“Human and climatically induced environmental change in the Mediterranean during the Medieval
Climate Anomaly and Little Ice Age: a case from central Italy

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Within the Anthropocene, human activities can play a major role in environmental change, however identifying human caused landscape change is challenging and requires combining high-resolution physical proxies with detailed historical records from the same locality. In this study we demonstrate that paleoenvironmental change is the complex result of both human activity and climatic variation. We use pollen and geochemical analyses from lake sediments in central Italy and archival records to analyze landscape change for the last 1400 years, including the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). Between ~870 and 925 AD deforestation coincided with intensification of agriculture associated with development of monastic estates that exploited increasingly larger land holdings as well as new settlement patterns in higher-elevation defensible locations (incastellamento). Above average temperatures probably allowed high elevation settlements to persist throughout the MCA, though social trends played a large role in the conversion of uplands into an agro-pastoral landscape. Cool temperatures and increased precipitation at the beginning of the LIA, ~1400 AD, combined with population loss to plague of >50 percent overwhelmed the technical capabilities of the population leading to abandonment of high elevation settlements and persistent flooding of the valley. The landscape rapidly reforested and the plain reverted to wetland. In 1601, during one of the coldest periods of the LIA, new hydrologic technology allowed the community to drain the wetlands and successfully mitigate the impacts of climate change. Despite increased LIA precipitation, the basin was steadily reclaimed and converted to agriculture by 1750 AD.

Introduction

Global concern over future climate change and its potential impact on society has placed a focus on understanding the relationship between climate and human activity. There is no doubt that climate influences human activities through extremes such as droughts, freezes, and floods, as well as periods of stasis such as prolonged periods of mild or inclement climate (Lamb, 1982; Ladurie, 1967; 1971; Pfister and Brázdil, 1999; 2006). However, human use of the environment takes place within a local socio-economic context, and while some land use decisions may be constrained by climatic limitations, a broad set of human (e.g. culture and technology) and environmental factors influence land use practices. There is now general recognition that paleoenvironmental change within the Anthropocene is the complex result of both human activity and climate (Dearing et al., 2008; Coombes et al., 2009; Munoz et al., 2010, McCormick et al., 2012), and that unicausal explanations of cultural expansion or collapse are overly simplistic (Dincauze, 2000; O'Sullivan, 2008; Aimers, 2011; Izdebski et al., 2015). Reconstructing human-induced paleoenvironmental change remains a challenge because sources describing human use of the landscape are limited, and distinguishing human impacts from climatic impacts is not a trivial problem. To the extent that we can combine high-resolution physical proxies of paleoenvironmental reconstruction with detailed historical records from the same locality we have the potential to gain new insights into the role of climate and human activities in impacting environmental systems (Berglund, 2003; Dearing et al., 2008; Coombes et al., 2009; Harris, 2013; Izdebski et al., 2015; Kemp et al., 2015). To achieve this we approach local climate changes within an historical framework of *longue durée* (Leed, 2010).

The Medieval Climate Anomaly (MCA), between ~900 – 1350 AD (Graham et al., 2011) and the subsequent Little Ice Age (LIA), between ~1400 and 1850 AD (Mann, 2002) are arguably the two most

important periods of recent climate change that impacted societies, particularly in Europe where the climatic influences have been extensively documented (Lamb, 1982, Ladurie, 1971; Pfister and Brázdil, 1999; 2006). The Medieval period was also a time of dramatic socio-economic change with the development of new economic models, expansion of the role of the church through monasteries, and shifting political influences (Hodges, 2012). Europe is one of the few places with extensive written documents for >1000 years, providing an opportunity to compare the historical record of socio-economic activity with the physical proxy record of environmental and climate change. A rich documentary record exists in the Rieti region of central Italy, through monastic writings and community records (Leggio 1986; 1989; 1992; 1994; 1995; 2007; Leggio and Marinelli, 1995; Lorenzetti, 1989, 1990, 1994, 2009). In this paper we take advantage of the trove of medieval documents from the Rieti region in central Italy and compare this with a high-resolution paleoenvironmental reconstruction using multiple proxies from sediment cores recovered in the Rieti basin to interpret landscape change within the context of both climatic change and historical development. Our goal is to use this case study to document abrupt environmental change in relation to the local history and regional climate in an effort to evaluate the extent to which these changes might be explained by socioeconomic factors, climate change, or the complex interaction of the two.

Study Area

Rieti (Reate in Latin) was settled by the Sabini in the Early Iron Age ~2800 years ago, although archaeological evidence indicates that the region was largely abandoned towards the end of the period with virtually no occupation by the time the Romans established a presence ~300 BC (Cifani, 2003). The Rieti Basin is an intermontane depression in the Central Apennines (Fig. 1) connected with Rome by the ancient Via Salaria (Coccia et al. 1992). Water level in the basin was controlled by the elevation of a

travertine sill at Marmore where the Velino River exits the basin (Calderoni et al., 1994) and local hydrologic engineering efforts have played a major role in environmental changes in the valley. During pre-Roman times the basin held one large lake, *Lacus Velinus*, though by early Roman time it is thought that the basin was an expansive wetland dotted with lakes (Lorenzetti, 1990; Calderoni et al., 1994). Written documents suggest that the Romans cut a channel through the travertine sill ~270 BCE to drain the basin for pasture and agriculture (Coccia et al., 1992). The basin has been continuously utilized for farming and pasture since then although maintaining drainage in the basin has been a continuous challenge. Following Roman occupation, the basin was controlled by the Ostrogoth until it fell to the Lombards in 590 AD. Monasteries have been important from an early time with the founding of the Farfa Monastery by the Benedictine Order between 550 and 560 AD and foundation of San Salvatore Maggiore Monastery within the Rieti basin in 735 AD (Leggio, 1992; 1995). The monasteries controlled use of the lakes including fishing and shrimp production (Coccia et al., 1992). During this period the governance of the region was established through the Duchy of Spoleto (Leggio, 1992). In 774 AD Charlemagne conquered northern Italy and Rieti became the southern frontier of the Carolingian Empire. An important period of urbanization began about 1000 AD with the chartering of multiple fortified hill towns around the basin (Coccia et al., 1992). Throughout the Medieval period, community records and historic maps dating from the 16th century describe the successive phases of drainage works critical to preventing the basin from becoming a marsh (Leggio 1992; 1995; 2007; Lorenzetti 1990; 1994).

Today, four remnant lakes persist, Lago Lungo, Ripasottile, Ventina and Pieidiluco (Fig 1). Our site, Lago Lungo, (369 a.m.s.l.) has a maximum depth of up to 7 m with a surface area of 0.78 km² (Riccardi, 2006). The basin is cultivated for maize and cereals and the hillsides and the surrounding hill slopes are covered in coppiced stands of mixed deciduous forest dominated by oaks and hop-hornbeam. Sedimentation rates in the Apennines are among the highest across Europe (Panagos et al., 2015), averaging 10-20 tons

ha⁻¹ yr⁻¹. Detailed description of local vegetation and geology are published in Mensing et al. (2015). The area has a Mediterranean precipitation pattern with 1117 mm annually falling predominantly in winter. Mean annual temperature varies between 4 °C in January and 21 °C in July (Fig. 4.29 in Leone, 2004). The 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; López -Moreno et al., 2011).

