2700 years of Mediterranean environmental change in central Italy: a synthesis of sedimentary and cultural records to interpret past impacts of climate on society

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Abstract

Abrupt climate change in the past is thought to have disrupted societies by accelerating environmental degradation, potentially leading to cultural collapse. Linking climate change directly to societal disruption is challenging because socioeconomic factors also play a large role, with climate being secondary or sometimes inconsequential. Combining paleolimnologic, historical, and archaeological methods provides a more secure basis for interpreting the past impacts of climate on society. We present pollen, non-pollen palynomorph, geochemical, paleomagnetic and sedimentary data from a high-resolution 2700 yr lake sediment core from central Italy and compare these data with local historical documents and archeological surveys to reconstruct a record of environmental change in relation to socioeconomic history and climatic fluctuations. Here we document cases in which environmental change is strongly linked to changes in local land management practices in the absence of clear climatic change, as well as examples when climate change appears to have been a strong catalyst that resulted in significant environmental change that impacted local communities. During the Imperial Roman period, despite a long period of stable, mild climate, and a large urban population in nearby Rome, our site shows only limited evidence for environmental degradation. Warm and mild climate during the Medieval Warm period, on the other hand, led to widespread deforestation and erosion. The ability of the Romans to utilize imported resources through an extensive trade network may have allowed for preservation of the environment near the Roman capital, whereas during medieval time, the need to rely on local resources led to environmental degradation. Cool wet climate during the Little Ice Age led to a breakdown in local land use practices, widespread land abandonment and rapid reforestation. Our results present a high-resolution regional case study that explores the effect of climate change on society for an under-documented region of Europe.

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1. Introduction

The extent to which past abrupt climate change has directly resulted in societal disruption or cultural collapse, and the ability of societies to adapt to these changes is strongly debated (Berglund, 2003; Diamond, 2005; Munoz et al., 2010), but is potentially significant for modern communities facing future climate change (Büntgen et al., 2011). Studies concerned with the link between climate and human affairs have increasingly recognized the need to examine societal change in parallel with climate change (Dearing et al., 2008; Coombes et al., 2009; Munoz et al., 2010; McCormick et al., 2012), although the tendency persists among physical
scientists to link cultural shifts directly to climate change (O’Sullivan, 2008; Aimers, 2011). Detailed historical analyses based on precisely dated documents have identified instances when climate has led to significant societal disruption or ‘collapse’, but these analyses also detail multiple examples in which socio-economic factors played the larger role in environmental change, with climate being secondary or inconsequential (Ladurie, 1971). For this reason, it is critical that studies attempting to elucidate the impact of climate on society closely couple paleoecologic methods with historical and archaeological methods (Dearing et al., 2008; O’Sullivan, 2008; Coombes et al., 2009; Harris, 2013).

The relationship between climate change and cultural response can be addressed in areas where multi-proxy studies of cores from lakes with very high sediment accumulation rates can be examined within the context of a well-documented written history (Berglund, 2003). Such a history may provide insights into human adaptive strategies that allowed societies to cope with past climate change (Fraser, 2011). Several recent high-resolution syntheses have drawn a link between climate stability and the expansion, and eventual contraction, of the Roman Empire (Büntgen et al., 2011; McCormick et al., 2012). These studies note that focused regional case studies with highly resolved datasets are still needed to test the potential effect of rapid climate change on human societies. Such datasets are particularly needed in under-documented regions of the Roman Empire, including southern Europe, and the regions near Rome.

In central Italy, archival materials are nearly continuously available from ~700 CE (common era) in the records of the Farfa Abbey (Leggio, 1995a) in northern Lazio, Central Italy, with some written records extending back to the Roman period (De Santis and Coarelli, 2009). These documents provide a written environmental history that can be compared with physical paleoecologic reconstructions. Paleoecologic reconstructions for the last 3000 years are still underrepresented in Italy (Roberts et al., 2004; Magri, 2007) with studies from the southern Alps and North Italy (Kaltenrieder et al., 2010; Joannin et al., 2014), the northern and central Apennines (e.g. Mercuri et al., 2002; Brown et al., 2013; Branch and Marini, 2014), the Tiber Delta (Di Ritz et al., 2010), and southern Italy, Sicily and Sardinia (e.g. Russo Ermolli and di Pasquale, 2002; Di Ritz and Magri, 2009; Tinner et al., 2009; Di Ritz and Melis, 2013; Sadori et al., 2013). These studies record the major changes in vegetation in relation to human activity during this time period but present very different impacts depending on sites and historical periods. In addition, the sampling resolution is generally at the centennial or millennial scale and cannot be easily compared with historical records. The last 3000 years are of particular interest because they encompass several important climatic changes often associated with cultural change, including the Roman Optimum (100 BCE – 200 CE; BCE – before common era), the Medieval Warm Period (MWP), ~950 to 1250 CE, and the Little Ice Age (LIA) ~1250 to 1850 CE, (Büntgen et al., 2011; Christiansen and Ljungqvist, 2017; Büntgen et al., 2011; McCormick et al., 2012) by providing a new site in southern Europe at the center of the Roman Empire. The results contribute to our understanding of Mediterranean forest dynamics and can be used to verify recent efforts to model the history of deforestation in Europe (Kaplan et al., 2009).

2. Study area

Lago Lungo (369 m above mean sea level) is one of four remnant lakes of ancient Lacus Velinus in the Rieti Basin (Fig. 1), an inter-montane depression in the Central Apennines that locally reach an elevation of 2217 m at Monti Reatini (Calderoni et al., 1994). The Velino, Salto and Turano Rivers flow into the basin, which is then drained by the Velino River, which plummets over a travertine sill at Marmore Falls. Other sources of inflow into the basin are numerous artesian springs that lie along the eastern edge of the basin. Water level in the basin is controlled by the elevation of the travertine sill (Calderoni et al., 1994). During prehistoric time, travertine built up during warm periods, raising the sill and expanding wetlands, and alternatively eroded during cold periods draining the valley (Calderini et al., 1998; Soligo et al., 2002). Between ~6000 and 3000 yr BP a large shallow lake (Lacus Velinus) filled the basin (Calderoni et al., 1994). Written documents suggest that the Romans cut a channel through the travertine sill to drain the land in ~270 BCE (Coccia et al., 1992). Since that time, water level in the basin has been controlled periodically by maintaining existing channels and cutting new channels (Lorenzetti, 1889). Historical maps suggest that the size and shape of lakes, their proximity to the Velino River, and the extent of wetlands in the basin has changed through time. Today, Lago Lungo has a maximum depth of up to 7 m with a surface area of 0.78 km2 and surface level maintained at 369 m above sea level (Riccardi, 2006). Inflow is from a network of ditches that drain surrounding wetlands, springs, and farmland. Lago Lungo is protected within Riserva Naturale dei Laghi Lungo e Ripassottile (Riccardi, 2006).

The geology of the region is characterized by recently uplifted marine sediments. The Central Apennines are primarily composed of Upper Triassic to Middle Miocene carbonates (Parotto and Praturlon, 1975; Cosentino et al., 2010). Rieti is a seismically active extensional basin within the Apennine thrust system and is partially filled with Upper Pliocene and Holocene continental and marine sediments (Cavaino and De Celles, 1999; Soligo et al., 2002). Travertine outcrops are present across the basin, associated with past periods of warm wet climate. Seismic activity has influenced the location and discharge of springs responsible for depositing the travertines (Soligo et al., 2002). The largest spring in the basin, Santa Susanna Spring, has a discharge of 4.1 m3 s−1 and is located ~3 km northeast of Lago Lungo (Spadoni et al., 2010).

Modern vegetation is dominated by agriculture in the basin and heavily managed forest on the surrounding slopes. Phragmites and Salix species grow in a narrow (~15 m) band of protected land within the reserve, while beyond the reserve border the basin floor is nearly entirely devoted to agriculture (Casella et al., 2009). Forest vegetation at lower elevations within the basin is characterized by temperate deciduous forest (e.g. Carpinus betulus L., Fraxinus spp., Ulmus campestris Auct.) with an important submediterranean component (Quercus pubescens Willd., Quercus cerris L., Carpinus orientalis Miller; Ostrya carpinifolia Scop.); in the foothills on steep, shallow soils some patches of Mediterranean trees and shrubs (Quercus ilex L., Phyllirea latisiliqua L., Pinus halepensis Miller) are present while in the mountain belt (above 800–900 m) beech (Fagus sylvatica L.) forests are common. Climatically the area is within a transition zone between warm and cool temperate climates with a Mediterranean precipitation pattern characterized by low precipitation during summer. Mean annual temperature varies
between 4 °C in January and 21 °C in July with annual precipitation of 1117 mm (Fig. 4.29 in Leone, 2004). The general temperature and precipitation regime is strongly controlled by the North Atlantic Oscillation (NAO) with warm dry climate predominating during positive phases of the NAO, and cool wet climate during negative phases (Hurrell, 1995; Piovesan and Schirone, 2000; López-Moreno et al., 2011).

3. Materials and methods

3.1. Core recovery

Previous studies of Lago Lungo recovered cores on land near the lakeshore using geologic drilling equipment and subsequently did not recover the upper sediments containing the last few thousand years (Calderoni et al., 1994). For this study, we worked on a floating platform anchored near the center of the lake. Cores were collected in 2009 and in 2012. Water depth at the core site was 4.2 m in 2009 and 4.4 m in 2012. Surface sediments were obtained using a clear plastic tube fitted with a piston to recover the sediment-water interface (core LUN12-2C). The unconsolidated surface sediments were stabilized with Zorbitrol (sodium polyacrylate absorbent powder) while the core was still in an upright position. Overlapping cores (LUN09 in 2009 and LUN12-1A, 1B, 2A, and 2B in 2012) were recovered with a modified square-rod Livingstone hand operated corer, extruded directly into rigid ABS (Acrylonitrile Butadiene Styrene) plastic tubing, and capped for transport.

LUN09 spanned sediment depths from 54 to 605 cm and was recovered in six sections. We used GPS to relocate the LUN09 core site in 2012 for taking the next set of cores. Cores LUN12-1A and 1B were taken within 2 m of each other and spanned from 10 to 870 cm depth (ten sections) and 60–1028 cm depth (twelve sections) respectively. Cores LUN12-2A, 2B and 2C were taken ~10 m from the other set and within 2 m of each other. LUN12-2A spanned from 60 to 1300 cm depth (fifteen sections) and LUN12-2B, the longest core, from 20 to 1438 cm depth (nineteen sections). LUN12-2C, the surface core, contains the sediment-water interface to 123 cm depth.

