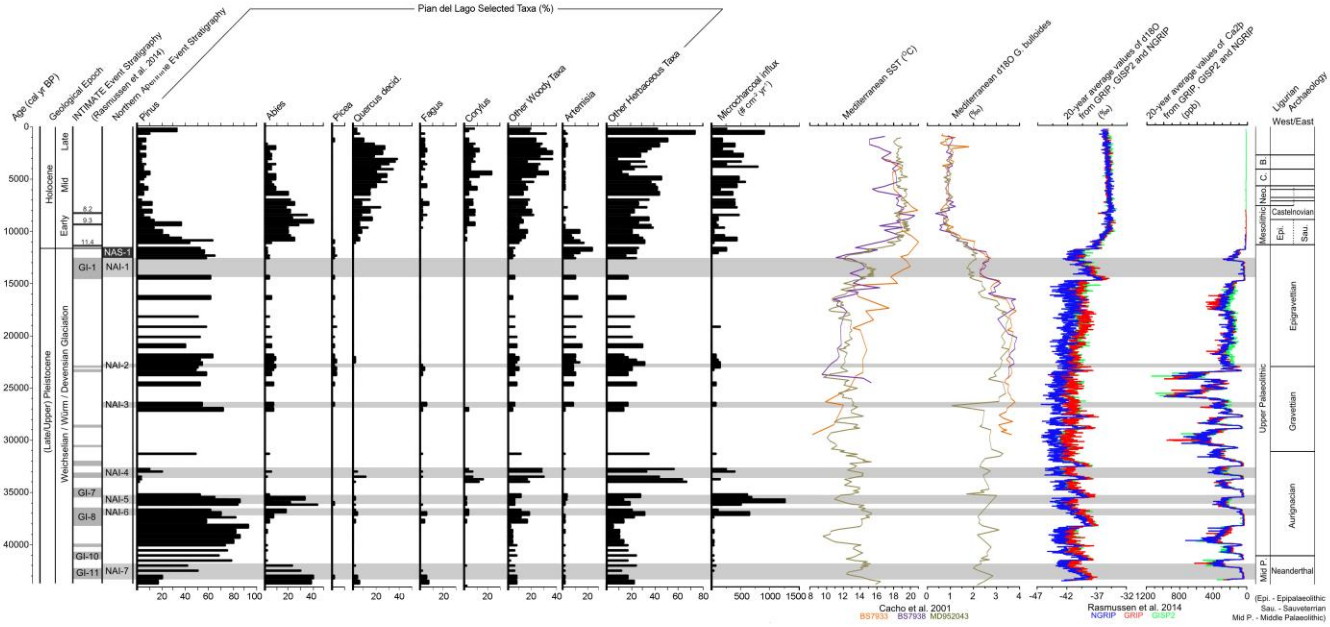

Figure 6: Selected taxa pollen diagram and event stratigraphy compared with the ice core and marine records, and INTIMATE event stratigraphy; grey bands indicate interstadial events identified in this research (in color online)

Several of the pollen-stratigraphical changes from Pian del Lago are interpreted here as vegetation responses to relatively mild climatic conditions (interstadial), in contrast to intervening colder climate phases (stadial). The biostratigraphical signature for the transition to interstadial conditions is highlighted by a seemingly 'abrupt' change to mesophilous woodland succeeded by the onset of cooler conditions indicated by a reduction in tree cover, poor pollen preservation and/or a major change in sedimentary deposition. Based on this assumption, we believe that they can be correlated with several of the well-recorded climatic fluctuations known as Dansgaard-Oeschger (D – O) events (Dansgaard et al., 1989; Rasmussen et al., 2014). Due to geochronological uncertainties and the poor pollen preservation of some parts of the sequence, the precise duration of each interstadial event at Pian del Lago is unclear, but it certainly appears that they varied considerably. Based on the ice core records for the D – O events, it is also acknowledged that the same climatic event may not have occurred at precisely the same time in different regional scale archives due to transmission variability in oceanic and atmospheric D-O changes (Moreno et al., 2014). For this reason, and following published protocols (Rasmussen et al., 2014), we decided to label the events recorded at

Pian del Lago as a Northern Apennine Interstadial (NAI) or a Northern Apennine Stadial (NAS) with an associated number, and attempted a correlation with the Greenland ice core records (GI and GS for interstadial and stadial, respectively), different Mediterranean marine sequences, and various central and southern Italian lake records (Table 4; Fig. 5 and Fig. 6; see Bosselin and Djindjian, 2002).