Methods

Sediment cores were recovered in 2009 and 2012 using a hand operated square-rod Livingstone corer from a floating platform anchored in the deepest part of the lake. Surface sediments were recovered with a plastic tube core specially fitted with a piston to produce minimal disturbance of the sediment-water interface. The unconsolidated surface sediments were stabilized with Zorbitrol (sodium polyacrylate absorbent powder) while the core was still in an upright position. Three overlapping cores were analyzed for this study; LUN12-2C, the surface core, LUN09 and LUN12-2B. Core chronology was developed from historical documentation of biostratigraphic markers and paleomagnetic secular variation (PSV) and the age model and detailed core stratigraphy are described in Mensing et al. (2015).

A total of sixty-six samples (0.625 cc volume) were processed for pollen analysis using acid digestion procedures (HCL, KOH, HF, Acetolysis, TBA; Faegri and Iverson, 1985). Slides were mounted with silicon oil. 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 – 605 cm depth.

Duplicate counts were similar so in the overlapping section we used only the counts from LUN12-2B because they were done at a later date. A minimum of 400 terrestrial pollen grains were counted per sample except for samples with very low concentration rates ($n = 21$, average accumulation rate = 7864 grains $\text{cm}^{-2} \text{yr}^{-1}$; average accumulation rate for all samples = 26,069 grains $\text{cm}^{-2} \text{yr}^{-1}$), 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 Paleoecology Lab, published keys and manuscripts (Punt and Malotau, 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 $>37 \mu\text{m}$, pore diameter was $> 2.7 \mu\text{m}$ and annulus thickness was $> 2.0 \mu\text{m}$, following Köhler and Lange (1979). Pollen percentages were calculated from the sum of terrestrial pollen and fern spores, excluding indeterminate grains and *Cannabis* type (which was retted in the lake at certain periods; Poni and Fronzoni, 2005). Accumulation rates (grains $\text{cm}^{-2} \text{yr}^{-1}$) were calculated by dividing concentration (grains cm^{-3}) 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.

We used cluster analysis to sort taxa into eco-functional groups using the Past software ((Hammer et al. 2001). This analysis helps identify the main vegetation and land use types so that when plotted over time historical trends in landscape dynamics can be easily compared. Hierarchical Clustering was performed using the unweighted pair-group average (UPGMA) function. Clusters are joined based on the average distance between all members in the two groups and the Rho similarity measure.

Elemental geochemistry data were measured the ITRAX x-ray fluorescence (XRF) scanner (Cox Analytical Instruments) at the Large Lakes Laboratory in Duluth, Minnesota. Cores were scanned at a resolution of 0.5 cm or 0.2 cm in banded sections using a molybdenum source, 30 second dwell-time, a voltage of 30 kV and an x-ray current of 30 mA to obtain peak areas for elements Si-Pb. Time series plots were generated for a subset of elements determined to be of interest as sedimentologic and lake geochemical proxies (including Ti, Fe, Mn, Ca, and Sr). Here only the Ti data will be presented.

Archaeological documentation is largely represented by surveys carried out in the 1980s by the University of Perugia (Carancini et al., 1986; 1990) and in the 1990s by the British School at Rome (Coccia et al., 1992; 1995). Historical documentation of the early medieval phase is well preserved in 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). Names for historical periods follow the system developed by Coccia et al. (1995) based on changes in archeologic ceramics in the Rieti Basin.

Results

Ninety different pollen types, nine non-pollen palynomorphs (NPP) and eleven algae types (not shown) were identified. Cluster analysis (Fig. 2) identified three eco-functional groups: Grassland and disturbance taxa; forest taxa; and cultivated plants and early pioneer forest taxa. *Pinus* grouped with grassland and disturbance taxa, possibly because it is not a common constituent of the local forest and appears in disturbed habitats through long-distance transport. Selected pollen and NPP are presented in Figs. 3 & 4). Four pollen zones for Lago Lungo follow Mensing et al. (2015). LL-2B (970 – 800 cm; 600 to 870 CE) corresponds to the Early Medieval period. LL-3 (800 – 335 cm; 870 to 1390 CE), corresponds to Medieval through Late Medieval time, LL-4 (335 – 140 cm 1390 to 1730 CE) corresponds to the Early Modern and Modern periods, and LL-5 (140 – 0 cm; 1730 CE to present) corresponds to the late Modern through Contemporary periods.

During LL-2B (600 to 870 AD) the Rieti basin is largely a forested landscape (Fig. 3). Deciduous oaks (*Quercus*) become increasingly important through this period and other mesophyllous forest taxa including hop-hornbeam (*Ostrya*), beech (*Fagus*), hazel (*Corylus*), hornbeam (*Carpinus betulus*) and members of the Rose family such as *Prunus*, *Pyrus*, *Malus*, *Sorbus*, *Crataegus* and *Rosa* (Rosaceae) remain present although in low percentages. Herbaceous taxa, predominantly grass (Poaceae),

members of the subfamily Chicorioideae, such as chicory, and Trilete and Monolete fern spores are present in quantities typically below 10% of the pollen sum (Fig. 3). Pollen of cereals is present but at <1%. Alder (*Alnus*) remains at a very high percentage (20%) until about 800 AD at which point it begins to decline sharply. Also about 800 AD sedimentation rates increase from 5 to 12 mm yr⁻¹, their highest levels for the core.

After 870 AD the forested landscape was rapidly converted to become dominated by grassland and disturbance taxa. Percentages of all forest taxa decline in importance, replaced by grass, chicory type, ferns and an increase in disturbance taxa such as Queen Anne's lace (Apiaceae), plantain (*Plantago lanceolata*), sage (*Salvia*), knotweed (*Polygonum aviculare*), *Silene*, (Caryophyllaceae), asters and yarrow, (Asteraceae). Cereal pollen increases by 870 AD to average between 2 and 4% until 1050 AD, and remains important throughout most of LL-3. At 870 AD there is also a quick rise in the non-pollen palynomorphs *Glomus*, an indicator of increased erosion, and *Sporormiella*, a coprophilous fungi associated with the dung of domesticated livestock (Fig. 4). The element Ti, a proxy for siliclastic input is increased in this zone (Fig. 4) as is the calculated sedimentation rate, indicating increased erosion washing terrigenous material into the lake. Trilete ferns become particularly important between 950 and 1100 AD. About 1100 AD sedimentation rates drop to 7 mm yr⁻¹, less than previous but still higher than the early medieval period. An interesting pattern in LL-3 is the high variability of tree pollen. Although the zone is dominated by herbaceous pollen, there are multiple short periods when tree pollen increases rapidly to 50% of the pollen sum. This variability is seen among all forest taxa but particularly oak and alder (Fig. 3).

By 1400 AD in LL-4 there is once again a rapid conversion of the landscape back to a forested environment with the highest percentage of arboreal pollen for the record (Fig. 3, 4). Forest recovery is particularly strong for oaks (deciduous and evergreen – *Q. Illex* type), hop-hornbeam, beech and alder. The period of peak forest recovery is between 1500 and 1650 AD when total pollen accumulation rate (primarily arboreal pollen) is far higher than at any other time in the record. Herbaceous pollen decrease rapidly in this zone and disturbance taxa that were common become rare (Fig. 3). Cultivated trees including olive (*Olea*) and walnut (*Juglans*) become important for the first time. Cereal pollen remains present but in lower percentages, however there is a big increase in hemp (*Cannabis*) pollen. The NPP *Glomus* declines to zero and *Sporormiella* is sharply reduced (Fig. 4). After 1600 AD percent arboreal pollen decline from a high of 89% to stabilize at about 60% for the rest of the record. Percent alder pollen also declines after 1600 AD from 15% to <2% by 1740 AD (Fig 3, 4).