LUN-09 was described, analyzed and stored at the Tuscia University Paleocology Laboratory in Viterbo, Italy. Cores LUN12-1A and 1B were transported to the Tuscia University Paleocology Laboratory for storage and subsequent u-channel sampling for paleomagnetic analyses. Cores LUN12-2A, 2B- and 1C were shipped to the United States National Lacustrine Core Facility (LacCore) in Minneapolis, Minnesota for initial core description, sampling for pollen, charcoal, smear slide and LOI analysis, and permanent storage.

3.2. Initial core description and analysis

Core LUN09 was split, photographed and the sediments described, analyzed and stored at the Tuscia University Paleocology Laboratory in Viterbo, Italy. Cores LUN12-1A and 1B were first logged whole using a Geoteck Multisensor Core Logger to measure density, acoustic wave velocity, electrical resistivity and loop-sensor magnetic susceptibility at 1-cm resolution. Cores were then split, the surface cleaned, imaged with a digital line scanner at ~300 dpi, then placed on a Geotek MSCL-XYZ core scanner and measured at 0.5-cm resolution for magnetic susceptibility and color. Magnetic susceptibility data and core images were input into an electronic
standard core description sheet and the sheets annotated for stratigraphy, sedimentology and correlation points between cores using both the images and the freshly split cores. Smear slides, taken every 20 cm and from selected strata, were used to aid in core description and to identify the major sedimentologic components.

The observed sedimentologic features and magnetic susceptibility data were used to correlate cores LUN12 2A, 2B, and 2C, often allowing for a visual match of individual suites of bands and layers between cores (Figs. 2 and 3). Areas of core distortion, caused by coring artifacts, and sections with no core recovery were identified, and a continuous 'master core,' hereafter referred to as LUN12-2, was constructed from the three cores, that spans a total sedimentary thickness of 14.4 m. Magnetic susceptibility was further used to correlate between core LUN12-2 and LUN12-1A and 1B, and LUN09, which were neither photographed nor logged in detail.

Samples (1.25 cm³) were taken every 10 cm (3–5 cm in sediment transition zones) from LUN12-2 for measuring percent total organic matter (%organic) and percent carbonate (%CaCO₃) using the loss on ignition method protocols at LacCore based on Dean (1974) and Heiri et al. (2001). Samples were weighed, dried at 100 °C for two hours. All samples were then combusted at 550 °C for four hours followed by combustion at 1000 °C for two hours.

Core LUN12-2 was transported to the Large Lakes Laboratory in Duluth, Minnesota for analysis using the ITRAX x-ray fluorescence (XRF) scanner (Cox Analytical Instruments) to provide elemental geochemistry data. The LUN12-2 core was scanned at a resolution of 0.5 cm throughout, except for the middle 7 sections (2B-5L through 11L), which were scanned at a resolution of 0.2 cm to pick up observed variations in sedimentary banding. The top section (LUN12-2C) was also scanned at a 0.2 cm resolution. The scanner was operating using a molybdenum source, 30 s dwell-time, a voltage of 30 kV and an x-ray current of 30 mA to obtain peak areas for elements Si–Pb. A principal component analysis using the rda function in the vegan 2.0-6 package in R, version 2.1.5.2 (R Development Core Team, 2012) was performed on the raw XRF data output, on both the whole core and on individual sections as an initial data analysis step to determine gross distribution patterns and co-variance of elements. Time series plots for core LUN12-2 were then generated for a subset of elements determined to be of interest as sedimentologic and lake chemistry proxies (Ti, Fe, Mn, Ca, and Sr). Raw counts of the element subset were normalized by centering and standardizing the data (raw data-mean of data/standard deviation), allowing for the comparison of the minima, maxima, and trends of major elements with very different ranges of counts within the core.

### 3.3. Rock magnetism and paleomagnetism

Natural and artificial magnetizations were measured at room temperature at the paleomagnetic laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome, on a narrow-access (45 mm diameter) automated pass through ‘2G Enterprises’ DC 755 superconducting rock magnetometer (SRM), housed in a Lodestar Magnetics shielded room. The cryogenic magnetometer is equipped with in-line orthogonal alternating field (AF) demagnetization coils, with optional application of a single-axis direct current (DC) field for production of an anhysteretic remanent magnetization (ARM). Rock magnetic and paleomagnetic properties were measured at 1-cm spacing on u-channel samples collected from 4 distinct and partly overlapping cores (LUN09, LUN12-1A, LUN12-1B and the lower 5.4 m of LUN12-2B).

To minimize sample dehydration and alteration, u-channel samples were stored in a refrigerated room until they were processed. For each u-channel, we first measured both the low-field magnetic susceptibility (χ), using a Bartington magnetic susceptibility probe MS2C in-line with the rock magnetometer, and the natural remanent magnetization (NRM). Then, all u-channels were AF demagnetized in 10 steps (using peak fields of 5, 10, 15, 20, 30, 40, 50, 60, 80 and 100 milliTeslas (mT), with remanence vectors measured after each demagnetization step, in order to investigate the stability of the NRM and to reveal possible secondary overprints.

Finally, an ARM was imparted using a 0.05 mT direct current (DC) bias field and an axial 100 mT peak AF, and translating the u-channel through the AF and dc coil system at a speed of 10 cm/s, the lowest speed allowed by the software running the measurements. The adopted procedure evaluates an ARM decay rate of ca 67 μT/half-cycle and results in the highest ARM intensity achievable with the employed instrumental setting and management software (Sagnotti et al., 2003; Sagnotti, 2013). The ARM was then measured and stepwise AF demagnetized using the procedure applied to the NRM.

From the AF demagnetization data of both the NRM and the ARM we computed the median destructive field (MDF), which is defined as the value of the peak AF necessary to reduce the remanence intensity to half of its initial value.

The raw magnetic moment data measured by the three orthogonal SQUID sensors of the SRM system were automatically corrected by compensating for the different shape and widths of
the response function curves of the three SQUID pick-up coils (Roberts, 2006). Moreover, we took particular care in avoiding eventual disturbance effects that may be introduced during the coring, cutting and sampling procedures and could result in remanence deflections due to plastic deformation of the soft sediments. We also disregarded the paleomagnetic data for ~5 cm at both ends of each u-channel to avoid disturbances linked to edge effects.

3.4. 210Pb, 137Cs, and 14C AMS analysis

Continuous 1-cm³ samples were taken from the full length of the surface core (LUN12-2C), freeze dried and sent to Flett Research Ltd. for 210Pb and 137Cs analysis. Plant macrofossils for 14C AMS dating were not found during the initial core description, therefore extensive efforts were made to obtain datable materials. To find plant macrofossils and macroscopic charcoal, we sieved a total of 525 cm of core (90 samples, 5 from LUN09 and 85 from LUN12). For LUN09 we subsampled 20-cm long sections of half the core (~200 cm³ per sample), soaked the sediments in a 5% solution of sodium metaphosphate for 12 h, and then sieved at 250 μm. We followed the same process for LUN12 but decreased the sample size to 5-cm long sections (~50 cm³). Two microscopic charcoal samples were picked by hand from samples that appeared to be richer in charcoal. We concentrated pollen from a 20 cm section of core for 14C AMS dating, following Newingham et al. (2007) then purified the concentrate using flow cytometry (Tennant et al., 2013).

One macrofossil (LTL 4680A) was submitted for AMS analysis at CEDAD at the University of Salento, Brindisi, Italy; all others were submitted to the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory, USA. All macrofossils were chemically pretreated with the standard acid-base-acid (ABA) treatment before being combusted under vacuum and graphitized according to standard procedures (Vogel et al., 1984).

To test for the magnitude of a potential aquatic reservoir effect, a Phragmites plant growing in the lake was uprooted and pieces of the roots, stem, and leaves were rinsed in deionized water before transport to LLNL for radiocarbon analysis. All samples were pre-treated, graphitized, and measured according to the same protocols as the fossil samples; dates on the roots and leaves were replicated.

3.5. Tephra analysis

Italy has a history of active volcanic eruptions, although most are well to the south of our site and no tephas from the last three millennia have been confirmed for our region (Giaccio et al., 2009; Sulpizio et al., 2014). Nevertheless, to test the potential for tephrochronology, twelve 10-40 cm thick samples were collected from LUN12-1B at age intervals, based on the paleomagnetic secular variation age model, discussed below, corresponding to periods of eruptions from Vesuvius, Phlegrean Fields, Ischia Island, Vulcano and the Lipari Islands. Eight samples were prepared on alloy stubs for morphological and textural observations and qualitative chemical analysis of components using a Zeiss EVO MA 10 scanning

![Fig. 3. High resolution images of the Lago Lungo Master core (LUN 12-2). Individual cores sections used in the master are labelled. White boxes represent core sections with no recovery. Running depth is a continuous measure (m) of the total core length.](image_url)
3.6. Pollen and charcoal analysis

A total of one hundred samples (0.625 cc volume) were processed for pollen analysis using acid digestion procedures (Faegri and Iversen, 1983); two samples from the surface core (LUN12-2C), forty from LUN09 (460–605 cm depth), and fifty-eight from LUN12-2B (460–1438 cm depth). A known quantity of an exotic tracer (Lycopodium) was added to each sample during processing (Stockmarr, 1971) and counted along with pollen for calculating pollen concentration. Pollen counts for LUN09 (6 m in length) were completed before recovering LUN12-2B (14.4 m in length), therefore we counted duplicate samples from each core for the overlapping section from 460 to 605 cm depth. Duplicate counts were similar, and in the overlapping section we used only the counts from LUN12-2B, which were done at a later date, for a total of ninety-one samples in the final pollen diagram. A minimum of 400 terrestrial pollen grains were counted per sample (mean = 441) except for samples with very low concentration rates (n = 23), in which case a sum of 200–300 grains were counted (mean = 222). Pollen count totals excluded aquatic pollen types, such as Typha, Nuphar and Potamogeton, algae, and non-pollen palynomorphs.