Pian del Lago local pollen assemblage zone (LPAZ)	**Event stratigraphy - northern Apennines**	**Lago Grande di Monticchio pollen zone (Allen et al., 2000)**	**Valle di Castiglione (Follieri et al., 1988)**	**INTIMATE event stratigraphy (Rasmussen et al., 2014)**
PdL-6b *~11,600-10,760* cal. BP	Start of Holocene	1 11,200 – present (11,200)	Holocene	Start of Holocene
PdL-6a *~12,480-11,600* cal. BP	NAS-1 *~12,480-11,560* cal. BP	2 12,800 – 11,200 (1600)	Younger Dryas	GS-1 *~12,896-11,703* a b2k
PdL-5 *~30,380-23,655* to *~13,430-11,310* cal. BP (*~26,880-12,480* cal. BP)	NAI-1 *~14,360-12,480* cal. BP	3 14,300 – 12,800 (1500)	Late Glacial Interstadial	GI-1 (1a-1e) *~14,692-13,099* a b2K
	NAI-2 *~23,030-22,800* cal. BP	4 25,900 – 14,300 (11,600)	Full Glacial	GI-2.1 *~23,020-22,900* a b2k
	NAI-3 *~26,880-26,400* cal. BP	5a 29,400 – 25,900 (3500)	Lazio VI and VII	No event
PdL-3 *~36,380-34,630* to *~34,400-31,080* cal. BP (*~35,470-33,250* cal. BP)	NAI-4 *~33,860-32,650* cal. BP	6 34,900 – 31,800 (3100)		GI-6 (*~33,740-33,360*) and GI-5 *~32,500-32,040* (5.2) and *~30,840-30,600* (5.1) a b2k
PdL-2 *~44,740-38,310* to *~36,380-34,630* cal. BP (*~41,950-35,470* cal. BP)	NAI-5 *~36,050-35,160* cal. BP	7 36,500 – 34,900 (1600)	Lazio IV	GI-7 *~35,480-34,880* a b2k
	NAI-6 *~37,130-36,650* cal. BP	8 37,600 – 36,500 (1100)		GI-8 *~38,220-36,580* a b2k
PdL-1b *~45,230-41,070* to *~44,740-38,310* cal. BP (*~43,440-41,950* cal. BP)	NAI-7 *~43,440-41,950* cal. BP	11 50,000 – 42,300 (7700)	Lazio II	GI-11 *~43,340-42,240* a b2k

Table 4: Event stratigraphy for the northern Apennines

From ~*43,440-41,950* cal. BP (NAI-7), the vegetation succession at Pian del Lago was characterized by the expansion of *Abies* and *Pinus*, as well as *Fagus*, *Quercus* (both deciduous and *Q. ilex*) and *Picea*. The predominance of these taxa also at Lago di Alice Superiore (Piedmont, northern Italy; Figure 5) suggests similar climatic conditions north of the Po Plain (Gianotti et al., 2015). At Valle di Castiglione (Lazio, central Italy; Figure 5), woodland mainly composed of *Picea*, *Fagus*, *Ulmus* and deciduous *Quercus* dominated during the Lazio II interstadial (Follieri et al., 1988, 1990, 1998). Similarly, at Lago Grande di Monticchio (Basilicata, southern Italy; Figure 5), the open woodland comprised *Quercus*, *Fagus* and *Abies*, with *Tilia*, *Ulmus* and *Fraxinus* (Allen et al., 2000). A marine record from the Bay of Salerno (Campania, southern Italy; Figure 5) similarly indicates this period favorable to meso-thermophilic vegetation (Russo Ermolli and Di Pasquale, 2002). The data from Pian del Lago are however quite different from several other southern European records that indicate a predominance of microtherm conifers (*Pinus*, *Picea* and *Larix*) or just a few broadleaved trees (deciduous *Quercus, Betula*, *Corylus*) (e.g. Peyron et al., 1996; Willis et al., 2000; Woillard, 1978). Instead the dominance of mesophilous trees at Pian del Lago, which are similar or even higher to those recorded during the Late Holocene, clearly indicate a temperate-humid climate. The record also appears to confirm the existence of a temperature gradient between northern/central (cooler) and southern (warmer) Italy based upon the presence (or absence) of *Picea* (see Allen et al., 2000; Beaudouin et al., 2005; Fletcher et al., 2010). According to Rasmussen et al. (2014), NAI-7 may be equated with Greenland Interstadial 11 (GI-11; ~*43,340-42,240* a b2K; Table 4). The timing also suggests a tentative correlation with the Hengelo Interstadial of north-western Europe (Behre and van der Plicht, 1992; Helmens, 2013; Rasmussen et al., 2014; Vandenberghe and van der Plicht, 2016).