In LL-5, the modern period, cultivated plants and pioneer forest taxa become important. The most significant changes are the presence of TCT pollen (*Juniperus* and *Cupressus*) and pine (*Pinus*) in abundance for the first time in the record and the absence of alder (Fig. 2). Mesophyllous taxa that had increased in abundance between 1400 and 1600 AD (beech, hornbeam, and elm), are now only present in minor amounts and oak and hop-hornbeam are the most common tree types. Cultivated taxa increase in importance with the arrival of maize (*Zea mays*) and peak in hemp pollen about 1790 (Fig. 3). Nettle (*Urtica*), a weed associated with cultivated fields also increases.

Discussion

Independent climate change reconstructions

There are no millennial-length high resolution temperature or precipitation reconstructions from peninsular Italy, therefore we rely on reconstructions from the western Mediterranean, Alps and northern Europe for independent climate records (Fig. 4).). The longest precipitation series available comes from a tree-ring reconstruction of the Palmer Drought Severity Index – (PDSI) in Morocco using *Cedrus atlantica* (Endl. Carrière; Esper et al., 2007). A reconstructions of the NAO from speleothems in Scotland (Baker et al., 2015) largely agrees with the PDSI reconstruction, with strongly positive NAO coinciding with periods of low precipitation in the western Mediterranean and negative phases coinciding with increased precipitation (Fig. 4). We therefore use the NAO as a proxy for precipitation for the period with no PDSI reconstruction (before 1000 AD). A lacustrine oxygen isotope record from Pergusa Lake in Sicily (Sadori et al., 2015) has been used to interpret precipitation for southern Italy and we use this record to corroborate the regional precipitation reconstructions.

The closest millennial length high-resolution temperature records are a speleothem temperature reconstruction from the central Alps (Magnini et al., 2005) and a a multi-proxy summer temperature reconstruction (Trachsel et al., 2012) using tree-ring widths and ring density as well as chironomids and biogenic silica from lake sediments, from the European Alps (Fig. 4). Advances of the Calderone glacier in the central Apennine along with periods of periglacial activity, although at a low temporal resolution, provide local evidence for extended cool periods (Giraudi, 2005) that we use to corroborate the regional temperature reconstructions.

Early Medieval Period

Between 600 and 870 AD the NAO was negative or neutral suggesting above average to average precipitation (Fig. 4). Isotope data from Pergusa Lake in Sicily indicate southern Italy was wetter between ~450 and 750 AD (Sadori et al., 2015), confirming that this was generally a wet period. Documents from Farfa monastery note that *Lago Maggiore* (Ripasottile) and *Lacus Totonni* (Lungo) enlarged however did not merge (Leggio, 1989) and that the plain was studded by numerous very small lakes (*lamae*) and wetlands. Temperature reconstructions from the Alps indicate a cooling trend from 630 – 750 AD followed by warming until 840 AD then cooling until about 920 AD (Fig. 4) (Magnini et al., 2005). Advances of the Calderone Glacier between ~700 and 1000 AD (Fig. 4) support this as a generally cool period in central Italy (Giraudi, 2005). . Percent arboreal pollen, particularly oak, increased consistently until 860 AD suggesting that for the most part, the Rieti Basin remained well forested; however, from 825 AD onward, alder steadily decline and after 860 AD forest cover declines rapidly (Fig. 4). Alder require a high water table and without constant management of the drainage system, the Rieti basin tends towards becoming marshland (Coccia et al., 1992). Given the descriptions of rising water in the valley, we interpret the decline in alder pollen as the beginning of forest clearing, not a climatic response, with the initial phase the clearing of riparian woodland in the valley. A doubling of sedimentation rates supports the interpretation of loss of forest cover near the lake and probably at higher elevations.

870 – 925 AD: Rapid conversion of forest and agricultural intensification

In less than a century, between ~870 and 925 AD, the Rieti basin and surrounding hills and mountains were converted from a well forested landscape to open fields in what would appear to be a dramatic environmental change (Fig. 4). The NAO switched from a negative to positive phase ~900 AD, suggesting a shift to a drier climate, although temperatures appear to have been cool or cooling during this period

(Fig 4.). The rapid forest change appears to have occurred during a cool transitional period.. The ninth century was a time of important socioeconomic transition throughout Europe with impacts on changes in land ownership and agrarian intensification (Hodges, 2012) and human impacts on the environment were driven by societal change as well as climatic change (Sereni,1972)

Monasteries in central Italy went through a transformation in the 8th and 9th centuries as seen in detail from an analysis of San Vincenzo Maggiore (Hodges, 1993; 1995) south of Rome. Archaeological and textual evidence support a shift from a sacred monastery to an economically important center with land holdings and increased intensification of agriculture and keeping of livestock. This shift appears to have been driven to some extent by economics, with a change in patron support away from the Beneventan royal household to a ritual economy in which families donated property in return for performance of penances and masses for intercession into heaven (Angenendt, 2008). This process made monasteries among the largest landholders of the time and increased their political power. At San Vincenzo, salvation was exchanged for land, making monasteries part of the feudal land arrangement with peasants and resulting in an agricultural intensification of their land holdings by ~840 AD (Hodges, 2012). While we do not have as clear a historical record of this transformation in Rieti, the San Salvatore Maggiore monastery under the auspices of Farfa was constructed in Rieti in 735 AD and there are records of donations of land to the monastery in the 8th and 9th centuries (Regesto di Farfa II, doc. 16; III p.102, doc.400; II, p.128, doc. 152, su cui Petrucci; Dupré, 1939; Barker et al., 1988; Leggio, 1992; Leggio and Marinelli, 1995). Archaeological evidence of the proliferation of silos and granaries throughout Europe in the 9th century provides evidence for a period of agricultural intensification and a shift to greater cereal production (Hodges, 2012). The ox plough allegedly arrived in central Italy in the 9th century making it possible to cultivate heavier soils (Fowler, 2002; Hodges, 2012), such as those on the valley floor of the Rieti Basin. At the same time there is archaeological evidence for increased

intensification of livestock, potentially associated with the increase seen in storage of grains (Hodges, 2012).

The sedimentary proxy records (Fig. 3, 4) provide evidence for agricultural and pastoral intensification and show a dramatic increase in cereals beginning ~860 AD, an increase in *Sporormiella*, an indicator of livestock, increased disturbance taxa and dramatic reduction in forest cover. Forest loss agrees with written records describing the first clearing of trees at higher elevations in the Rieti area (Leggio, 1989). In 1053, an exceptional flood was partially attributed to the increased rate of forest clearing in the Reatini Mountains from the 9th through 11th centuries (Leggio, 1986).

Exploitation of upper elevations during the Medieval Period

By Medieval time, and continuing into the late medieval period archaeology of the Rieti Basin shows that major settlements were relocated to higher elevations and more defensible positions (Coccia et al., 1995). Invasion by Arab Muslims resulted in the burning of San Salvatore Maggiore monastery in 891 AD, Farfa in 897 AD and the town of Rieti in 900 AD (Schuster, 1921). From the 10th century onward written sources first begin referring to fortifications (Coccia et al., 1992). Medieval sites were either castles, nucleated settlements, or small sites close to one of these two types of defensible settlement. The land close to the basin floor became more remote from the main settlements and highly vulnerable to devastation as Rieti became a contested border region between the Papal State and the Kingdom of Naples (Coccia et al., 1995). Isolated patches of farmland were abandoned during this new period termed *incastellamento*, and the practice of living in dispersed settlements largely ended (Leggio, 1989).