Pollen and non-pollen palynomorphs were identified using reference material in the Tuscia University Paleoenecology Lab, published keys and manuscripts (Punt and Malotaux, 1984; Punt et al., 1991; Chester and Raine, 2001; Blackmore et al., 2003; Beug, 2004; van Geel and Aptroot, 2006; Cugny et al., 2010; van Geel et al., 2011). TC pollen (Taxaceae and Cupressaceae) was assumed to be Juniperus, a native taxa. Species of Quercus were identified as either Q. pubescens – robur L. type, or Q. cerris L. (deciduous) or Q. ilex L. (evergreen) following Van Benthem et al. (1984). For plotting purposes Quercus is represented as deciduous or evergreen (Q. ilex type). Members of the family Poaceae were identified as cereals if grains were >37 μm, pore diameter was >2.7 μm and annulus thickness was >2.0 μm, following Köhler and Lange (1979). Pollen percentages were calculated from the sum of terrestrial pollen, excluding indeterminate grains and Cannabis type (which was retted in the lake at certain periods). Accumulation rates (grains cm\(^{-2}\) yr\(^{-1}\)) were calculated by dividing concentration (grains cm\(^{-2}\)) by the number of years per sample (yr cm\(^{-1}\)) and normalizing by number of Lycopodium counted. Aquatic taxa, algae, and non-pollen palynomorphs are presented as accumulation rates, since they appear intermittently in the record and total quantity represents actual abundance better than does percentage. Zonation was interpreted from a constrained single-link dendrogram created using CONISS in the PolPal plotting program (Nalepka and Walanus, 2003). Data input included the fifty-three terrestrial taxa with at least one strata of >1% of the pollen sum, excluding Cannabis type and indeterminate grains.

Charcoal particles were counted on pollen slides in two size fractions, 50–125 um and >125 um —longest dimension (Sadori and Guardini, 2007). All fragments that met the criteria of being black and having a visible cellular structure were counted.

3.7. Archaeological, historical and archival documents

The bulk of the archaeological documentation is represented by two surveys carried out in the area in the 1980s by the University of Perugia and in the 1990s by the British School at Rome (Coccia et al., 1992, 1995).

The early medieval phase is well documented by one of the most important collections of Europe: the archive of the Farfa Abbey, which contains a body of documents concerning the history of the territory between the 8th and the 12th century AD. The late medieval phase (13th–15th century) is well documented through the archive of the Comune of Rieti and that of Rieti cathedral (Caciorgna, 1998, 2000; Leggio, 1998). The history from 16th century onward has been analyzed in detail by means of additional archive (Dupré, 1939; Lorenzetti, 1989) and map collections in the Archivio di Stato in Rome and Rieti (Lorenzetti, 1990, 1994, 2009). In correlating the sedimentary evidence with historical evidence we have provided names and time periods following the system developed by Coccia et al. (1995) based on changes in archeologic ceramics in the Rieti Basin.

4. Results and discussion

4.1. Chronology

Developing a core chronology based largely on 14C dating proved challenging given that the carbonate bedrock introduces the potential for significant old-carbon effects and plant macrofossils were hard to find and not well-distributed throughout the core. We therefore developed two independent age models, one...
based on historical documentation of biostratigraphic markers along with the information provided by the paleomagnetic secular variation (PSV), and another based on radiometric analyses (Fig. 4).

### 4.1.1. Biostratigraphic markers

Historical documentation of specific biotic changes within the basin (biostratigraphic markers we refer to as cultigens) were compared with the pollen reconstruction to provide estimated dates in the upper section of the core. *Zea mays* (corn) was introduced into Europe only after the first voyage of Columbus in 1492 CE. The first historical documents noting cultivation of *Z. mays* in Italy are from 1605 CE and most documents indicate that cultivation was initially sparse, introduced into central Italy after 1700 (Messedaglia, 1927). The first documented planting of *Z. mays* in the Rieti Basin is given as between 1740 and 1760 CE (De Felice, 1965; Covino, 1995) and we attribute a date of 1750 CE to the core depth (134 cm) with the first appearance of *Zea* pollen (Table 1).

Cannabis cultivation in the Rieti Basin for rope production expanded in the mid-17th century, peaked in the late 18th century, and eventually declined by the mid-19th century (Galli, 1840; Zuccagni-Orlandini, 1843; Nigrisoli, 1857; Celetti, 2007). The peak in Cannabis-type pollen (see Results Fig. 12) is coincident with the first appearance of *Zea* pollen. We designated a date of 1660 CE to the beginning of the rise in Cannabis-type pollen (160 cm), and a date of 1830 CE to the end (110 cm), a time when alternative fibers such as linen and cotton began replacing Cannabis across Europe (Lavrieux et al., 2013; see also Rull and Vegas-Vilarrubia, 2014 for the rapid decline of hemp).

Reforestation associated with land abandonment following the Black Plague in 1349 CE depth has been documented repeatedly throughout Europe (van Hoof et al., 2006; Yeloff and van Geel, 2007; Sköld et al., 2010; Fraser, 2011). Written documents from Rieti described a similar pattern of land abandonment and reforestation towards the end of the 14th century (Leggio, 1995b; Naspi, 2010) and we gave a date of 1390 CE to the major transition from a deforested to forested landscape evident in the pollen record about 335 cm depth.

### 4.1.2. Paleomagnetic analysis

The measured rock magnetic properties (κ, NRM, ARM, MDF) were used to correlate cores LUN12 1A, 1B, 2A, 2B, 2C and LUN09 between overlapping sections and enabled us to build a composite magnetic section for the lake (Fig. 5). We constructed an age model based on the rock magnetic data and biostratigraphic cultigens described above.

The NRM demagnetization data allowed the unambiguous identification of a Characteristic Remanent Magnetization (ChRM) throughout all the sequence. The data indicate that the whole sequence is characterized by an almost single-component NRM, unambiguously isolated after removal of a weak viscous overprint in AF steps of 5–10 mT (Fig. 6). The orientation of the ChRM was defined by principal component analysis (Kirschvink, 1980) by fitting a line between the 10 and 50 mT AF demagnetization steps. The maximum angular deviation for each determined ChRM direction is 1° on average, with a full range of variation between 0.1° and 5°. The MDF of the NRM typically ranges between 15 and 40 mT indicating that magnetite is the main magnetic carrier in the sequence.

The ChRM declination of individual u-channels was arbitrarily rotated to align trends between adjacent sections. The stratigraphic trends in the ChRM declination and inclination are characterized by large amplitudes and high-frequency oscillations around the expected values for a geocentric axial dipole (GAD) field at the site. These wide oscillations and amplitudes are however unexpected, considering the recent models of paleosecular variation (PSV) of the geomagnetic field over the last millennia (Gallet et al., 2002; Pavón-Carrasco et al., 2009; Korte et al., 2011). In any case, these variations are consistent between the analyzed cores and the reconstructed ChRM directional trends are replicated in the overlapping sections of the distinct cores (Fig. 7).

To estimate relative paleointensity (RPI) variation, we normalized the NRM by κ and by the ARM intensity. The NRM/ARM ratio was computed also from the values measured after the 20 mT and 40 mT AF steps. All the normalization methods resulted in a similar pattern and therefore support a general coherency between the different normalization procedures and indicate a reliable reconstruction of the RPI trend. After removal of data affected by edge effects at the u-channel breaks, lithological boundaries and magnetic susceptibility spikes, the broadly smoothed paleomagnetic trends can be correlated to the available PSV curvatures and models for Europe: the directional (declination and inclination) archaomagnetic PSV curve (Gallet et al., 2002) built with a high quality archaomagnetic dataset from France, and the full geomagnetic field vector (declination, inclination and intensity) provided by the archaomagnetic SCHA.DIF.3k model of Pavón-Carrasco et al. (2009) (Fig. 7). This correlation enabled us to point out various depth-age tie-points from prominent PSV features.

In order to estimate the temporal error of the paleomagnetic tie-points we have calculated the temporal resolution of the regional model SCHA.DIF.3k at the geographic coordinates of Lago Lungo. For each tie-point, the three geomagnetic field elements, i.e.
declination, inclination, and intensity, are defined by a temporal Probability Density Function (PDF). The PDF depends on the value of the geomagnetic field element at the corresponding time and its uncertainty (the $\sigma_95$ in the case of the directional elements and the intensity standard deviation, $\sigma_F$, for the intensities). The combination of the three PDFs for each geomagnetic element provides a final PDF which area allows us to calculate the minimum and maximum time for each tie-point. Then, the temporal resolution of the regional model is given by the difference of this maximum and minimum. Table 1 contains the paleomagnetic tie-points used in this study with the geomagnetic field elements and their uncertainties, at 95% confidence levels, according to the SCHA.DIF.3k model predictions (Pavón-Carrasco et al., 2009).

4.1.3. $^{210}$Pb, $^{137}$CS, and $^{14}$C AMS analysis

$^{137}$CS activity was significantly above background for the core interval 24–41 cm with maximum activity at 28–29 cm depth, assumed to be 1963 CE. The CRS model of $^{210}$Pb activity indicated an age of 1954 CE at 33.5 cm depth, and it was concluded that the CRS model provided a reasonable estimate of age in this core. The $^{210}$Pb chronology produced a date of 1905 CE at 50.5 cm depth.

Fifteen radiocarbon dates were obtained from twelve depths in the LUN09 and LUN12-1B cores (Table 2 and Fig. 4). Sieving yielded six plant macrofossils and two macroscopic charcoal samples; all remaining plant macrofossils and microscopic charcoal were found during the sub-sampling process. Sorting of pollen by flow cytometry yielded 1.5 million pollen grains which were divided into two samples (of 900,000 and 600,000 pollen grains) to obtain replicate dates for the interval 172–202 cm in LUN09. The same interval yielded a sample of leaf fragments large enough to produce replicate radiocarbon dates. The leaf replicates produced essentially identical radiocarbon ages, but were significantly younger than the pollen replicates, by ~400 years. The pollen replicates are likely older because they integrate grains from the whole 30 cm sediment sample, whereas the leaves may represent a single depth of younger age.

The radiocarbon samples generally fit into two categories, based on their age and depth in the core. Between 1000 and 260 cm four samples have calibrated radiocarbon ages of ~2800 years cal yr BP, with a fifth (343 cm) dating to 3500 cal yr BP. Because of the similarity in age, despite a wide stratigraphic range, and the variety of materials (Table 2), it seems likely that these samples represent the occasional tapping of some remnant deposit formed at or before 2800 yr BP.

The second group of samples ($n = 10$) cluster between 266 and 159 cm, and produce radiocarbon ages ranging from 1800 to 780 cal yr BP. This second group also represents a wide range of sample types, and may be the result of a period of widespread and active erosion, caused by wetter overall climate or more intensive human disturbance of the landscape, or both. The two groups of dates overlap at ~260 cm depth.