From ~*37,130-36,650* cal. BP (NAI-6), the vegetation cover at Pian del Lago was characterized by the presence of *Corylus* and *Abies*, as well as *Pinus*, *Quercus, Alnus* and *Fagus*, and may be equated with Greenland Interstadial 8 (GI-8, ~38,220-36,860 a b2K; Table 4). There is no indication at Pian del Lago for the interstadial event evidenced during pollen zone 9 at Lago Grande di Monticchio and denoted by Lazio III at Valle di Castiglione (Follieri et al., 1998). Instead, NAI-6 chronologically correlates with zone 8 at Lago Grande di Monticchio (characterised by steppic vegetation dominated by *Artemisia*; Allen et al., 2000). As noted above, this difference in timing for the D-O event may be due to transmission variability between different parts of southwestern Europe or alternatively chronological uncertainties within the age models.

Between ~*36,050* and *35,160* cal. BP (NAI-5) the expansion of *Abies*, *Pinus*, and *Artemisia* at Pian di Lago indicates a further increase of wooded steppe vegetation, also recorded by Allen et al. (2000) at Lago Grande di Monticchio during pollen zone 7 (*Betula*, *Quercus, Ulmus* and *Fagus*), and by Follieri et al. (1998) during Lazio IV at Valle di Castiglione (deciduous *Quercus*, *Corylus*, *Fagus*, *Tilia*, *Ulmus* and *Carpinus*). Although the event appears to be chronologically correlated with the early stages of Greenland Interstadial 7 (GI-7, ~35,480-34,880 b2K), once again there is no clear sub-division of GI-7 based on the pollen data (GI-7a, b and c) (Table 4). The timing also suggests a tentative correlation with the Danekamp I Interstadial of north-western Europe (Behre and van der Plicht, 1992; Bosselin and Djindjian, 2002; Helmens, 2013; Rasmussen et al., 2014; Vandenberghe and van der Plicht, 2016).

During the period ~*33,860-32,650* cal. BP (NAI-4) the vegetation succession at Pian di Lago was characterized by the expansion of *Corylus*, as well as *Pinus* and *Quercus*. Similarly, at Berceto (Emilia Romagna, northern Italy, Figure 1), the presence of *Pinus* and *Picea* forests support the occurrence of a warming event (Bertoldi et al., 2007). According to our findings, this may be equated with either Greenland Interstadial 6 or 5 (GI-6 and 5; ~*33,740-30,600* a b2K), or possibly both, with no clear stadial events (GS-6 and GS-5.2). However, this event appears to be chronologically correlated with Lago Grande di Monticchio pollen zone 6 (Table 4), a stadial event (Allen et al., 2000), which is anomalous. Tentatively, the event may be correlated with the Danekamp II / Arcy Interstadial of north-western Europe (Behre and van der Plicht, 1992; Bosselin and Djindjian, 2002).

From *35,470-33,250* cal. BP, the Pian di Lago pollen record is interrupted by the deposition of Serpentinite, suggesting major erosion in the catchment area. The chronology indicates that this event occurred between GI-7 and GI-6 and may reflect a deterioration in climate (stadial). Support for this interpretation is provided by both the marine and ice core records, and it may be equated with GS-7, a colder climatic event dated to ~34,740 a b2K (Cacho et al., 2001; Rasmussen et al., 2014).

A second major erosional event indicated by the deposition of Serpentinite occurred at Pian del Lago between ~*33,220* and *26,880* cal. BP. Both the chronology and the comparison with marine and ice core records suggest that this episode may be equated with Heinrich 3 (~*30,000-29,000* cal. BP) or GS-5.1 (~*30,600-28,900* a b2K), or possibly GS-4 (~*28,600-27,780* a b2K) and GS-3 (~*27,540-23,340* a b2K) (Guiot et al., 1993; Rashid and Grosjean, 2006; Rasmussen et al., 2014). The increase in herbaceous taxa supports the existence of cooler conditions. The absence of clear biostratigraphical evidence for GI-4 (~*28,900-28,600* a b2K) and GI-3 (~*27,780-27,540* a b2K) during the zone is interesting, although the reason remains unknown (Rasmussen et al., 2014). In contrast, at Berceto, pollen zone BER-4 has been tentatively correlated with the Tursac Interstadial of north-western Europe, occurring sometime after 34,325-33,191 cal. BP (29,620 ±290 BP) and characterised by the presence of *Pinus* and *Picea* forests (Bertoldi et al., 2007).

During the period *~26,880-26,400* cal. BP (NAI-3) the vegetation cover at Pian del Lago is dominated by *Pinus* with *Abies*, *Betula*, *Picea*, *Fagus* and deciduous *Quercus*. This diverse range of taxa has been correlated with Lago Grande di Monticchio pollen zone 5a (Table 4; Allen et al., 2000). In agreement with the Pian del Lago sequence, this detailed record indicates an increase in woody taxa (especially *Pinus*), suggesting warmer conditions. Interestingly, this event cannot be linked with the ice core records (Rasmussen et al., 2014), but it does correlate with a major excursion in the δ18O marine record from the Mediterranean (Cacho et al., 2001) as well as with Lazio VI and VII Interstadials of central Italy (Follieri et al., 1998) (Figure 6). For this reason, NAI-3 should be regarded as a highly significant climatic event in the northern Apennines that may require revision of the ice core event stratigraphy given the clear evidence in Figure 6 for climatic amelioration at this time (see Rasmussen et al., 2014).