There is historical and archaeological evidence across Europe to suggest that the aristocracy reestablished authority over rural territories during the 9th century (Hodges, 2012). In Rieti, the Duchy of Spoleto gave land to families of the aristocracy in upland areas around Rieti to build churches and establish small settlements to exploit the land for economic gain and secure the frontier border (Leggio, 1989). Between 1050 and 1200 AD at least forty-one settlements are mentioned for the first time in the Farfa documents (Coccia et al., 1992), most built above 500m elevation and some above 1000m (Fig. 1). Evidence for agriculture at higher elevations is supported by the many terrace walls found at elevations between 700 and 1,000 m (Coccia et al., 1992). Both written records and archaeological evidence suggest a population increase during this period and increasing use of higher elevation sites suitable for farming and pasture (Coccia et al., 1992). Forest cutting up to 1400 m to provide openings for agriculture and grazing as well as production of wood implements resulted from incorporation of the San Egidio monastery into the Cistercian monastery of San Pastore (Leggio, 1994).

Declines in all upland forest taxa and dramatic increases in disturbance taxa such as ferns, chicory, grass and plantain between 900 and 1250 AD support the argument for extensive exploitation of the hill slopes surrounding the Rieti Basin. High values of sedimentary Titanium and *Glomus* support increased erosion and sedimentation rates (Fig. 4). The historical evidence suggests that concerns for safety combined with agricultural expansion to exploit new socioeconomic relationships, rather than climatic pressure, initiated conversion of forests for cultivation and pasture. Warmer than average temperatures combined with drier than average climate undoubtedly facilitated the successful expansion of agriculture around high elevation settlements. A sustained period of warmer drier climate appears to have supported the continued expansion of the upland environment for several centuries. Sicily also experienced warmer drier climate between 1100 and 1350 and the region became a major supplier of wheat for the urban centers of northern Italy (Sadori et al., 2015).

Human Impacts on the Valley Floor during the MCA

The presence or absence of alder pollen is our best indicator of the level of the water table and the presence of wetlands in the Rieti valley. Increases and decreases in alder are associated with management of the basin in response to increased flooding and expansion of marshland. From the 14th through 16th centuries, periodic reclamation projects were designed to drain the basin (Dupre, 1939; Lorenzetti, 1989; 2009). Records of major floods of the Tiber River through Rome began an upswing in the 14th century, reached a maximum in the 15th century with a total of seventeen major floods, an average of one every six years, and continue through the 16th century (Bersani and Bencivenga, 2001). Fluctuations in percent alder pollen coincide with these wet phases, with declines often associated with either dry periods, or the timing of reclamation projects (Fig. 4).

Between 1000 and 1100 AD alder pollen is nearly absent (Fig. 4), suggesting that the wetlands must have been effectively drained and deforested. High percentages of cereal pollen during this period further suggest that the valley was effectively farmed, even if not widely inhabited (Coccia et al., 1992). A positive phase of the NAO between 950 and 1050 AD (Fig. 4) and associated drier climate probably made draining the valley an easier task.

Between 1100 and 1200 alder pollen increases. Although precipitation was well below average, and temperatures remained above average, written records attest to the growth of wetlands in this period, both through extraordinary events such as the flood of 1053, and in forms of economy linked to the

exploitation of wetlands for fish and shrimp as well as transport by boat (Leggio, 1994; 1998). The valley was covered by numerous water bodies by ~1200 (Dupré, 1939). In 1209 the municipality of Rieti donated marsh lands near Ripasottile to the Cistercian monks of the San Matteo monastery to reclaim it (Leggio and Serva, 1991; Leggio, 1994; Caciorgna, 1998). The wetlands had an economic potential, but it was far below the full agricultural potential of the same land after reclamation (Coccia et al., 1992). The Benedictine and Cistercian orders are documented to have worked extensively to expand agriculture through building and maintaining ditches and draining land both to reduce risk of malaria and reclaim land (Sabbatani 2005; Fraser 2010). New reclamation efforts began in 1209 AD and records from 1212-1214 AD indicate that the Cistercians were plowing the plain and intensifying cereal cultivation. (Leggio, 1994; Caciorgna, 1998). As the value of the reclaimed land increased legal challenges were made to better determine property boundaries (Dupré, 1939; Leggio, 1994). By 1250 increasing population was also putting greater pressure on expanding agricultural production in the valleys leading to new efforts to drain more wetlands and in 1277 the municipality of Rieti obtained permission from the Farfa monastery to excavate a new channel to divert water. The work appears to have increased flooding in the town of Terni below the Marmore falls leading to complaints and did not effectively drain the wetlands in Rieti (Leggio and Serva, 1991; Leggio, 1994). An increase in alder pollen between 1300 and 1320 suggests continued expansion of wetlands in the basin and this is supported by numerous documents showing concern over the increasing problem of wetlands and floods (Leggio, 1995). In 1325 AD the town of Rieti built a new water diversion channel (Leggio, 1995), which appears to have been successful given the decline in alder pollen (Fig. 4), however, the climate was becoming less favorable creating new challenges to the population.

Little Ice Age cooling, abandonment of high elevations and flooding of the plain

By 1250 AD a cooling trend had begun (Fig. 4), by ~1310 AD the northern hemisphere experienced a temperature anomaly of -0.8°C (Büntgen et al., 2011; Christiansen and Ljungqvist, 2012; Trachsel et al., 2012). and by 1400, glacial expansion had begun in the central Apennines (Giraudi, 2005). The black plague of 1348 AD, followed by subsequent plagues in Rieti in 1363, 1374 and 1400 AD resulted in a local population decline of $>50\%$ (Leggio, 1989). In 1384 AD, the Rieti council discussed the problems of flooding in the plain, concern over the associated decrease in harvests and interruption of transport on roads, even though rainfall was not excessive (Leggio, 1995). There was also a concern that the expanding marshes were leading to the return of malaria. High elevation settlements in the Sabini and Reatini mountains were abandoned at this time (Leggio, 1995). Work begun in 1385 AD on digging a new canal was quickly abandoned due to widespread famine after poor harvests and instead the solution of cutting trees along the banks to increase the flow of water was implemented. Between 1385 and 1410 AD the community archives of Rieti contain regular mention of flooding, disputes with the people of Terni downstream, and mention of constructing new canals to solve the mounting hydrologic problems in the basin (Lorenzetti, 2009).

Tree-ring reconstructions show a continuous increase of precipitation between 1400 and 1450 AD (Esper et al., 2007) in association with the NAO shifting to a negative phase (Trouet et al., 2009; Baker et al., 2015). A shift to wetter climate is also seen in southern Italy between 1400 and 1800 (Sadori et al., 2015). Though temperatures were variable, on average they were much cooler than during the MCA (Fig. 4). The shift to a cooler wetter climate brought environmental changes that the local municipalities were not well equipped to address. There was a sharp break in settlement patterns in the second half of the 14th century with the diminishing population increasingly moving into fortified settlements for greater security in response to repeated mercenary attacks and a decrease in the total number of settlements (Leggio, 1989; Coccia et al., 1992). Abandonment of settlements at higher elevations led to

rapid reforestation of previously productive land (Fig. 4). We suggest that the apparently rapid restoration of the forest ecosystem in just a few decades was due to medieval land use practices of swidden agriculture and forest coppicing. Swidden maintained a heterogeneous landscape with patches of cultivated land and forest, and trees were coppiced to provide fodder for livestock and fuel for cooking. Vegetative propagation from coppice was an important mechanism for the quick establishment of high forest. 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, 1995) 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).