We considered the relatively fragile uncharred leaf macrofossil $^{14}$C dates (Table 2) the most reliable upon which to develop a radiometric chronology (Hatté et al., 2001). Although we were unable to identify leaf fragments to species, all appeared to be terrestrial. Macrofossils from core LUN-12 were considered more reliable than those from LUN-09 because they were recovered from 5-cm thick sections rather than 20 cm-thick sections. Since the sections from each core overlapped stratigraphically, we used the $^{14}$C dates from leaf macrofossils in LUN-12 (Table 2, samples with

![Fig. 5. Stratigraphic trends of k, NRM and ARM of the various cores, correlated to a common depth.](image-url)
center depths of 166, 193.5, 213.5, 238.5, 268.5, and 998.5 cm) in addition to the 210Pb date (from 50.5 cm) to build an alternative age model.

4.1.4. Age model selection

To directly compare the two age models, we replotted the LUN-12 PSV data using the radiometric dates as tie points (Fig. 8), and compared this fit with the available PSV curves and models for Europe (Gallet et al., 2002; Pavón-Carrasco et al., 2009). Comparison of the two age models shows that the 14C-based age model (Fig. 8) produces a poor fit between the LUN-12 PSV data and the PSV curves and models for Europe, especially when compared with the age model based on biostratigraphic markers and PSV tie points (Fig. 7). Note that each age model spans 3000 years, however in the 14C-based model 3000 yr BP is at 10 m depth and in the PSV model this is at 14.4 m depth. The 14C-based age model also produces age—depth relationships that are inconsistent with the written history. For example, the 14C based age model gives a date of 1380 CE for the depth of 134 cm, the first occurrence of Z. mays pollen, a physical impossibility given the introduction history of that crop. The 14C-based age model also results in dramatic changes in sedimentation rates at 268 cm depth from 6.92 to 0.96 mm yr⁻¹. Although this is physically possible, there is no indication in the appearance of the sediments (Fig. 3), or the geochemistry (Fig. 10) to support such a change at this depth. An organic rich interval occurs between 180 and 250 cm depth. The nature of the sediments, the magnetic properties and the geochemistry of this interval strongly indicate that it was deposited during a period of dramatically reduced terrigenous input in the basin. In the PSV based age model (Fig. 7) this interval would span about one century around 1530–1650 CE, a period of intense cold when historical maps indicate a very wide lake covering most of the basin. Conversely, in the 14C based model (Fig. 8) this stratigraphic interval would correspond to about three centuries in the early medieval time (600–900 CE), a warm period for which historical sources indicate widespread forest cutting and therefore a greatly increased terrigenous input in the basin. Down core, further issues in interpreting the data emerge, including deforestation and draining of the basin by 400 BCE, more than a century before archaeological and written records suggest any Roman impacts.

Given the problems associated with the 14C-based age model, we conclude that the PSV age model produces the most accurate chronology. In the PSV model, all three paleomagnetic measurements (inclination, declination and intensity) can be tied to the European PSV model through the full length of the core (Fig. 7), sedimentation rates do not change abruptly (Fig. 4), and the pollen record is consistent with known history. In addition, the 210Pb date, although not used to create the model, was consistent with the model. In contrast, most of the 14C ages fall within only one meter of the core. The clustering of macrofossils argues for the potential that macrofossils were transported to the lake irregularly, perhaps during a wet phase through flooding, erosion and redeposition of old materials. We do not have a complete explanation for the unusual 14C dates, but radiocarbon dating of the different parts of the modern Phragmites shows that unidentified plant material that is from an aquatic plant might be 500 years too old (or more) (Table 2). Terrestrial plants that can grow in standing water (e.g.
Salix) generally produce reliable $^{14}$C dates (Hatté et al., 2001), and several of the dated samples were identifiably terrestrial, suggesting this is only a partial explanation. We intend to further explore the complexities of $^{14}$C production and uptake within the study area.

### 4.2. Geochemical proxies

Several elements (Ca, Sr, Ti, Fe, Mn, and S) serve as proxies for siliclastic input, and authigenic or endogenic mineral fractions. The relationship of these elements can be seen in biplots of Principal Components 1 and 2 (Fig. 9), where the eigenvectors (red arrows) of the elements are superimposed over the data points, and 3 eigenvector trajectories (numbered 1, 2, and 3) are interpreted to have sedimentologic significance. The Medieval Period (MP) and Little Ice Age (LIA) intervals are plotted separately to show changes in elemental behavior between these two intervals (Fig. 9a, b). Ca is representative of the calcium carbonate (CaCO$_3$) component of the sediments, indicated by the good correlation between the Ca XRF and percent CaCO$_3$ derived from LOI (Fig. 10), and shows a distinct separate trajectory on the PCA plots (Fig. 9). Sr can co-precipitate with Ca as SrCO$_3$ when the lake waters are saturated with CO$_3$ (Haenssler et al., 2013), seen in the profile when Sr and Ca track together. Sr can also behave conservatively as a detrital element, tracking closely with Ti (Kylander et al., 2011). Ti is used in this study as a proxy for siliclastic detrital input into the lake (Haberzettl et al., 2008), controlled by erosion, weathering, and runoff within the catchment. Ti is representative of other conservative clastic elements such as K, Rb, and Zr that have near-identical profiles throughout the core, and are seen to have near identical eigenvectors with Ti (Fig. 9). Fe, while at times also behaving as a detrital element (Fig. 9b), is also influenced by redox processes and subject to remobilization at the sediment–water interface (Croudace et al., 2006). Mn is also influenced by redox processes, forming highly insoluble oxides in oxygenated conditions (Kylander et al., 2011) and is used here as an indication of changes in redox behavior of the upper few cm of the sediment. Mn shows a distinct trajectory in the PCA biplots, where Fe follows the behavior of Mn most closely in the MP (Fig. 9a). Sulfur shows an interesting profile and has been used as an indicator of evaporative balance and lake level changes, as it precipitates in chemically concentrated lake waters (Haenssler et al., 2013).

### 4.3. Core stratigraphy

Core stratigraphy is delineated by gross sedimentologic characteristics that are supplemented with petrographic observations, and time series curves of $\kappa$ and geochemistry. The sequence is subdivided into four stratigraphic intervals that are assigned names based on their chronostratigraphic significance. The sedimentology of these intervals is described below.

#### 4.3.1. Archaic through Early Medieval interval: 1438–800 cm, Age: 700 BCE–870 CE

This interval represents a number of historical periods (Coccia et al., 1995); including the Archaic (700–500 BCE), pre-Roman (500–300 BCE), Roman (300 BCE–400 CE), Late Antique (400–600 CE), and Early Medieval (600–800 CE) periods.
Fig. 8. PSV trends for core LUN12-1A and 1B, plotted as a function of the 210Pb and 14C AMS dates. In relation to the PSV reference curves and models (Archeomagnetic data from France, Gallet et al., 2002; scha.dif.3k of Pavón-Carrasco et al., 2009).

Table 2

Macrofossil 14C dates for cores LUN09 and LUN12 and modern Phragmites plant. MAP is the median age probability. Min and max represent the 2 sigma error. Difference is the age difference between the PSV age model and 14C age model graphed in Fig. 4. Dates marked with * are those used in the 14C age model and indicated with arrows in Fig. 8.

<table>
<thead>
<tr>
<th>Core</th>
<th>Depth (cm)</th>
<th>Lab ID</th>
<th>Material</th>
<th>14C age (yr BP)</th>
<th>± mg C</th>
<th>min (cal yr BP)</th>
<th>MAP (cal yr BP)</th>
<th>Max (cal yr BP)</th>
<th>MAP year CE</th>
<th>Difference cal 14C-PSV</th>
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<td>161–171</td>
<td>162752</td>
<td>Leaf fragment</td>
<td>840</td>
<td>100</td>
<td>0.036 567</td>
<td>777*</td>
<td>939</td>
<td>1175</td>
<td>543</td>
</tr>
<tr>
<td>LUN-09-1</td>
<td>172–202</td>
<td>152975</td>
<td>Leaf fragments</td>
<td>930</td>
<td>90</td>
<td>680</td>
<td>844</td>
<td>1048</td>
<td>1105</td>
<td>573</td>
</tr>
<tr>
<td>LUN-09-1</td>
<td>172–202</td>
<td>152973</td>
<td>Leaf fragments</td>
<td>960</td>
<td>60</td>
<td>737</td>
<td>859</td>
<td>965</td>
<td>1090</td>
<td>588</td>
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<td>211–216</td>
<td>162754</td>
<td>Leaf fragments</td>
<td>1145</td>
<td>40</td>
<td>0.138 967</td>
<td>1054*</td>
<td>1171</td>
<td>895</td>
<td>771</td>
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<td>155264</td>
<td>Sorted pollen</td>
<td>1255</td>
<td>30</td>
<td>0.31 1085</td>
<td>1211</td>
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<td>1445</td>
<td>40</td>
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<td>1340</td>
<td>1400</td>
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<td>158.5–159.5</td>
<td>155262</td>
<td>Sorted pollen</td>
<td>1343</td>
<td>50</td>
<td>1.02 1174</td>
<td>1271</td>
<td>1345</td>
<td>680</td>
<td>1050</td>
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<tr>
<td>LUN12-1C</td>
<td>236–241</td>
<td>162755</td>
<td>Bark</td>
<td>1600</td>
<td>35</td>
<td>0.187 1406</td>
<td>1476</td>
<td>1557</td>
<td>475</td>
<td>1113</td>
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<tr>
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<td>266–271</td>
<td>162767</td>
<td>Leaf fragments</td>
<td>1645</td>
<td>30</td>
<td>0.616 1712</td>
<td>1780*</td>
<td>1865</td>
<td>170</td>
<td>1363</td>
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<tr>
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<td>152974</td>
<td>Seed</td>
<td>2680</td>
<td>35</td>
<td>2.748 2785</td>
<td>2849</td>
<td>835</td>
<td>2382</td>
<td>2382</td>
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<td>162757</td>
<td>Leaf fragments</td>
<td>2745</td>
<td>35</td>
<td>0.275 2763</td>
<td>2833*</td>
<td>2925</td>
<td>885</td>
<td>1108</td>
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<td>Charcoal</td>
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<td>970</td>
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<td>152102</td>
<td>Charcoal</td>
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<td>100</td>
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<td>3530</td>
<td>3826</td>
<td>1580</td>
<td>2979</td>
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<tr>
<td>Modern phragmites</td>
<td></td>
<td></td>
<td>14C age (yr BP)</td>
<td>± mg C</td>
<td>Fraction modern</td>
<td>± Cal yr BP (2-sig range)</td>
<td>year CE</td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>0.647 1.0158</td>
<td>0.0038</td>
<td>5</td>
<td></td>
<td>1955</td>
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<tr>
<td>163123</td>
<td>Root</td>
<td>&gt;Modern</td>
<td>0.945 1.0238</td>
<td>0.0039</td>
<td>5</td>
<td></td>
<td>1955</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>162759</td>
<td>Stem</td>
<td>540</td>
<td>0.836 0.9350</td>
<td>0.0033</td>
<td>515–560</td>
<td></td>
<td>596–632</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>163124</td>
<td>Stem</td>
<td>270</td>
<td>1.031 0.9686</td>
<td>0.0034</td>
<td>283–433</td>
<td></td>
<td>0.0039</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All measured at CAMS-LLNL, except LTL 4680A, measured at CEDAD.
% all d13C values assumed to be ~25 per mil, as per Stuiver and Polach (1977).
Sedimentologically, the interval consists of a dark, discontinuously laminated, silty to clayey marl. The color is dark gray to black and fades to an olive color within hours of being exposed to air, indicating the presence of unstable monosulfides, or other redox-sensitive minerals in a reduced state. Small (<1 mm) black streaks in the core are aggregates of sub-micron-sized opaque black minerals within a clay matrix. Microscopic examination shows that the carbonate phase is significant (≥50%) in the form of calcite rhombohedrons (ranging from 2 to 20 μm), detrital carbonate allochems (<5 μm), Phacotus algal grains (5–10 μm), and rare fragments of Charophyte algae (>10 μm). The silt fraction is largely quartzofeldspathic, subangular, and occurs throughout, becoming an increasingly larger component towards the top of this interval. There is a diatom component (estimated at <10%) consisting predominantly of cyclotelloid phytoplankton with smaller amounts of araphid periphyton.