At Pian del Lago, the presence of high pollen values of *Artemisia*, along with many other herbaceous taxa, between ~*26,400* cal. BP (~*29,930-23,400* cal. BP) and ~*9970* cal. BP (~*10,270-9620* cal. BP) is of significance for several reasons:

(1) At ~*26,400* cal. BP, it coincides with a sustained increase in *Pinus* and *Abies*. This persists until approximately ~*19,040* cal. BP (~*20,980-17,870* cal. BP), when *Abies* declines and there is a temporary reduction in *Pinus*. This is also concurrent with the formation of diatomite at Pian del Lago. Thereafter, *Pinus* re-expands until ~*10,640* cal. BP (~*11,270-10,090* cal. BP), when it is succeeded by *Abies* and *Quercus*. Throughout this period, the high presence of *Artemisia* indicates the existence of an open steppe woodland and shrubland cover, perhaps benefitting from climatic amelioration following the Last Glacial Maximum, which may have favoured soil development and the colonisation of a more diverse range of taxa. Our suggestion is supported by the ice core records, which arguably indicate a more sustained period of stable climatic conditions from ~23,340 (GI-2.2) and ~23,030 (GI-2.1) a b2K, and throughout Greenland Stadial 2.1 (GS-2.1), which spans the period 22,900-14,692 a b2K (Rasmussen et al., 2014). This overall trend is also reflected in the

Mediterranean marine sequences (Cacho et al., 2001). GI-2.2/GI-2.1 has been correlated with the Laugerie Interstadial of north-western Europe (~23,500-22,000 cal. BP), whilst at Berceto, Bertoldi et al. (2007) have tentatively linked the temporary expansion of *Pinus* and *Picea* at this time with the Lascaux Interstadial (~21,000-20,000 cal. BP) (Behre and van der Plicht, 1992; Bosselin and Djindjian, 2002).

(2) The 'Younger Dryas' chronozone, a stadial event conventionally placed between ~12,900 and 11,700 a b2k (GS-1 starts at ~12,896 a b2K in the ice core records; Rasmussen et al., 2014), has been recorded in a number of terrestrial and marine sequences in southwestern Europe, including the northern Apennines, and is characterised by the prevalence of a colder/drier climate (e.g. Lowe, 1992; Ponel and Lowe, 1992; Lowe and Watson, 1993; Lowe et al., 1994a, b; Watson, 1996; Cita et al., 1996; Watts et al., 1996a, b; Bertoldi et al., 2007; Vescovi et al., 2010a,b). The notable increase in *Artemisia* pollen values at Pian del Lago from *~12,480-11,600* cal. BP may be assigned to the 'Younger Dryas' (PdL-6a, NAS-1; Table 4). At Prato Spilla C (Emilia Romagna, northern Italy; Figure 5), the marked decline in *Quercus* and the expansion of a range of steppe herbs, including *Artemisia*, provides the clearest evidence for the event in the northern Apennines (Lowe, 1992), whilst it can be correlated with Lago Grande di Monticchio pollen zone 2 (Allen et al., 2000; de Beaulieu et al., 2017). The presence of an additional site in the northern Apennines with evidence for the 'Younger Dryas' stadial is an important confirmation of the widespread impact of this event in southwestern Europe.

(3) The persistence of *Artemisia* until *~9970* cal. BP is surprising, especially given the clear evidence for the expansion of those warmth loving taxa that characterise the early postglacial. This may reflect an ongoing landscape instability rather than a climate signal, which is supported by the continued deposition into the Pian del Lago basin of mineral-rich sediment rather than organic-rich sediments.

Prior to the onset of GS-1, there are records in the northern Apennines for GI-1, a pronounced interstadial lasting ~1500 years (~*14,692-13,099* b2K) documented in the ice core records (Rasmussen et al., 2014; Table 4). Despite the evidence for a *Pinus* dominated woodland at the beginning (~*14,360* cal BP) and at the end (*12,480* cal. BP) of this phase, the presence of this event at Pian del Lago is unclear. This may be attributed to either poor pollen preservation, or to a muted response to a warmer period in this part of the northern Apennines. At Prato Spilla C (from ~>*14,350* cal BP), the Interstadial was characterised by the expansion of warm mixed forest including *Quercus*, *Tilia*, *Betula* and *Corylus* (Lowe, 1992), whilst at Lago Grande di Monticchio broadleaved deciduous forests with *Quercus*, *Corylus*, *Fagus*, *Ulmus*, *Tilia* and *Alnus* were present (Allen et al., 2000).