Increased flooding also reduced agricultural land in the plain, but efforts to drain the land resulted in increased flooding of towns downstream leading to disputes and even armed clashes (Dupré, 1939). Local disputes led Braccio da Montone, governor of Umbria (including Rieti and Terni), to commission Fioravante Fioravanti of Bologna to construct a new canal, *Cava Reatina* (Fig. 4), which when completed in 1422 unfortunately resulted in flooding of the Tiber in Rome (Dupré. 1939).

Repeated efforts over the next century to clean the canals and keep the plain drained were largely unsuccessful because repeated floods continually filled the drainage channels with sediment (Dupré, 1939). Paintings and maps of the basin from the 16th century show that Lungo and Ripasottile were joined into one large lake (Fig. 5), and after one flood in 1445 AD the land registry recorded a land owner having 38 small lakes on their property (Archivio di Stato di Rieti; Lorenzetti, 1989).. Once again a major work was commissioned, *Cava Paolina*, completed in 1547 AD, at the direction of the Pope, although the state of hydrologic knowledge was still limited. The small decline in alder pollen suggests

that there was some short term success (Fig. 4), however it did not make a lasting impact (Lorenzetti, 2009). Similarly, *Cava Gregoriana* (1575 AD) was a failure. Finally, in 1596 the architect Giovanni Fontana was commissioned to create a new channel by Pope Clemente VIII (Lorenzetti, 2009). Fontana was later commissioned to build the Fontana dell' Acqua Paola that brought clean drinking water from near Lake Bracciano to Janiculum Hill in Rome, and is still functioning today. The abilities of hydrologic engineers in Renaissance Italy had been continually improving and Fontana's skills resulted in a drainage canal that finally effectively reclaimed much of the Rieti basin, dramatically modifying the landscape and opening new lands that resulted in producing fortunes for several important families (Lorenzetti, 2009; Archivio di Stato di Rieti, Archivio della famiglia Vecchiarelli, nn. 23, 25, 28, 30). Precipitation reconstructions show that this was a period of about average precipitation (Fig. 4) however it was one of the coldest periods of the LIA when freezing temperatures were challenging communities throughout Europe (Ladurie, 1971). Despite being in the middle of the LIA, the improved technology combined with sufficient labor and financial support resolved the drainage problems that had plagued the community for two centuries. As precipitation again increased in the 1600s, Ripasottile and Lungo still remained merged into one lake (Fig. 5) but the slow continuous decline in alder pollen demonstrate that the reclamation project was successful and by 1750 AD most of the basin was completely reclaimed. Dispersed settlements once again appeared on the plain and increased throughout the modern period (Coccia et al., 1992). Permanent agriculture was established including expansion of hemp production and introduction of maize (Fig. 3).

In the last 200 years, pioneer forest taxa such as *Juniperus*, and *Phillyrea* have invaded meadows and woodlands, and *Pinus* was planted as part of reforestation projects (Fig. X). Cultivated trees such as *Olea* and *Juglans* have expanded on the landscape, and as cultivation has increased associated agricultural weeds (*Urtica*) have also increased (Fig. 3).

Conclusions

Our study demonstrates that within the Anthropocene, paleoenvironmental change may be the result of the complex interaction between human activity and climatic variation. The MCA and LIA provide an important climatic backdrop to environmental change in the Rieti basin of central Italy, but examination of the socioeconomic context within which land use change took place demonstrates that the timing and magnitude of environmental impacts was closely linked to local activities. There are three important phases in our record for interpreting landscape change within the context of both climatic and historical events. The first phase was between 870 and 925 AD with rapid forest conversion into grassland and pasture prior to the warm dry optimum of the MCA. Climate reconstructions of the MCA suggest that above average temperatures and drier conditions did not appear until after 925 AD, however rapid conversion of the environment from a forested landscape to an open landscape had already occurred by that date. Forest clearing and increased cereal production in Rieti coincide with a Europe-wide trend in the 8th and 9th century for an intensification of agriculture associated with the development of monastic estates that exploited increasingly larger land holdings (Hodges, 2012). This landscape conversion also coincides with a new settlement pattern in higher-elevation defensible locations, and a tendency for the aristocracy to reestablish authority over rural territories (Hodges, 2012). Social trends, rather than climate, played a large role in the initial conversion of the uplands into an agro-pastoral landscape. As the MCA reached an optimum, these high-elevation settlements thrived and no doubt were able to persist due to a warm dry climate; however political instability was crucial to the exploitation of high-elevation sites.

The second phase was the early stages of the LIA when a shift to a cool and wet climate appears to have clearly overwhelmed the technical capabilities of the population to either maintain their high elevation

settlements or drain the wetlands in the plain. Cool temperatures and increased precipitation led to land abandonment and a rapid return of forest. The pattern of land abandonment and reforestation has been documented repeatedly throughout Europe (Tinner et al., 2003; van Hoof 2006; Yeloff and van Geel, 2007; Fraser, 2010; Sköld et al., 2010). It has further been shown that cool climate was the most significant element affecting food prices in Germany during the LIA (Pfister and Brazdul, 1999). In the plain, increased precipitation resulted in continued flooding, expansion of wetlands, and reduced arable land. Despite concerted efforts to reclaim the plain, the community was unsuccessful and the landscape reverted to an environment similar to that before the MCA. Decimation of the population through repeated plagues certainly played a part in this, but it is clear that extended cool and wet conditions led to disruption of the local society. In contrast, the wet phase beginning in 1400 in Sicily led to economic recovery and a diversified agricultural system (Sadori et al., 2015). The NAO produces a see-saw effect with dry climate in the eastern Mediterranean during negative phases, but wet climate in the western Mediterranean (Dermody et al., 2012). When the Romans controlled the entire Mediterranean, they were able to exploit this effect by shifting the location of their resource base (Dermody et al., 2014). Medieval populations had to simply adapt to local climate change. This is clearly illustrated by the different impacts the shift in NAO at the beginning of the LIA had on people in Syria as compared with our site in central Italy. In Syria, an abrupt shift to drier climate ~1400 AD is associated with heavy depopulation and a shift from a sedentary village life to a nomadic life (Kaniewski et al., 2012).

The final phase of landscape change in Rieti that is important in this context occurred in 1601 AD with the construction of *Cava Clementina* and the successful reclamation of the basin. This occurred during one of the coldest periods of the LIA (Ladurie, 1971) and is not associated with a more favorable change in climate. Rather, it is clearly associated with a technological advancement in hydrologic engineering during the Renaissance and illustrates a pre-industrial example of successful mitigation of environmental

impacts caused by climate change. By 1750 AD the modern landscape was well established and human impacts largely overwhelm the climate signal on the landscape. Within the last 200 years, pioneer forest taxa have invaded through a process of secondary succession, and planting of cultivated trees and crops has become widespread.