Some trends are observed in the lower and upper portions of this interval. At the base, the carbonate component is highest in the core and shows a gradual decline until 1250 cm (~300 BCE). This is indicated in both a decrease in Ca counts and %CaCO₃ determined...
by LOI, with a proportional increase in siliclastic components, as seen in the counts of Ti and Fe (Fig. 10). The $k$ has a baseline of $-10 \times 10^{-5}$ SI, at the bottom of the core, then increases to $-20 \times 10^{-5}$ SI, at 1150 cm reciprocating the decreased carbonate fraction. Sediment accumulation rates decrease with the drop in carbonate from $-7$ mm yr$^{-1}$ to the lowest rate in the core ($-3$ mm yr$^{-1}$). The top $-1$ m of this interval, during the Early Medieval Period (875–800 cm; 800–900 CE), shows some interesting sedimentological and geochemical features, although the distinction from the sediment below is not readily seen macroscopically in the core photos (Fig. 3). The $k$ signal shows large, frequent peaks above $100 \times 10^{-5}$ SI (Fig. 10), sediment accumulation rate rapidly increases to $-12$ mm yr$^{-1}$ and there is a brief increase in carbonate content relative to siliciclastics. The uppermost $-45$ cm, above 815 cm (870 CE), shows a large elemental shift commensurate with a decrease in organic matter and carbonate content. Diatoms are absent above 815 cm.

4.3.2. Medieval interval: 800–335 cm, Age: 870–1390 CE

This interval consists of gray thin bedded clay and silty–clay bands 1–30 mm thick, intercalated with varicolored reddish-brown, black, and buff-colored bands 2–10 mm thick. The reddish-brown to black layers appear to be rich in Fe and Mn, based on alignment of the core photos to the scanning XRF signal (Figs. 3 and 10). Fe and Mn show a close correspondence in the MP and have a similar eigenvector trajectory (Fig. 9a). The buff layers are 2–12 mm thick carbonate-rich bands that locally are hard and concretionary. Fine silty sand bands, 5–20 mm thick are interspersed throughout this interval, and contain as much as 80% quartzo-feldspathic grains. The carbonate fraction consists of small rhombohedrons, (2–5 μm), small detrital allochems (2–5 μm), Phacodus fragments (5–10 μm), and Charophyte fragments (10–80 μm). Sediment accumulation rates are high, a result of increased siliciclastic input, with correspondingly lower organic matter and carbonate fractions than the preceding interval. Diatoms are absent from this entire interval, with the exception of very rare fragmented or corroded frustules. The trends of the major elements, which shift dramatically at a core depth of 815 cm, persist throughout this interval. The top of this interval is marked by a very large $k$ peak not seen in the elemental data and a drop in sediment accumulation rate (Fig. 10).

4.3.3. Early Modern – Modern: 335–140 cm, Age: 1390–1740 CE

At a depth of 335 cm, the sedimentology of the shifts markedly. Siliciclastic content declines rapidly and then becomes variable, dominated by organic-rich calcareous material containing gastropod fragments and diatoms. Much of the organic matter appears to be aquatic in origin. Within this interval are two light yellowish zones rich in thin carbonate stringers and lenticular concretions. Petrographically, the carbonate is largely dendritic and asciicular, and of unknown genesis. A subordinate fraction of the carbonate is definitively algal, composed of Charophyte and Phacodus grains. Chemically, counts of siliciclastic elements (i.e. Ti) in this interval are the lowest in the core, and Ca and Sr have several maxima (Fig. 10). Mn and Fe are decoupled throughout this interval, and large peaks in S are observed for the first time, concurrent with

Fig. 11. Selected pollen taxa of trees, vines and shrubs, and total pollen accumulation rate. Unfilled lines represent 5X exaggeration.
4.3.4. Late modern to Contemporary interval 0–140 cm, Age: 1740–2000

This interval is composed of mottled and homogeneous to discontinuously laminated gray—black marl. The gray color appears to be related to carbonate content, with the lighter bands showing a higher percentage of carbonate grains. Diatoms are common as is aquatic organic matter. The carbonate fraction is more heterogeneous than lower intervals, and is composed of a mix of calcite rhombohedra, detrital allochems, Phacodus, and subordinate amounts of dendritic grains. There is a clay-sized siliclastic component, containing small amounts of fine (2–5 μm) silt grains.

4.4. Pollen, non-pollen palynomorphs and charcoal

We identified ninety different pollen types, nine non-pollen palynomorphs and eleven algae types. Pollen taxa with percentages consistently >1% are presented for trees (Fig. 11) and herbs (Fig. 12) and for the most abundant aquatic pollen, algae, and non-pollen palynomorphs (Fig. 13). Dominant taxa and percentages are summarized in Table 3.

Five pollen zones were interpreted from the dendrogram. Zone 1 (1438–1145 cm; 700 BCE to 1 CE) includes the Archaic, pre-Roman and Roman republican periods (Coccia et al., 1992). Zone 2 has been divided into two subzones; Zone 2A (2A, 1145–970 cm; 1 CE to 600 CE) corresponds to the Roman Imperial period through Late Antique period, and Zone 2B (970–800 cm; 600 to 870 CE) corresponds to the Early Medieval period. Zone 3 (800–335 cm; 870 to 1390 CE), corresponds to Medieval through Late Medieval time, Zone 4 (335–140 cm 1390 to 1730 CE) corresponds to the Early Modern and Modern periods, and Zone 5 (140–0 cm; 1730 CE to present) corresponds to the late Modern through Contemporary periods.

4.5. Interpretation of major phases of environmental change

There is a strong coupling between sedimentological and palynological shifts indicating that the factors affecting the lake’s depositional environment were also at work affecting the plant cover in the surrounding landscape. The resolution of our age model is centennial to sub-centennial and allows us to identify the major shifts in environmental change to compare with the rich collection of archeological and archival evidence and independent climatic reconstructions. The record allows for recognition of distinct periods or phases within the last 2700 years. Here we discuss the seven most important environmental phases in a historical context and the potential climatic and human causes that may have caused those changes.

4.5.1. Pre-Roman: a climate driven system (700–300 BCE)

Environmental change during the pre-Roman period appears to be largely a response to climate rather than human activity. The
climate was cool and wet at the beginning of our record. The Calderone glacier, 50 km to the east in the Gran Sasso d’Italia mountain group, advanced between 900 and 750 BCE and periglacial soils are found in the Apennines during the same period (Giraudi, 2005; Giraudi et al., 2011). Archaeological excavations and surveys from near Lago Lungo reveal small settlements along the 375 m contour, suggesting habitation in a generally marshy environment around small lakes (Coccia et al., 1995). The Sabini, who inhabited the region, were an advanced culture and primarily exploited the land for pastoralism with little evidence of forest modification (Cifani, 2003). The literary tradition reports that in the Rieti Basin the cults of Vacuna and Hercules played an important role, the first as the deity of water and woods and the latter the god of springs and cattle (Alvino and Leggio, 2006; Camerieri, 2011).

There was a well-developed floodplain forest (Alnus glutinosa and Fraxinus excelsior) probably covering much of the basin floor and lakeshore and a rich mesophyllous forest (Fagus, deciduous and evergreen Quercus, Ulmus, C. betulus, Acer, and Corylus) on the uplands (Fig. 14). The abundance of Fagus pollen, and the presence of *Asterosporium*, a spore associated with Fagus, suggests that beech forests grew on the lower mountain slopes well below 1000 m, while today they are restricted above 900–1000 m (Piovesan et al., 2005). The mix of tree species as well as monolete and trilete ferns (e.g. Osmundo-Alnion and Alno-Ulmion alliances; Cutini et al., 2010) supports an interpretation of a minimally impacted forest (Russo Ermolli et al., 2014). This widespread mixed floodplain mesophyllous forest confirms that the landscape ecology of Central Italy was less affected by the Mid Holocene ‘mediterraneanization’ than other southern regions of the Mediterranean basin (Sadori et al., 2011).

The maximum highstand of *Lacus Velinus*, determined by geomorphic and archaeological evidence (Ferrelli et al., 1992), is reported to have occurred in the Iron Age (beginning ~850 BCE). The lake environment was a hydrologically open hard-water system (Ferrelli et al., 1990) deep enough to support aquatic phytoplankton (i.e. cyclotelloid diatoms). Carbonate content and Ca relative abundance show a gradual decline in Lago Lungo from 700 to 400 BCE. The sediment accumulation rate during this period remains low, indicating that the decrease in carbonate is not due to dilution by clastic input. Instead, the carbonate trend reflects a change in lake chemistry affecting carbonate saturation and precipitation. The *Lacus Velinus* highstand reached an elevation of 375 m a.s.l., then dropped to ~372 m a.s.l. during pre-Roman time (pre 270 BCE), prior to any human modifications to the basin (Ferrelli et al., 1990). The coincidence of a larger deeper lake in ~850 BCE, receding during pre-Roman times from its highstand supports the role of the water balance in affecting the observed carbonate trend. The gradual decline in carbonate content may reflect climatically-driven changes in lake hydrochemistry, although the specific drivers affecting carbonate deposition in this system need more investigation.