5.1.1 Palaeolithic Cultural History

The upper Late Pleistocene vegetation history and event stratigraphy from Pian del Lago can be correlated with main cultural changes occurred in the wider region, including the Maritime Alps (western Liguria) and the northern Apennines. PdL-1a (> ~*43,400* cal. BP) and PdL-1b (> ~*43,400-41,940* cal. BP) can be equated with the late Middle Palaeolithic. Lithic tools (Neanderthal) attributed to the Middle Palaeolithic have been found near Pian del Lago, as well as other sites in the northern Apennines (e.g. Pianaccia di Suvero, Liguria; Ronco del Gatto, Emilia-Romagna). It is tempting to correlate NAI-7 (~*43,440-41,950* cal. BP) with a phase of late Neanderthal activity at Pian del Lago, although the lack of precisely dated, well-stratified archaeology makes this association uncertain.

During the Upper Palaeolithic (~42,000-11,000 cal. BPPdL-2 to PdL-6a), the presence of six interstadials at Pian del Lago (NAI-6 to NAI-1) provides considerable potential for examining the relationships between human activity, climate variability and environmental change (see Kaniewski et al., 2005; Maggi, 2015). The Aurignacian (~42,000-34,000 cal. BP in Italy; Mussi et al., 2006) has provided approximately 30 known sites in Italy, and only a small number of these are from the Maritime Alps and northern Apennines (e.g. Pian del Lago, Balzi Rossi sites, Ronco del Gatto; Mussi et al., 2006). The sequence at Mochi (Balzi Rossi), for example, has a stone tool assemblage indicating population movement between southern France, the Maritime Alps, northern Apennines and the Adriatic coast, and the exploitation of a range of animals. Several key radiocarbon dates spanning ~41,500-37,500 to ~38,000-35,000 cal. BP (level G) encompass both NAI-6 (*~37,130-36,650* cal. BP) and NAI-5 (*~36,050-35,160 cal. BP*). Whether occupation was facilitated by periods of warmer (interstadial) climate remains unclear due to chronological uncertainties. Nevertheless, the pollen data from Pian del Lago provide a valuable insight into the environment occupied by earliest European Modern Humans in this part of the northern Apennines.

During the Gravettian (~34,000-20,000 cal. BP in Italy), lithic tools have once again discovered at Pian del Lago and Ronco del Gatto, as well as at the cave of Arene Candide in the Maritime Alps (Pettitt et al., 2015). The latter has provided stratified radiocarbon dates from charcoal and human remains, e.g. an age of ~27,899-27,338 cal. BP from a human femur (known as 'Il Principe') spanning GS-4 (starts ~28,600 a b2k), GI-3 (starts ~27,780 a b2k) and GS-3 (starts ~27,540 a b2k) of the Greenland ice core event stratigraphy (Rasmussen et al., 2014). Whether the period of occupation is correlated with the ameliorating conditions of GI-3 is uncertain without further dating evidence. Therefore, once again the absence of enough well-stratified, precisely dated sites means that comparison with the event stratigraphy from Pian del Lago (NAI-4 ~33,860-32,650 cal. BP; NAI-3 ~26,880-26,400 cal. BP; NAI-2 ~23,030-22,800 cal. BP) is unfortunately problematic.

The Epigravettian cultural period (~20,000-11,000 cal. BP in Italy) witnesses an important increase in evidence for human occupation in the Maritime Alps, but unfortunately there is little evidence from the northern Apennines. Charcoal records from cave sites (e.g. Arene Candide, Arma di Nasino, Arma dell' Aquila and Arma dello Stefanin; Barker et al., 1990) indicate the exploitation of regional vegetation composed of *Abies* and *Pinus*. During the Lateglacial Interstadial (NAI-1, ~*14,360-12,480* cal. BP, from Pian del Lago), charcoal data from Arma dello Stefanin and isotopic data from Arene Candide (Barker et al., 1990) suggest a significant climatic oscillation with an increase in mean annual temperature to 8-10 ^{o}C, and the exploitation of more thermophilous vegetation, such as *Quercus pubescens*, *Q. ilex*, *Corylus*, *Acer*, *Ulmus*, *Fagus*, *Alnus*, *Ostrya/Carpinus* and *Prunus*. Arene Candide has also provided a unique insight into Epigravettian funerary practices, which are believed to represent a social response to harsh climatic conditions during the Younger Dryas stadial (NAS-1, ~*12,480-11,560* cal. BP, from Pian del Lago) (Sparacello et al., 2018). It is tempting to suggest therefore that the archaeological records indicate a response by human groups to late-glacial climatic variability both in terms of an adaptation to changing resource availability, and transformation of socio-cultural practices.