Bibliography

- Aimers, J., 2011. Drought and the Maya; The story of artefacts. *Nature* 479, 4-5.
- Angenendt, A. 2008. 'Donationes pro anima: gift and counter gift in the early Medieval liturgy', in J.R. Davis and M. McCormick (eds) *The Long Morning of Medieval Europe: New Directions in Early Medieval Studies*: 131-54. Aldershot: Scolar Press.
- Baker, A., Hellstrom, J.C., Kelly, B.F.J., Mariethoz, G. And Trouet, V. 2015. A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia. *Nature Scientific Reports*, 5: 10307.
- Barker, G. Clark, J. Giorgi, T. Leggio, J. Moreland,. 1988. *Insedimento altomedievale ed uso della terra nei dintorni di Farfa. Approccio storico-archeologico*, in *Archeologia laziale IX*. Nono incontro di studio del Comitato per l'archeologia laziale, Quaderni del Centro di studio per l'archeologia etrusco-italica, 16, Roma. pp. 424-431.
- Berglund, B.E., 2003. Human impact and climate changes—synchronous events and a causal link? *Quat. Int.*, 105, 7-12.
- Bersani, P., Bencivenga, M., 2001. *Le piene del Tevere a Roma dal V secolo a.C. all'anno 2000*, Roma: Presidenza del Consiglio dei Ministri: 8.
- Beug, H.J., 2004. *Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Geiete*. Pfiel (ed.), Munchen, 542.
- Blackmore, S., Steinmann, J.A.J., Hoen, P.P., Punt, W., 2003. The Northwest European Pollen Flora, 65. *Betulaceae and Corylaceae. Rev. of Palaeob. and Palynol.*, 123, 71-98.
- Bottema, S. 1975. The interpretation of pollen spectra from prehistoric settlements (with special attention to Liguliflorae). *Palaeohistoria*, 57, 17-35.

- Büntgen, U., Teleg, W., Nicolussi, K., McCormick, M., Frank, D., Trouet, V., Kaplan, J.O., Herzing, F., Heussner, K.-U., Wanner, H., Luterbacher, J., Esper, J., 2011. 2500 years of European climate variability and human susceptibility. *Science*, 311, 578-582.
- Caciorgna, M.T. 1998. Popolamento e agricoltura: aspetti della politica territoriale del comune di Rieti nel Duecento. In M.G. Grillotti di Giacomo and L. Moretti (eds.), *I valori dell'agricoltura nel tempo e nello spazio*, vol. I, Brigati, pp. 82-97.
- Caciorgna, M.T. 2000. Confini e giurisdizioni tra Stato della Chiesa e Regno. In E. Hubert (ed.), *Une région frontalière au Moyen Âge. Les Vallées du Turano et du Salto entre Sabine et Abruzzes*, Paris, pp. 307-326.
- Calderini, G., Calderoni, G., Cavinato, G.P., Gliozzi, E., Paccara, P., 1998. The upper Quaternary sedimentary sequence at Rieti Basin (central Italy): a record of sedimentation response to climatic changes. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 140, 97-111.
- Calderoni, G., Carrara, C., Ferreli, L., Follieri, M., Gliozzi, E., Magri, D., Narcisi, B., Parotto, M., Sadori, L., Serva, L., 1994. Palaeoenvironmental, palaeoclimatic and chronological interpretations of a late Quaternary sediment core from Piana di Rieti (central Apennines, Italy). *Giorn. Geol.*, 3, 56/2, 43-72.
- Carancini, G.L., S. Massetti, F. Posi, 1986. Gli insediamenti di età protostorica individuati nell'alveo dell'antico *Lacus Velinus*: dati e considerazioni. *Quaderni di Protostoria* 1 , pp. 65-91;
- Carancini, G.L. S. Massetti, F. Posi, P. Curci, P. Dionisi. 1990. Seconda relazione sulle ricerche di superficie eseguite nell'alveo dell'antico *Lacus Velinus* (TR-RI), in G. L. Carancini (ed.), *Miscellanea Protostorica*, Roma, pp. 1-185.
- Chester, P.I., Raine, J.I., 2001. Pollen and spore keys for Quaternary deposits in the northern Pindos Mountains, Greece. *Grana*, 40:6, 299-387.

- Christiansen, B, Ljungqvist, F. 2012. The extra-tropical Northern Hemisphere temperature in the last two millenia: reconstructions of low-frequency variability. *Clim. Past* 8, 765-786.
- Cifani, G. 2003. Storia di una frontiera. Dinamiche territoriali e gruppi etnici nella media valle tiberina dalla prima età del ferro alla conquista romana, Roma.
- Coccia, S., Mattingly, D.J., Beavitt, P., Elton, H., Foss, P. George, I., Hunt, C.O., Leggio, T., Patterson, H., Roberts, P., Brehm, T., Sudell, T., Sherratt, M. and Morton, K. 1992. Settlement History, Environment and Human Exploitation of an Intermontane Basin in the Central Apennines: The Rieti Survey 1988-1991, Part I. *Papers of the British School at Rome*, 60, 213-289.
- Coccia, S., Mattingly, D. J., Brehm, B., Elton, H., Foss, P., George, I., Leggio, T., Patterson, H., Roberts, P., Sudell, T., 1995. Settlement History, Environment and Human Exploitation of an Intermontane Basin in the Central Apennines: The Rieti Survey 1988-1991, Part II. Land-Use Patterns and Gazetteer. *Papers of the British School at Rome*, 63, 105-158.
- Coombes, P.M.V., Chiverrell, R.C. and Barber K. 2009. A high-resolution pollen and geochemical analysis of late Holocene human impact and vegetation history in southern Cumbria, England. *Journal of Quaternary Science*, 24(3), 224-236.
- Cugny, C., Mazier, F., Galop, D., 2010. Modern and fossil non-pollen palynomorphs from the Basque mountains (western Pyrenees, France): the use of coprophilous fungi to reconstruct pastoral activity. *Veg. Hist. Archaeobot.*, 19, 391-408.
- Dearing J.A., Jones R.T., Shen J., Yang X., Boyle J.F., Foster G.C., Crook D.S., Elvin M.J.D., 2008. Using multiple archives to understand past and present climate-human-environmental interaction: the lake Erhai catchment, Yunnan Province, China. *Journal of Paleolimnology*, 40: 3-31.
- Dermody, B.J., van Beek, R.P.H, Meeks, E., Klein Goldewijk K., Scheidel, W., van der Velde, Y., Bierkens, M.F.P., Wassen, M.J., and S. C. Dekker S.C. 2014 A virtual water network of the Roman World. *Hydrol. and Earth Syst. Sci.*, 18, 5025-5040.

- Dermody, B.J., de Boer, H.J., Bierkens, M.F.P., Weber, S.L., Wassen, M.J., and S. C. Dekker S.C. 2012. A seesaw in Mediterranean precipitation during the Roman Period linked to millennial-scale changes in the North Atlantic, *Climate of the Past* 8, 637-651.
- Dincauze, D.F. 2000. *Environmental archaeology*, Cambridge
- Dupré E.T. 1939. , *Il lago Velino. Saggio storico-geografico*, Consorzio di bonifica della Piana reatina nel decennale della legge Mussolini, Rieti.
- Esper, J., Frank, D., Büntgen, U., Verstege, A., Luterbacher, J. and Xoplaki, E., 2007. Long-term drought severity variations in Morocco, *Geophys. Res. Lett.*, 34, L17702, doi:10.1029/2007GL030844.
- Fægri, K. and Iversen, J. 1985. Textbook of Pollen Analysis 4th edition. Hafner Press, New York.
- Fowler, P. 2002. Farming in the First Millennium AD: British Agriculture between Julius Caesar and William the Conqueror. Cambridge: Cambridge University Press.
- Fraser, E.D.G., 2010. Can economic, land use and climatic stresses lead to famine, disease, warfare and death? Using Europe's calamitous 14th century as a parable for the modern age, *Ecol. Econ.*, doi:10.1016/j.ecolecon.2010.02.010.
- Giraudi, C. 2005. Middle to late Holocene glacial variations, periglacial processes, and alluvial sedimentation on the higher Apennine massifs (Italy). *Quat. Res.* 64, 176-184.
- Graham, N.E., Ammann, C.M., Fleitmann, D., Cobb, K.M., Luterbacher, J. 2011. Support for global climate reorganization during the "Medieval Climate Anomaly." *Clim. Dyn.* 37, 1217-1245.
- Guiot, J. Corona, C., ESCARSEL members. 2010. Growing Season Temperatures in Europe and Climate Forcings Over the Past 1400 Years. *PLoS ONE* 5 (4), e9972, doi:10.1371/journal.pone.0009972
- Hammer, O., Harper, D.A.T., and P. D. Ryan, 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. *Palaeontologia Electronica* 4(1): 9pp.