4.5.2. Roman Republican: initial manipulation of the drainage system (300–1 BCE)

About 270 BCE, the Romans are purported to have created *Cava Curiana*, a drainage canal cut through the travertine sill at the

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**Fig. 13.** Selected aquatic pollen, algae, non-pollen palynomorphs and charcoal. Units for charcoal are accumulation rate of number of pieces. Unfilled lines represent 5X exaggeration.
location of the Marmore Falls to facilitate drainage and reclamation of the basin (Leggio and Serva, 1991). There is a magnetic susceptibility spike at ~300 BCE as well as an inflection point in many of the geochemical curves, including carbonate, Ti and S, which may be associated with the channel cutting. The sediment remains dark gray to black with anoxic sulfides similar to the Pre-Roman core interval, and no discernible sedimentological change accompanies the magnetic susceptibility spike. However, if channel cutting served to lower Lago Lungo and temporarily isolate it from the larger lake system, then the subtle increases in the S signal seen above the magnetic susceptibility spike may reflect a more isolated stagnant lake with slightly more sulfide mineralization. The steady decline in Alnus pollen beginning ~200 BCE (Fig. 14) supports an interpretation of a lowered water table; however, large areas of the valley must have remained wet given the continued persistence of Alnus. The decline in Alnus was permanent, indicating that after this change the basin never again reached the same extent of flooded forest. Pliny the Elder (Naturalis historia 3, 109) described the Rieti basin as covered by dense forest and beyond the change in Alnus, there is no evidence for forest degradation (Fig. 14).

4.5.3. Imperial Roman through Late Antique: intensification of land use (1–600 CE)

Climatically, the period from 1 to 200 CE is considered part of the Roman Optimum, with exceptional climate stability and favorable conditions that coincide with the rise of Imperial Rome

Table 3
Description of key pollen taxa, non-pollen palynomorphs, algae, and charcoal results, summarized by pollen zonation. Percentages and accumulation rates are averages for the zone unless indicated otherwise.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Key taxa</th>
<th>Description of pollen, non-pollen palynomorphs, algae, and charcoal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 5</td>
<td>Poaceae</td>
<td>Modern landscape established. Poaceae (22%) is the most common single pollen type and herbs (10.3%) have increased. Tree pollen (60.2%) is dominated by deciduous Quercus (19.7%), Juniperus (13.3%) and Ostrya (9.2%) with minor amounts of Fagus, Fraxinus ornus and Corylus (each &lt;1.5%). Alnus (1.5%) is nearly absent. Olea (3.8%) is important and shrubs ( Phillyrea 2.9%) are now more abundant. Total pollen accumulation rate is 54,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;.</td>
</tr>
<tr>
<td>1400–2000 CE</td>
<td>Quercus</td>
<td>Abrupt return to a forest phase. Percentage of tree pollen (73.0%) nearly as high as pre-Roman, although Quercus (30.2%) now much more common than other taxa; Alnus (10.8%), Ostrya (9.4%), Fagus 3.9%, Ulmus, Fraxinus ornus, Corylus and Carpinus betulus (each &lt;1.6%). Tree crops emerge; Olea (1.4%) and Juglans (1.8%). Poaceae (11.5%) and herbs (7.2%) decrease, ferns (2.1%) nearly disappear. TC (Juniperus) increases to 10.6% at 134 cm and Cannabis type peaks at 31.4%. Highest pollen accumulation rate (137,500 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Late Modern &amp; Contemporary</td>
<td>Olea</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Zone 4</td>
<td>Quercus</td>
<td>Total forest pollen remains stable (60.5%) but diversity decreases. Poaceae (11.6%), herbs (15.6%) and total ferns (10.4%) also change little, but triplet ferns increase. Deciduous Quercus (20.9%), Alnus (13.4%) and Salix (2.0%) increase but all other tree taxa decline; Ostrya (7.3%), Fagus 4.5%, Corylus (2.6%), Carpinus betulus (-1.1%), Glomus (500 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;) and charcoal (1325 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;) both increase. Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>335–140 cm</td>
<td>Poaceae</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>1390–1740 CE</td>
<td>Alnus</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Moderate</td>
<td>Ostrya</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Quercus</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>800–335 cm</td>
<td>Poaceae</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
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<tr>
<td>870–1390 CE</td>
<td>Alnus</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
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<tr>
<td>Medieval</td>
<td>Cichorioideae</td>
<td>Abrupt transition to a deforested phase. Pollen of Poaceae (19.1%), herbs (21.0%) and fern (24.2%) more abundant than trees (31.7%). Triplet ferns average 17.7% and reach 55.7%. Cereals increase (1.6%) and associated weeds of cultivated land increase; Cichorioideae (6.2%), Plantago, Amaanthaceae, Asteraceae, Total pollen accumulation rate is low (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Zone 2B</td>
<td>Quercus</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>1145–970 cm</td>
<td>Alnus</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>1–600 CE</td>
<td>Quercus</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Roman imperial and Late Antique</td>
<td>Fagus</td>
<td>Total pollen accumulation rate decreases (14,800 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Zone 1</td>
<td>Alnus</td>
<td>Forest taxa, particularly Alnus, decrease but remain dominant (63.1%) and grasses (12.9%), herbs (12.7%) and ferns (9.1%) increase. Main tree pollen types are Ostrya (12.3%), Alnus (12.0%), deciduous Quercus (11.5%), Fagus (11.3%), Corylus (3.6%) and Carpinus betulus (2.1%). Herbs typical of disturbance begin to increase, including Cichorioideae (1.8%), Brassicaceae (1.5%), Ranunculaceae (1.4%) and Plantago (1.0%). Cereals (0.6%) increase and are consistently present. Glomus, an indicator of erosion, increases (380 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;) and charcoal reaches a peak (900 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;) in the 1st to 2nd centuries.</td>
</tr>
<tr>
<td>1438–1145 cm</td>
<td>Ostrya</td>
<td>Forest phase dominated by tree pollen (81.3%). Herbs (5.9%), Poaceae (6.2%) and ferns (4.4%) are a small component of the pollen. Tree pollen is diverse composed of Alnus (21.2%), deciduous Quercus (18%), Fagus (8.6%) with small quantities of Corylus (3.3%), Carpinus betulus (3.2%), Urtica (1.6%) and Fraxinus excelsior (1.3%). Asterosporium is at a maximum (260 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>700 BCE–1 CE</td>
<td>Quercus</td>
<td>Total pollen accumulation rate is high (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
</tr>
<tr>
<td>Pre-Roman &amp; Roman Republic</td>
<td>Carpinus betulus</td>
<td>Total pollen accumulation rate is high (55,000 grains cm&lt;sup&gt;-2&lt;/sup&gt; yr&lt;sup&gt;-1&lt;/sup&gt;).</td>
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</table>

Alnus requires standing water, and a reduction in Alnus suggests a reduction in wetland area in the valley. This interpretation supports the argument that the Romans first drained the Rieti Basin in the first quarter of the 3rd century BCE, as recorded by historians (Sisani, 2009). This reclamation work appears to have been sufficiently successful to have lowered the water table enough to reduce the flooded forests. The Roman water works do not appear to have changed land use practices. Archeological surveys indicate that local settlements were consolidated (Coccia et al., 1995) but in the 1st century BCE Varro emphasized the importance of sheep pasturing (Varr. 2.2.9) and the geographer Strabo described the Rieti valley as a place of domestic livestock, mules particularly (Strab. 5.3.1). The increase in disturbance taxa during this period supports an interpretation of increased pasturage.
Reconstructed temperatures during this period were mild (Fig. 14), similar to the first half of the 20th century (Christiansen and Ljungqvist, 2012; northern hemisphere extratropical 2000 temperature reconstruction — ftp://ftp.ncdc.noaa.gov/pub/data/paleo/contributions_by_author/christiansen2012/christiansen2012.txt URL and data accessed). What is particularly striking is that while the population of Rome expanded to more than one million (Lo Cascio and Malanima, 2005) there is no evidence for intensive exploitation of the Rieti Basin through land clearance or deforestation. Forests declined during the Imperial period in relation to the Republican period (66% vs. 81% total AP respectively; Table 3, Fig. 14), though the extent of degradation appears limited. The impact on the forest shows alternating phases of more pressure (1st and 4th century) or less (3rd century (see also Russo Ermolli et al., 2014) consistent with the demographic and socio-economic trends of Rome (Leggio, 2000; Costambeys, 2009).

Fig. 14. Summary diagram with selected data. Arboreal pollen includes all tree taxa presented in Fig. 11 except Alnus. Disturbance taxa include all herbs plus trilete ferns shown in Fig. 12. Diatoms were identified from smear slide analysis. Stratigraphic intervals follow Fig. 10.

Around 1 CE there is an abrupt increase in disturbance species (e.g. Rumex, Brassicaceae, Cichorioideae, Apiaceae, and trilete spores) although a diverse flooded forest assemblage persisted. Pollen of cereals are present, but not abundant (Fig. 12) and Sporormiella, an indicator of domesticated livestock, is consistently present. Archeological evidence of settlement is restricted to the alluvial fans and low hill-slopes above the valley floor, concentrated between 380 and 480 m with no evidence of large settlements above 600 m (Coccia et al., 1995). The main nucleated settlement was Reate (Cifani, 2003) and the economy was probably oriented towards pastoralism and trade with the nearby Apennine communities. We infer that the basin was partially cleared for pasture but remained marshy and that livestock grazing was more important than agriculture, although even pasturage may not have been intensive.

A number of other pollen reconstructions from the Italian peninsula have also found only limited evidence of deforestation during the Roman Imperial period, including sites near Naples (Russo Ermolli and di Pasquale, 2002), Colli Euganei west of Venice (Kaltenrieder et al., 2010), Calabria (Joannin et al., 2012), Abruzzo (Branch and Marini, 2014) and near Ostia, the ancient port for Rome (Di Rota et al., 2010; Sadori et al., 2011). Our findings contrast with arguments for extensive forest clearing and burning in the vicinity of Rome (e.g. McNeil, 1992; Hughes, 2011) and support the argument that deforestation was localized and degradation limited (Grove and Rackham, 2001).