5.2 Holocene

The transition to the Early Holocene at Pian del Lago (~*11,600* cal. BP, PdL-6b) is marked by the progressive expansion of mesophilous woodland dominated by *Abies* and the decline of *Pinus*, probably *P. mugo*. Broadleaved woodland, such as deciduous *Quercus*, *Alnus, Betula*, *Corylus and Fagus* are still scarce, but are gradually starting to increase. This is consistent with previous work at Pian del Lago, which indicates the main expansion of *Abies* from *12,220-10,910* (start of Bg2) to *11,270-10,170* (start of Bg3) cal. BP (Cruise 1990a, 1990b; Cruise et al., 2009). At ~*9970* cal. BP (290 cm), there is unequivocal evidence for a major environmental change, which may be linked to ameliorating climatic conditions of the Early Holocene. This is marked by the formation of peat and a decline of *Pinus* and *Artemisia*, and a spread of broadleaved trees, namely deciduous *Quercus*, *Q. ilex*, *Corylus*, *Alnus*, *Fagus*, *Ostrya*, *Tilia*, *Ulmus* and *Fraxinus*, and mesophilous conifers (*Abies*) and heathland (Ericaceae). This is partly in agreement with the findings of Cruise et al. (2009) who record the main period of peat initiation shortly before 9550-9090 cal. BP (from 259 cm) in core Barg94. However, the authors also record peat formation shortly after *12,220-10,910* cal. BP (from

396 cm) in core Bg89. This indicates intra-site differences in the timing of the event, which may be attributed to sub-surface topographical variability and proximity of the core to the basin edge.

The sustained evidence for burning at Pian del Lago during the Early Holocene based on microcharcoal data could be due to human activity. During the Mesolithic (~11,000-7800 cal. BP) the primary zone of human occupation was seemingly in the northern Apennines rather than the Maritime Alps (see 5.1). There is extensive indication of human activity (e.g. Pianaccia di Suvero, Passo della Camilla, Bosco delle Lame) characterised by rich artefactual assemblages, including scalene triangles, truncated and backed blades, bilateral backed points and microburins made from jasper and flint (Biagi and Maggi, 1984; Maggi, 1999; Maggi, Negrino, 2016). These sites suggest increasing exploitation at higher altitudes and principally around inter-montane basins. At Mogge di Ertola (Liguria), for example, sedimentological and pollen data suggest deforestation by burning during the Late Mesolithic (Cevasco et al., 2013). Alternatively, the increased fire frequency could be related to drier climatic conditions during the Early Holocene, and possibly periods of short-term climate change. There is no pollen evidence for the '9.3' climatic event (~*9350-9240* a b2K, respectively) at Pian del Lago, although there is possible evidence for the '11.4' (~*11,520-11,400* b2K – Pre-Boreal Oscillation) and '8.2' (~*8300-8140* a b2K) events; the former is marked by high percentages of *Artemisia* pollen together with *Pinus mugo*, *Juniperus* and *Betula* (c.f. Di Rita et al., 2013, 2015; de Beaulieu et al., 2017), whilst the latter is marked by a temporary decline in *Abies* woodland, which is also recorded in other parts of the northern Apennines (Branch, 2013; Cruise et al., 2009; Lowe, 1992; Watson, 1996). During the earliest part of the Holocene (~11,500-10,500 cal. BP) aridity has been used to explain the hiatus in sedimentation at several northern Apennines sites, while the expansion of *Corylus* and the temporary decline of *Abies* has been connected to higher summer temperatures and drought causing an increase in fire events (see Branch, 2013; Finsinger et al., 2006; Mercuri et al., 2011; Peyron et al., 2011).

Cruise et al. (2009) suggested that fluctuating values of *Abies* and the presence of cereal pollen at Pian del Lago between ~*8450-7880* and ~*8050-7550* cal. BP (start and end of Bg3b) were associated with human activity (Early Neolithic). Throughout the Middle Holocene, *Abies* values continued to vary whilst herbaceous and heathland taxa increased suggesting increasing human impact on the environment. In addition to these previously published results, the present study also underlines significant evidence for sustained burning activity in the area probably connected to the use of agro-silvo-pastoral practices during the Neolithic, Copper Age and Bronze Age (see Colombaroli et al., 2007, 2008; Tinner et al., 1999).