- Harris, W. V., 2013. Defining and Detecting Mediterranean Deforestation, 800BCE to 700CE. In *The Ancient Mediterranean Environment between Science and History*, Harris Ed, Brill Collections: Classical Studies E-Books Online, Collection 2013, 173-194.
- Hodges, R. 1993. *San Vincenzo al Volturno 1: The 1980-86 Excavations part 1*, London: British School at Rome.
- Hodges, R. 1995. *San Vincenzo al Volturno 2: The 1980-86 Excavations part 2*, London: British School at Rome.
- Hodges, R. 2012. *Dark Age Economics: A new Audit*. Bristol Classical, London. 158 pp.
- Hurrell, J. W., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science*, 269(5224), 676-679.
- Izdebski, A., Holmgren, K., Weiberg, E., Stocker, S., Büntgen, U., Florenzano, A., Gogou, E., Leroy, S., Luterbacher, J., Martrat, B., Masi, A., Mercuri, A., Montagna, P., Sadori, L., Schneider, A., Sicre, M., Triantaphyllou, M., Xoplaki, E. 2015. Realising consilience; How better communication between archaeologists, historians and natural scientists can transform the study of past climate change in the Mediterranean. *Quat. Sci. Rev.* <http://dx.doi.org/10.1016/j.quascirev.2015.10.038>.
- Kaniewski, D., Van Campo, E., Weiss, H. 2012. Drought is a recurring challenge in the Middle East. *PNAS*, 109, (10) 3862-3867.
- Kemp, J., Olley, J.M., Ellison, T., McMahon, J. 2015. River response to European settlement in the subtropical Brisbane River, Australia. *Anthropocene*, [doi:10.1016/j.ancene.2015.11.006](https://doi.org/10.1016/j.ancene.2015.11.006)
- Köhler, E., Lange, E. 1979. A contribution to distinguish cereal from wild grass pollen grains by LM and SEM. *Grana*, 18, 133-140.
- Ladurie, L. 1967, *Histoire du climat depuis l'an mil*, Paris
- Ladurie, E. LeRoy, 1971. *Times of Feast, Times of Famine: A History of Climate Since the Year 1000*. Doubleday, NY.

- Lamb, H. H. 1982. *Climate History and the Modern World*. Routledge, London. 445 p.
- Leed R.E 2010. *The longue Durée and world Systems analysis*, Albany, NY
- Leggio, T. 1986. *Ermanno di Reichenau, l'alluvione del 1053, i laghi reatini e Giulio Cesare, Il Territorio*», 2, 275-277.
- Leggio, T. 1989. *Forme di insediamento in Sabina e nel Reatino nel medioevo. Alcune considerazioni*, Bullettino dell'Istituto storico italiano per il medio evo e archivio muratoriano, 95, 165-201.
- Leggio, T. 1992. *Da Cures Sabini all'abbazia di Farfa. Trasformazioni del paesaggio tra Tevere, Corese e Farfa dall'età romana al medioevo*, Passo Corese.
- Leggio, 1994. *Momenti della riforma cistercense nella Sabina e nel Reatino tra XII e XIII secolo*, Rivista storica del Lazio, 2, 17-61.
- Leggio, T. 1995. *Un difficile rapporto tra uomo e ambiente: il paesaggio della conca reatina tra boschi ed acque*, in *I valori dell'agricoltura nel tempo e nello spazio*, a cura di M.G. Grillotti di Giacomo e L. Moretti, Atti del Convegno geografico internazionale, Rieti 1-4 novembre 1995, vol. I, Brigati 1998 (Gruppo di ricerca dell'Associazione dei Geografi italiani "Geografia comparata delle aree agricole europee ed extraeuropee"), pp. 99-115.
- Leggio, T. 2007. *Pesca ed acque nel medioevo reatino*, Rieti (Studi e ricerche. Quaderni della Riserva naturale dei laghi Lungo e Ripasottile).
- Leggio, T. And Marinelli, M. 1995. *Il paesaggio della Conca reatina, Problemi ed esperienze di una ricerca multidisciplinare*, i Rieti.
- Leone, A., 2004 . *Ambiente e territorio agroforestale: linee guida per la pianificazione sostenibile e gli studi di impatto ambientale*. Ed. Franco Angeli, vol.95.
- López-Moreno, J., Vicente-Serrano, S., Mórán-Tejeda, E., Lorenzo-Lacruz, J., Kenawy, A., Beniston, M. 2011. Effects of the North Atlantic Oscillation (NAO) on combined temperature and precipitation

winter modes in the Mediterranean mountains: observed relationships and projections for the 21st century. *Global and Planetary Change*, 77, 62-76.

Lorenzetti, R., 1989. Studi e materiali per una Storia Sociale e Economica della Sabina. Ricerca dell'Istituto Eugenio Cirese promossa dalla Regione Lazio Assessorato alla Cultura, Rieti.

Lorenzetti, R., 1990. Lacus Velinus. Per la salubrità dell'aere et per l'abundantia. La bonifica dell'agro reatino dall'antico Lacus Velinus alla riorganizzazione del territorio, Milano.

Lorenzetti, R. 1994. La Sabina. Il territorio di carta, Roma.

Lorenzetti, R. 2009. La terra e le acque. Trasformazioni e persistenze del paesaggio della Valle Reatina, Rieti.

Mann, M. E. 2002. Little Ice Age, Vol. 1, The Earth system: physical and chemical dimensions of global environmental change, *Encyclopedia of Global Environmental Change*. Michael C MacCracken and Dr John S Perry eds.. John Wiley & Sons, Ltd, Chichester, 2002

McCormick, M., Buntgen, U., Cane, M., Cook, E., Harper, K., Huybers, P., Litt, T., Manning, S., Mayewski, A., More, A., Nicolussi, K., Tegel, W. 2012. Climate change during and after the Roman Empire: Reconstructing the past from scientific and historical evidence. *J. Of Interdisciplinary History*, 43:2, 169-220.

Magnini, A., Spötl, C., Verdes, P. 2005. Reconstruction of temperature in the central Alps during the past 2000 yr from $\delta^{18}\text{O}$ stalagmite record. *Earth and Planetary Science Letters* 235, 741-751.

Mensing, S.A., Tunno, I., Sagnotti, L., Florindo, F., Noble, P. Archer, C., Zimmerman, S., Pavón-Carrasco F., Cifani, G., Passigli, S., Piovesan, G. 2015. 2700 years of Mediterranean environmental change in central Italy: A synthesis of sedimentary and cultural records to interpret past impacts of climate on society. *Quat. Sci. Rev.* 116, 72-94.