The Roman Empire supported a complex trade network and one possible reason for the lack of exploitation of the Rieti Basin may have been the ‘globalization’ of production of Imperial Rome. Rieti was interconnected with Rome and likely benefited from external resources, potentially reducing pressure on local resources (Champion, 1995). Local sites, such as Rieti, would not have been sufficient to support the large urban population of Rome and may have been spared from environmental degradation while distant regions were exploited. Egypt appears to have enjoyed exceptionally favorable conditions between 1 and 200 CE (McCormick et al., 2012) and food production and transport may have been more efficient from such distant locations as opposed to local sites with limited agricultural capacity and barriers to transport. Rieti was on
the Via Salaria, one of the most important trans-Apennine roads between Rome and the Adriatic Sea (Coccia et al., 1992), but the Marmore Falls prevent easy access by water to the Tiber River making it difficult to ship bulky resources (e.g. wheat, charcoal) to Rome. Another possibility is that, in order to prevent deforestation and soil erosion and to mitigate Tiber flooding in the area of Lacus Velinus, the forests were provided some level of protection as sacred woods, following the Sabini cult of Vacuna, identified as Victoria or Diana by the Romans (Coccia et al., 1992; Alvino and Leggio, 2006).

Between 400 and 600 CE, during the Late Antique period, sometimes referred to as the Migration Period, we see a further degradation of the forest with a decline in Ostrya and increase in grassland (Poaceae), indicating more intensive coppicing of forests and possibly an intensification of local resource extraction. The Late Antique or Migration Period (400–600 CE), a time with cooler than average temperatures and general disruption following the Roman Empire (Büntgen et al., 2011; Christiansen and Ljungqvist, 2012), is sometimes identified as a period of climatic instability which may have contributed to cultural upheaval (McCormick et al., 2012). In Rieti, there are few indications of upheaval, however trade networks appear to have been disrupted requiring greater reliance on local products. With the fall of Rome, the Ostrogoths ruled Rieti between 400 and 570 CE and maintained the Roman system of governance (Leggio, 1989). Archaeological data support the presence of a thriving community (Coccia et al., 1995) though limited ceramics from this period indicate a potential breakdown in the trade system (Coccia et al., 1992). A decline in Ostrya and increase in disturbance taxa suggest possibly more intensive coppicing of forests and an intensification of local resource extraction, with less reliance on traded goods.

4.5.4. Early medieval: intensification of forest disturbance and sedimentation (600–900 CE)

This phase represents a transition period with a complex series of changes in the vegetation, sedimentary, magnetic and geochemical proxies. Between 600 and 735 CE temperatures in the northern hemisphere remained cooler than average (Christiansen and Ljungqvist, 2012) though in central Europe, climate became milder, with warming temperatures and an increase in precipitation (Büntgen et al., 2011). At our site, loss of forest biodiversity began –600 CE, particularly the softer hardwoods (Fagus, Tilia, Ulmus, Acer, and F. excelsior) (Zone 2B, Fig. 11) and there was an increase in disturbance taxa (Fig. 12) and erosion (Glymus, Fig. 13). High percentages of Ulmus indicate that the valley floor remained marshy, suggesting that human impacts were concentrated on the hill slopes.

A cool to mild climate should not have resulted in loss of forest biodiversity and we suggest that this environmental shift resulted from a change in the governing authority and associated changes in land use. The Lombards gained control of Rieti around 590 CE (Naspi, 2010). There are few written documents for this period, but Rieti has been described as changing from a city of stone to a city of wood (Leggio, 2000) and between –600 and 800 CE, the softer desirable hardwoods appear to have been selectively removed initiating the decline in forest biodiversity (Fig. 11). In addition, the Farfa Monastery of the Benedictine order, established in the end of the 6th century in the Sabini Mountains (Fig. 1), became increasingly important in the 8th century. The monks were responsible for managing large areas of the landscape, including the Rieti Basin (Leggio, 1994) and forest cutting was widespread (Leggio and Serva, 1991).

From –735 CE (900 cm depth) until –870 CE (800 cm depth) the forest recovers somewhat, with an increase in Quercus and Ostrya, although there is no increase in the soft hardwoods. Disturbance indicators decrease, Ti decreases, carbonate and Ca increase, and MS is high and variable. Written sources describe an increase in flooded area, expansion of Lago Lungo (lacus Totoni) and Lago di Ripasottile (lago Maggiore) and the formation of many lanae (little lakes) (Leggio, 1994, 1998). This would appear to be a climatic impact, rather than a human induced change, though dominance of Quercus and Ostrya in the overstory suggests an actively coppiced forest.

4.5.5. Medieval through Late Medieval: peak deforestation and sedimentation (900–1390 CE)

The most extensive degradation of the environment occurred during the Medieval Period (~870–1390 CE) when forest cover was greatly reduced and herbs and ferns increased (Fig. 14). Temperatures in the northern hemisphere began warming after 900 CE with a well-defined peak between 950 and 1050 CE (Fig. 14) and a maximum temperature anomaly of 0.6 °C (Christiansen and Ljungqvist, 2012). Climate reconstructions from the central eastern Alps (Büntgen et al., 2011) and central Italy (Guio and Corona, 2010) show elevated temperature from 700 to 1250 CE with a thermal maximum of 0.3 °C between 1053 and 1171 CE (Trachsel et al., 2012). A precipitation reconstruction (Palmer Drought Severity Index – PDSI) using Cedrus atlantica (Endl. x Carrier) from Morocco (Esper et al., 2007; Trouet et al., 2009) shows that the period from 1050 to 1400 CE was anomalously dry across the western Mediterranean (Fig. 14). The initiation of forest cutting throughout the Rieti Basin coincides with the period of warmest temperatures, and climate change appears to have been a strong catalyst leading to environmental degradation; however socioeconomic changes are also important during this period.

Sediment accumulation rates reach their highest levels by 900 CE. The high percentages of indeterminate pollen (Fig. 12) as well as Cichorioideae, a taxon commonly found on disturbed sites with pollen particularly resistant to degradation (Bottema, 1975), support an interpretation of high erosion and increased bare soil. Cichorioideae have been demonstrated to be good indicators of open landscapes dominated by pastures and cultivated fields (Florenzano et al., 2015). Some of the indeterminate pollen are likely degraded tree taxa, could suggest that the level of deforestation may not have been as high as the pollen diagram indicates; however there is no reason to believe that the percentage of indeterminate pollen are skewed towards tree types since many herbaceous taxa are equally subject to degradation. Fern spores (tritele) are very high between 925 and 1075 CE. Ferns require mineral soil for regeneration, further supporting an interpretation that large areas with thin soils must have been present and loss of tree cover must have been widespread. The elemental proxy for erosion, the detrital element Ti, remains high throughout the MP, supporting the claim that deforestation and agricultural land use peaked during this time. Sediments throughout this phase are varicolored silty and clayey bands (Fig. 3) indicative of episodic sedimentation and potentially greater fluvial influence. The very high sediment accumulation rates begin to decline after 1100 CE. Written and archeological evidence support the hypothesis for a large increase in population, leading to saturation of the lower elevation sites for agriculture, and a push to exploit higher elevations. During the Medieval period, settlements were constructed at elevations above 1000 m (Coccia et al., 1992). Terraced walls related to farming were found between 700 and 1000 m (Coccia et al., 1995) and active deforestation and a series of 'hospitals' for tending to farm workers have been documented at 1400 m (Naspi, 2010). It also seems reasonable to conclude that warmer temperatures allowed farming and grazing to be successful at higher elevations. As population grew and settlement expanded upslope, farmers likely pushed the limits of what local resources were...
capable of supporting. Introduction of the heavy plough, horse collar and harrow were technological innovations that may have partially offset the limits of local production by permitting a more intensive agriculture (Sereni, 1973).

Documents record an increase in deaths due to malaria (Bruce-Chwatt and de Zulueta, 1980; Sabbatani, 2005) which may have also contributed to building settlements at higher elevation (Leggio, 1994). Settlement was not dispersed, but largely concentrated in fortified settlements or castles (incastellamento) for security. More than forty settlements in the Rieti Basin are first mentioned in the Farfa monastery documents in the period between 1050 and 1200 CE, of which fifteen of these hill towns are still occupied (Coccia et al., 1992). Dispersed settlements did not completely disappear, but the broad pattern was one of the population concentrated into fortified settlements in defensible locations governed by powerful and wealthy lords (Leggio, personal communication). A sharp decline and intermittent absence of Alnus from the record indicates that the valley must have also been heavily managed and utilized for cereal production. Only through constant maintenance of the drainage system was it possible to prevent the basin from becoming marshland (Coccia et al., 1992). This maintenance was probably aided by a drier than normal climate (Fig. 14) and large available labor force. A possible explanation for the new phase of exploitation of the valley is that the slopes were not sufficient to maintain the needs of the increasing population (Naspi, 2010).

Following the MWP thermal maximum, the initial cooling of the LIA began, reaching a temperature anomaly of −0.8 °C about 1310 CE (Fig. 14; Büntgen et al., 2011; Christiansen and Ljungqvist, 2012; Trachsel et al., 2012). The black plague of 1347 CE, and subsequent famines and plagues resulted in a local population decline of >50% by 1400 CE (Leggio, 1989). Cooler than average temperatures between 1350 and 1390 CE appear to have been a catalyst leading to collapse of the local land management system. As high elevation settlements were abandoned (Leggio, 1995b; Naspi, 2010) disturbance species decreased, and forest taxa and Alnus begin to steadily increase (Fig. 14).

4.5.6. Little Ice Age: rapid reforestation and reduced sedimentation (1390–1700 CE)

A combination of climatic change, plague, earthquakes and political instability led to a collapse of the local system by the early 15th century. Precipitation increased and temperatures remained cool (Büntgen et al., 2011; Christiansen and Ljungqvist, 2012). By ~1390 CE, the PDSI reconstruction from Morocco records anomalously wet conditions (Fig. 14), with peak wetness in the 15th and ~1390 CE, the PDSI reconstruction from Morocco records an anomaly of about 1310 CE (Fig. 14; Büntgen et al., 2011; Christiansen and Ljungqvist, 2012; Trachsel et al., 2012). The black plague of 1347 CE, and subsequent famines and plagues resulted in a local population decline of >50% by 1400 CE (Leggio, 1989). Cooler than average temperatures between 1350 and 1390 CE appear to have been a catalyst leading to collapse of the local land management system. As high elevation settlements were abandoned (Leggio, 1995b; Naspi, 2010) disturbance species decreased, and forest taxa and Alnus begin to steadily increase (Fig. 14).