However, archaeological evidence for the Early Neolithic *'Impressa Ligure'* Pottery Culture (~7800-7000 cal. BP) and the Middle Neolithic Square Mouthed Pottery Culture (~7000-6300 cal. BP) is mainly confined to the Maritime Alps (e.g. Barker et al., 1990; Biagi et al., 1987; Maggi, 1990; Rowley-Conwy, 1997). Indeed, the western part of Liguria has provided the earliest records of Neolithic occupation in North-Central Italy (e.g. Arene Candide cave). The evidence suggests movement of human communities over considerable distances, including parts of the northern Apennines, to exploit clay, flint and obsidian. Subsistence practices included the cultivation of *Triticum* spp., *Hordeum* spp., *Lens culinaris* and *Vicia* (Nisbet, 2006), and animal husbandry (Rowley-Conwy, 1997). Charcoal records indicate the exploitation of *Quercus pubescens*, *Q. ilex*, *Acer*, *Fraxinus*, *Ulmus*, *Fagus*, *Pinus*, *Pistacia*, *Phillyrea*, *Olea*, *Taxus*, *Erica arborea* and *Arbutus unedo* (e.g. Nisbet, 1997). By the Late Neolithic Chassey Culture (~6300-5700 cal. BP), intensification of animal husbandry and cultivation had reduced the diversity of woodland taxa, especially deciduous trees, in the Maritime Alps and probably led to the formation of 'Mediterranean macchia' dominated by *Quercus ilex*, *Arbutus unedo*, *Erica arborea*, *Rhamnus alaternus*, *Phillyrea*, *Olea* and *Pistacia lentiscus* (Girod, 1997; Maggi and Nisbet, 1990; Nisbet, 1997).

Despite the considerable lower number of known Neolithic archaeological sites in the northern Apennines compared to the Maritime Alps (e.g. Pianaccia di Suvero; Biagi et al., 1987; Maggi, 1983), palaeoecological results from several records (e.g. Braggio Morucchio et al., 1989; Cruise, 1990a, 1990b; Branch, 2002, 2004, Cruise et al., 2009) have provided consistent evidence for increasing human impact on the environment (e.g. burning activities, pastoralism, cultivation), supporting our results from Pian del Lago:

a) The vegetation succession from *Abies* and *Corylus* to deciduous *Quercus*, *Q. ilex* and *Erica arborea* together with the presence of cereal pollen during the Early Neolithic at Sestri Levante and Rapallo (<100 m asl) (Bellini et al., 2009b).

b) The temporary reduction in *Abies* woodland during the Late Mesolithic/Early Neolithic transition (from ~8100 cal yrs BP) accompanied by evidence for burning, increase in herbaceous taxa and expansion of *Fagus* and *Corylus* woodland at Mogge di Ertola (1015 m asl) (Guido et al., 2013).

c) An increase in light loving taxa (i.e. *Fraxinus* and *Ostrya*), a slight reduction in *Ulmus* woodland, the expansion of *Fagus* woodland (~6100 cal yrs BP) and the beginning of a sustained decline in *Abies* during the Middle Neolithic and early part of the Late Neolithic at Lago Riane (1279 m asl) (Branch, 2013).

d) The decline in *Ulmus*, *Tilia* and *Fraxinus* (~7000 cal. BP), during the Middle Neolithic at Prato Spilla ‘A’ (Lowe et al., 1994a, 1994b).

e) The decline in *Abies* and expansion of *Fagus* from ~7000-5000 cal. BP at Lago del Greppo (Vescovi et al. 2010a).

f) The decline of *Abies* at ~6000 cal. BP at Pavullo and Lago di Massaciuccoli (Colombaroli et al., 2007; Mariotti-Lippi et al., 2007; Vescovi et al., 2010b).

From ~*3205* cal. BP (170 cm; PdL-7b) peat formation at Pian del Lago ends and is substituted by clay deposition and possible lowering of the summer water table, which resulted in poor pollen preservation. However, there is a clear anthropogenic signature in the palaeoecological record with an abundance of microcharcoal fragments indicating the use of burning activities in the area, a reduction in woodland taxa, the evidence for *Castanea*, *Juglans*, *Olea* and *Vitis* cultivations, as well as the presence of nitrophilous taxa (i.e. Chenopodiaceae, *Plantago* and *Rumex*) probably connected to grazing practices. These findings are consistent with those of Cruise et al. (2009) who also recorded a notable reduction in *Abies* and other tree taxa associated with burning. However, in contrast to the current study, these authors concluded that the charcoal evidence indicated “light, controlled burning” (p. 999) rather than woodland clearance by fire. In our opinion, this is unlikely given the significant rise in microcharcoal influx and the deposition of colluvium in the basin, suggesting a sustained period of landscape disturbance consistent with woodland clearance from the Late Bronze Age and Iron Age onwards.