- Munoz S., Gajewski K., Peros M.C., 2010. Synchronous environmental and cultural change in prehistory of the northeastern United States. *PNAS*, 107 (51): 22008-22013.
- Nalepka, D. and Walanus, A. (2003). Data processing in pollen analysis. *Acta Palaeobotanica* 43, 125-134.
- O'Sullivan, P., 2008. The 'collapse' of civilizations: what paleoenvironmental reconstruction cannot tell us, but anthropology can. *The Holocene*, 18(1), 45-55.
- Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy*, 54, 438-447.
- Pfister, C., Brázdul, R. 1999. Climatic variability in sixteenth-century Europe and its social dimension: A synthesis. *Climatic Change* 43, 5-53.
- Pfister, C., Brázdul, R. 2006. Social vulnerability to climate in the “Little Ice Age”: an example from Central Europe in the early 1770s. *Climate of the Past* 2, 115-129.
- Punt W., Malotau, M., 1984. The Northwest European Pollen Flora, 31. Cannabaceae , Moraceae and Urticaceae; *Rev. Palaeobot. Palynol.*, 42, 23-44.
- Punt, W., Johanna, A.A.B., Hoen, P.P., 1991. The Northwest European Pollen Flora, 45 Oleaceae. *Rev. Palaeobot. Palynol.* 69, 23-47.
- Riccardi, R. 2006. Studi geografici sui laghi L:ungo, Ripasottile e Ventina. *Quaderni della Riserva Naturale dei laghi Lungo e Ripasottile* 1, 47 p.
- Sabbatani, S. 2005. Tentativi di lotta al paludismo e alla malaria nel Medio Evo. Ruolo dei Monaci Benedettini e Cistercensi nella nascita della Medicina Monastica e nelle bonifiche ambientali nel Medio Evo. *Le infezioni in medicina*, 3, 196-207.
- Sadori, L., Giraudi, C., Masi, A., Magny, M., Ortu, E., Zanchetta, G., Izdebski, A. 2015. Climate environment and society in southern Italy during the last 2000 years. A review of the

environmental, historical and archaeological evidence. *Quat. Sci. Rev.*

<http://dx.doi.org/10.1016/j.quascirev.2015.09.020>.

Schuster, I. 1921. L'imperiale abbazia di Farfa, Città del Vaticano 1921 (rist. anast. 1987)

Sereni, Emilio. 1972. Agricoltura e mondo rurale. *Storia d'Italia* 1,133-252.

Sköld, E., Lageras, P., Berglund, B. 2010. Temporal cultural landscape dynamics in a marginal upland area: agricultural expansions and contractions inferred from palynological evidence at Yttra Berg, southern Sweden. *Veget. Hist. Archaeobot.* 19, 121-136.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. *Pollen et Spores*, 13, 615-621.

Tinner w., Lotter, A. F., Ammann, B., Conedera, M., Hubschmid, P., van Leeuwen, J., Wehrli, M. 2003.

Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. *Quat. Sci. Rev.* 22, 1447-1460,

Trachsel, M., Kamenik, C., Grosjean, M., McCarroll, D., Moberg, A., Brázdil, R., Riemann, D. 2012. Multi-archive summer temperature reconstruction for the European Alps, AD 1053–1996. *Quaternary Science Reviews*, 46, 66-79.

Trouet, V., Esper, J., Graham, N.E., Baker, A., Scourse, J.D., Frank, D.C., 2009. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science*, 324, 78.

Van Benthem, F., Clarke, G.C.S., Punt, W., 1984. The Northwest European Pollen Flora, 33. Fagaceae. *Rev. Palaeobot. Palynol.*, 42, 87-110.

van Geel, B., Aptroot, A. 2006. Fossil ascomycetes in Quaternary deposits. *Nova Hedwigia*, 82, 313-329.

van Geel, B., Gelorini, V., Lyaruu, A., Aptroot, A., Rucina, S., Marchant, R., Sinninghe Damsté, J. S., Verschuren, D., 2011. Diversity and ecology of tropical African fungal spores from a 25,000-year palaeoenvironmental record in southeastern Kenya. *Rev. Palaeobot. Palynol.*, 164, 174-190.

van Hoof, T.B., Bunnik, F.P.M., Waucomont, J.G.M., Kürschner, W.M. and Visscher, H. 2006.

Forest re-growth on medieval farmland after the Black Death pandemic -Implications for

atmospheric CO₂ levels. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **237**, 396-411.

Vecchio, B., 1974. Il bosco negli scrittori italiani del Settecento e dell'età napoleonica. Einaudi (ed.), Torino.

Yeloff, D. and van Geel, B. 2007. Abandonment of farmland and vegetation succession following the Eurasian plague pandemic of AD 1347-52. *Journal of Biogeography* **34**, 575-582.

Figure captions

Fig 1. Site map with medieval settlements first noted in monastery records between 1050 and 1250 AD.

Dates represent first year of first mention (when known) in Farfa monastery documents (Coccia, 1992).

Names in bold are still occupied. AP – **Apoleggia** (1152); BU – Butro (1150); CA – Casarine; CB –

Collebaccaro (1128); CF – Castelfranco; CG – **Contigliano** (1157); CL – **Cantalice** (1081); CO – Cocione

(1152); FG – Fortemonte Gambaro (1112); GR – **Greccio** (1091); LA – **Labro** (1152); LR – La Rochetta; MO

– **Moggio** (1152); MR – Monte Rotundo; PB – **Poggio Bustone** (1117 AD); RI – **Rivodutri** (1171); SC –

Santa Maria in Consanano; SM – San Matteo (1205); SP – S. Pastore (1254); TM – Torre di Morro

Vecchio.

Fig. 2. Cluster analysis of all pollen types >1% showing the ecological relationships between taxa. Three groups are identified from left to right; grassland and disturbance taxa, forest taxa, and cultivated plants/pioneer forest taxa. The numbers in the cluster refer to Bootstrapping (1000 replicates with columns subjected to resampling): the percentages of replicates where each node is still supported are given on the dendrogram.

Fig. 3. Selected herbaceous pollen types and indeterminate pollen for Lago Lungo, Rieti Basin.

Fig 4. Summary diagram with select data from Lago Lungo and independent climatic proxies. Drainage projects represent: (a) new unnamed channel construction in 1325 AD; (b) *Cava Reatina* in 1422 AD; (c) *Cava Paolina* in 1547 AD; (d), *Cava Gregoriana* in 1575 AD; (e) *Cava Clementina* in 1601 AD.

Precipitation proxies: PDSI Morocco (Esper et al. 2007); NAO Scotland (Baker et al., 2015); Effective moisture in southern Italy (Sadori et al., 2015). Temperature proxies: Alps multi-proxy (Trachsel et al., 2012); Alps speleothem (Magnini et al., 2005); Glacial advances central Apennines (Giraudi, 2005). Independent climate reconstructions were smoothed using a weighted moving average and a Gaussian kernel with standard deviation set to 1/5 of the window size (of n points).

Fig. 5 – Map of the Rieti Basin produced by F. Magini of Bologna and published in 1632 AD; Patrimonio di San Pietro, Sabina, et ducato di Castro [Kartenmaterial]. Lago di Ripasottile and Lago Lungo have merged and are named Lago di Rieti. Four historic drainage channels can be seen leading away from Lago delle Marmore. Map provided by Bern University Library, ZB

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