The rock magnetic parameters (Fig. 5) indicate a significant event at the very end of the Medieval interval (337 cm depth, −1380 CE) followed immediately by changes in the geochemical data (Fig. 10) and representing a permanent change in the sedimentary dynamics in the lake. All clastic proxies (k, Ti, and smear-slide petrography) dropped to zero at 335 cm depth. Such a change required an abrupt adjustment to the sedimentary environment, cutting off all access of siliciclastic input. This shift coincided with a series of physical influences on the environment (strong earthquakes in central Italy (Galli and Nasso, 2009) and increased precipitation) as well as socioeconomic influences (depopulation following the Black Plague, local political instability). Historical documents of the second half of the 14th century report difficulties in managing the drainage system of the basin and consequent famine (Leggio and Serva, 1991). The geochemistry is very distinct with large peaks in Sr, S, and Ca (Fig. 10) that are indicative of changes in water chemistry and potentially a rearrangement of source waters to include a more SO4-rich source.

Increasingly cooler temperatures pushed people out of the highest elevation settlements, resulting in widespread land abandonment (Leggio, 1995b; Naspi, 2010) and rapid recovery of forests. Recurring plagues through the first half of the 16th century (Barbiera and Dalla-Zuanna, 2009; Tozzi, 2009; Alfani, 2010) reduced the Italian population to its lowest level in Medieval time (Fig. 14) by the mid-15th century (Capasso and Malanima, 2007). The peak in percent arboreal pollen and pollen accumulation rate ~1600 CE coincides with the coolest temperatures during the LIA (Ladurie, 1971). This pattern of land abandonment and reforestation following demographic decline from the black plague, and deterioration of the climate has been documented repeatedly throughout Europe (van Hoof et al., 2008; Yeloff and van Geel, 2007; Fraser, 2011). While the reforested phase in many northern European sites lasted until the 18th century (Leggio, 1971) for two centuries in Italy. Political instability and the persistent presence of mercenary bands made it increasingly unsafe to pasture livestock far from settlements and hunting and fishing became increasingly important (Lorenzetti, 1989). By the mid-15th century, the meat of deer and wild boar was less expensive than that of domesticated animals and predators such as bears and wolves were present (Leggio, 1995a) providing evidence for return of a functioning forest ecosystem. This pattern of the increased importance of game over domesticated animals has been documented in France as well (Vecchio, 1974).

Despite extensive land clearing and erosion during the Medieval Period, forests quickly recovered during the Little Ice Age (Fig. 14), although forest biodiversity did not return to the level of the Roman and pre-Roman periods. One possible reason for the quick recovery may have been associated with the practice of coppicing, in which, although dramatically thinned, stems remain in the landscape and stem sprouts grow rapidly in the absence of repeated cutting. High percentages of Alnus indicate that the basin must have been flooded through much of this period. The lake expansion in the 15th century was so widespread in the basin that the 1445 CE cadaster reported thirty-eight small lakes (Leggio and Serva, 1991); moreover in the historical maps of 1500–1600 CE the flooded area is expanded, often reported as a single lake.

Tree crops, particularly Olea (olive) and Juglans (walnut), became more important after 1390 CE (Fig. 11). Around 1350 CE, a set of local regulations were codified governing the pruning and maintenance of tree crops (Caprioli, 2008). During Medieval time, olives as well as walnut were not important food crops in this interior area of the Sabina (Leggio, 1995b; Naspi, 2010) but after 1390 CE they increased in abundance and became a larger proportion of the diet. Following an initial increase in Olea pollen, there is a distinct decrease in abundance between ~1550 and 1650 CE. Coincident with an intense cold period documented throughout central and southern Europe, with the coldest temperatures occurring in the late 16th and early 17th centuries (Ladurie, 1971; Trachsel et al., 2012; Moriondo et al., 2013). At least seven different years with olive-killing frosts were recorded in Provence, France between 1565 and 1600 CE (Ladurie, 1971). The Rieti basin is a marginal environment for olives and the decline in pollen is likely attributable to repeated killing frosts.

After 1600 CE Alnus pollen shows a continuous and permanent decline providing evidence for a lowering water table (Fig. 14)
despite steady or increased precipitation (Esper et al., 2007). Since
the 13th century, many efforts had been made to construct new
channels to remove water from the basin, including an unnamed
channel in 1325 CE, Cava Reatina (1422 CE), Cava Paolina (1547 CE)
and Cava Gregoriana (1575 CE). These efforts were largely unsuccess-
ful until construction of Cava Clementina in 1601 CE (Lorenzetti,
1989; Leggio and Serva, 1991). Decline in Alnus after 1600 CE ap-
ppears to be a response to human activity rather than climate.

4.5.7. Late Modern and Contemporary: modern forest with lake
eutrophication (1700 CE to present)

By the 18th century, the vegetation structure was essentially modern. Drainage of the basin removed all flooded forest and
agriculture included introduced crops such as Z. mays (Fig. 11). Cannabis type production peaked in the late 18th and early 19th
centuries, with the very high pollen percentages likely associated
with retting in pools adjacent to the lake (Celetti, 2007). The slopes
remained forested but contained much less biodiversity than the
original landscape, even though pollen percentages suggest that
total forest cover is not significantly less now than during the pre-
Roman period. The successional species Juniperus communis and
J. oxycedrus are now an important forest constituent whereas for
most of the record they were a minor component of the vegetation.
The lakes appear to have become increasingly eutrophic with
dramatic increases in diatoms, soft-bodied algae and calcareous
algae towards the present (Fig. 13). The intensity of human impacts
increased such that the human signal of environmental change is
much stronger than the climate signal.

5. Conclusions

Our 2700 year paleoenvironmental reconstruction on the fringes of Rome records a complex interaction between climate and
socioeconomic conditions as drivers of environmental change. The
influence of Rome on the Rieti Basin during the Roman Republican
Period seems to be modest. Despite the channel excavations that
formed the falls at Marmore and drained the basin, our multi-proxy
record indicates that the effects on both the aquatic ecosystem and
landscape were minimal. During the Imperial Roman Period, a time
of generally milder climate referred to as the Roman Optimum, there
is no evidence for deforestation in the Rieti Basin and only limited
impact on the environment, although Rome reached one million
inhabitants. The Roman Empire supported a complex trade
network that allowed importing resources from distant regions,
similar to modern globalization. Rieti was interconnected with
Rome and likely benefited from external resources, which reduced
pressure on its local resources, resulting in preservation of the
environment. With the fall of Rome, despite a cooler climatic period
associated with an interval of general disruption in central Europe
referred to as the Migration Period, the Ostrogoths filled the power
vacuum in Rieti and generally maintained an environment similar
to that which existed during the Roman period. Only with the
arrival of the Lombards and establishment of local monasteries at
the start of the Medieval Period (~600 CE) does deforestation become
apparent, with clearing for agriculture and selective removal of desirable tree species for housing and manufacture. This
period is manifested in a strong signal in the Lago Lungo record that
transgresses all of the biological, geochemical, and sedimentological
proxies.

The climatically optimal Medieval Warm Period appears to have
been a catalyst for expanded land use and widespread environ-
mental degradation. Local population was higher than during Ro-
man time, placing greater pressure on local resources, but another
possibly crucial difference was the lack of an interconnected trade
network capable of supplementing local resources. As population
grew and settlements expanded upslope, they likely pushed the
limits of what local resources were capable of supporting. When a
cooling trend began in the 13th century, the highest elevations
began to be abandoned and the forests began to recover somewhat.
By the late 14th century, plague devastated the local population.
Persistently cooler and wetter climate led to wide scale land aban-
donment and rapid reestablishment of the forest and wetlands.
Climate change, coinciding with earthquakes produced marked
changes in the local sedimentological regime of Lago Lungo,
including diversion of siliclastic input and altered lake hydro-
chemistry. The Medieval period in Rieti has a complex socioeco-

conomic history, but the evidence supports the argument that the
shift from warm and mild climate to cool and wet climate was an
important catalyst in disrupting the community. This disruption
lasted for nearly two centuries. By the 1600s, despite being one of
the coldest periods of the LIA, improved methods in hydrologic
works led to the eventual permanent draining of the basin and
renewed agricultural expansion which has continued to today.

The detailed reconstruction of climatic and environmental
changes from sedimentary records is dependent upon reliable
dating of the sedimentary sequences. In the case of Lago Lungo,
interpretation of the 14C dates is challenging; however the sedi-
ments are characterized by good paleomagnetic properties, with an
almost single-component ChRM that can be easily isolated with
stepwise AF demagnetization. The ChRM inclination and declina-
tion values oscillate around the mean values expected for the GAD
field at the site, but the amplitude and the frequency of the varia-
tion are too high for geomagnetic secular variation. The paleo-
magnetic trends (ChRM inclination, declination and relative
paleointensity) can be replicated at high-resolution between four
distinct cores, ruling out disturbance as a cause for this variation.
Regardless of the high-amplitude and high-frequency variation,
when broadly smoothed the reconstructed paleomagnetic trends
can be correlated to the reference curves from models of paleo-
secular variation (PSV) during the last 3000 years, as reconstructed
from archeomagnetic data collected across Europe. Together with
constraints coming from pollen and sediment analysis, the paleo-
magnetic trends allow the construction of a high-resolution age
model and indicate that some changes observed in the pollen
assemblage and in sedimentation in the Rieti basin can be associ-
ated to societal factors and others to climatic change. Paleomag-
netism is a powerful tool for providing alternative age models for
study sites with 14C records that are difficult to interpret. The rich
documentary record for the region provides an opportunity to
further explore questions of environmental change in relation to
societal versus climatic causes. Addressing some of these questions
will require further refinement of our age model to reduce temporal
uncertainty.

Contributions by authors

Mensing co-led the field coring, analyzed pollen, contributed to
development of the age model and climate proxy framework, and
oversaw the project; Tunno assisted in field coring and analyzed
pollen and charcoal; Sagnotti and Florindo conducted all rock
magnetism and paleomagnetism analyses and developed the PSV
age model; Noble created the core description, conducted smear
slide analysis and analyzed elemental chemistry; Archer analyzed
elemental chemistry; Zimmerman conducted all radiocarbon ana-
lyses and helped develop the age model; Pavón-Carrasco helped
develop the age model and associated error analysis; Cifani and
Passigli conducted historical archival research (Section 3.7),
contributed interpretation of historical documents, and specifically
authored historical sections in paragraphs 4.5.1, 4.5.2; 4.5.3 by G.
Cifani and paragraphs 4.5.4, 4.5.5, 4.5.6, 4.5.7 by S. Passigli;
Piovesan coordinated all Italian research components, co-led the field coring, interpreted pollen results in relation to local forest ecology, contributed to development of the age model and climate proxy framework and contributed to historical research. All co-authors contributed to writing the manuscript.

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