This conclusion is consistent with the archaeological evidence, which clearly indicates that the pattern of human settlement and subsistence shifted from a dependence on the exploitation of lowland and coastal resources to a greater dependence on upland resources during the Copper Age (~5800-4200 cal. BP) and Bronze Age (~4200-2900 cal. BP). Sites are concentrated at altitudes between 400 m and 800 m asl (Bronze Age 'Castellari'), along watersheds and mountain hilltops (e.g. Uscio, northern Apennines) that are considered important strategic locations for access to mountain pastures (transhumant pastoralism), although artefactual remains have also been located at higher elevations. The period also witnesses the initiation of large-scale Copper Age mining (Maggi and Pearce, 2005, 2013), and the introduction of agricultural terracing during the Middle Bronze Age (~3800 cal. BP; Maggi, 2004). As noted above, there were pronounced changes in the vegetation and environment during this period, and into the Iron Age and historic periods, which have been attributed to human activities including cultivation, animal husbandry and woodland management (e.g. *Juglans, Castanea* and *Olea*). The impact of climate change remains uncertain, but there is an increasing body of evidence to indicate that both human activities and vegetation succession were occasionally affected by abrupt events, e.g. 4200 cal. BP (Branch, 2013; Di Rita and Magri, 2019).

6. Conclusions

The palaeoenvironmental data presented here confirm the importance of Pian del Lago as a unique biostratigraphic archive for reconstructing the environmental history of the northern Apennines. In particular, the results of pollen analysis have made it possible to shed light on the upper Late Pleistocene and Early Holocene; periods poorly documented in this geographical area. The identification of seven interstadials from ~*43,000* cal. BP to the beginning of the Holocene is of considerable significance for our understanding of vegetation response in southwestern Europe to periods of abrupt climate change. Overall, the record indicates that for much of the upper Late Pleistocene, steppic taxa (mainly *Artemisia* and Chenopodiaceae) with shrubland of *Juniperus, Salix* and *Ephedra,* typical of central and northern Europe, were less prevalent in the northern Apennines. Tree species (e.g. *Pinus, Abies* and *Alnus*) apparently persisted throughout the period, although it should be noted that phases of poor pollen preservation (possibly equated with stadials) may have resulted in an expansion of steppic taxa. The presence of herbaceous taxa throughout the Pian del Lago sequence nevertheless indicates that the woodland was open in structure, supporting the hypothesis advocated for greater moisture stress during this period (cf. Allen and Huntley, 2000; Fletcher et al., 2010).

As noted, the chronological uncertainties associated with the Pian del Lago sequence preclude detailed discussion of the rate and duration of the main vegetation changes. The data from Lago Grande di Monticchio indicate, however, that vegetation succession during the upper Late Pleistocene was so rapid that it may have contributed to the magnitude of environmental variations in mountain ecosystems by affecting biogeochemical cycles (Fletcher et al., 2010). If this hypothesis is correct, it would be worth testing by undertaking further multi-proxy palaeoenvironmental and palaeoclimatic research at Pian del Lago (e.g. diatoms, Cladocera, Chironomids) coupled with the development of a chronology of higher precision (e.g. radiocarbon dating, U-series dating and tephrochronology).

The persistence of *Pinus*, *Picea* and *Larix* along with mesophilous taxa (i.e. *Abies*, *Quercus* decid., *Corylus* and *Alnus*) during the Last Glacial Maximum (LGM) is noteworthy. According to Bertoldi et al. (2007), *Picea* was a typical species of interstadial periods in Emilia (eastern northern Apennines), whilst at Pian del Lago it sharply characterises the maximum expansion of the Würm glaciation, along with *Larix*. Today, relict formations of *Picea* near Passo del Cerreto (~60 km from the study site) and Sestaione Valley (~110 km away) can possibly be linked to its expansion in the northern Apennines (cf. Branch and Marini, 2013; Ravazzi, 2002). If regional pollen transportation is excluded, the site of Pian del Lago could therefore have been an intermediate area where *Picea* was present, linking the south-western Alps and the north-western Apennines. This part of the northern Apennines can therefore be regarded as a favourable environment for the persistence - even during climatically unfavourable periods - of relatively demanding vegetation communities creating a refuge for mesophilous species, which then spread across southern Europe during the Early Holocene. Indeed there is now a growing body of palaeoenvironmental research in northern Italy and other parts of Europe indicating the presence of arboreal populations, especially conifers but also mesophilous taxa, during the climatically more hostile phases of the upper Late Pleistocene (e.g. Drescher-Schneider et al., 2007; Guiter et al., 2008; Jalut et al., 2010; Kaltenrieder et al., 2009; Miola et al., 2003; Müller et al., 2003; Willis and Van Andel, 2004; Willis et al., 2000).

Finally, this new investigation at Pian del Lago highlights the importance of using, whenever possible, heavy-duty percussion or rotary drilling equipment to explore basins (large and small) for palaeoenvironmental research. The equipment permitted the recovery of core samples to a much greater depth than the previous investigation (Cruise et al., 2009), which has provided a record of climate and environmental change that is unique to the northern Apennines.

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