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# GEOGRAFIA FISICA E DINAMICA QUATERNARIA

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Federico DI RITA [1*], Fabrizio LIRER [2], Giulia MARGARITELLI [3], Fabrizio MICHELANGELI [1] & Donatella MAGRI [1]

# CLIMATE AND HUMAN INFLUENCE ON THE VEGETATION OF TYRRHENIAN ITALY DURING THE LAST 2000 YEARS: NEW INSIGHTS FROM MICROCHARCOAL AND NON-POLLEN PALYNOMORPHS

**Abstract:** Di Rita F., Lirer F., Margaritelli G., Michelangeli F. & Magri D., *Climate and human influence on the vegetation of Tyrrhenian Italy during the last 2000 years: new insights from microcharcoal and non-pollen palynomorphs.* (IT ISSN 0391-9838, 2019).

The history of vegetation in the Italian peninsula during the last 2000 years was shaped by a complex interplay of several factors, including the history of human societies, changes in land use, and the succession of climate events. In order to disentangle these factors, we present a multidisciplinary record from a marine core collected in the Gulf of Gaeta, interpreted in the light of other palaeoenvironmental records from Tyrrhenian Italy. Pollen records, complemented by new data on Non-Pollen Palynomorphs (NPPs) and microcharcoal, are used to reconstruct changes in the vegetational landscape, stock-breeding activities, fire, and land use. Foraminiferal and oxygen isotope data provide independent information on climate changes. NAO-index and sunspot data support the interpretation of changes in atmospheric circulation. In this paper, by examining the effect of climate and human activity on the landscape during a series of periods of the last 2000 years, representing cultural or climate phases (Roman Period, Dark Ages, Medieval Climate Anomaly, Little Ice Age, and Modern Period), we found that human impact produced a general and progressive decline of forest vegetation. However, irrespective of the societal cultural phase, forest declines occurred when negative NAO oscillations induced dry climate, especially during sunspot minima.

**Key words:** Pollen, Non-pollen palynomporphs, Microcharcoal, Roman period, Dark Ages, Medieval Climate Anomaly, Little Ice Age.

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**Riassunto:** Di Rita F., Lirer F., Margaritelli G., Michelangeli F. & Magri D., *Clima e influenza antropica sulla vegetazione dell'Italia tirrenica negli ultimi 2000 anni: nuovi contributi da microcarboni e palinomorfi non pollinici.* (IT ISSN 0391-9838, 2019).

La storia della vegetazione degli ultimi 2000 anni nella penisola italiana è stata determinata da una complessa interazione di diversi fattori, tra i quali spiccano la storia delle società umane, i cambiamenti nell'uso del suolo e la successione di eventi climatici. Al fine di distinguere l'effetto di questi fattori, abbiamo svolto uno studio multidisciplinare di una carota di sedimenti marini campionata nel Golfo di Gaeta e interpretata alla luce di altre ricerche paleoambientali dell'Italia tirrenica. I dati pollinici, integrati da palinomorfi non pollinici e da concentrazioni di microcarbone, sono stati usati per ricostruire i cambiamenti nel paesaggio vegetale, attività di allevamento, incendi e uso del suolo. I dati degli isotopi dell'ossigeno e dei foraminiferi forniscono informazioni indipendenti sui cambiamenti climatici. Le curve dell'indice NAO e delle macchie solari sostengono l'interpretazione dei cambiamenti nella circolazione atmosferica. In questo articolo, esaminando l'effetto del clima e dell'attività umana sul paesaggio in una serie di periodi storici degli ultimi 2000 anni, che rappresentano fasi culturali o climatiche (Periodo Romano, Medio Evo, Anomalia climatica medievale, Piccola Età Glaciale e Periodo moderno), abbiamo documentato un declino generale e progressivo della vegetazione forestale prodotto dall'attività antropica. Tuttavia, indipendentemente dalla fase storica, si sono registrate riduzioni delle foreste anche quando oscillazioni NAO negative hanno indotto siccità del clima, specialmente durante i minimi dell'attività solare.

**Termini chiave:** Polline, Palinomorfi non pollinici, Periodo Romano, Medio Evo, Anomalia climatica medievale, Piccola Età Glaciale.

## INTRODUCTION

The vegetation dynamics of the last few thousands of years was influenced by a variety of factors, including climate change, human impact, and various biological and pedological processes (e.g., inter- and intraspecific competition, diseases, soil degradation, fire, etc.) (Zielhofer & *alii*, 2017; Milli & *alii*, 2016; Melis & *alii*, 2017; Cacciari & *alii*, 2020). Despite this complexity and the inherent difficulty of any palaeoenvironmental study, also involving problems of taphonomy of fossil assemblages, sampling strategies, and chronological control, pollen analysis is an extremely valuable technique to reconstruct past climate changes, based on the proven relationship between climate and plant distribution. For this reason, palynological studies have fully participated in the challenges of the NextData Project (http://www.nextdataproject.it), especially in the investigation of climate and its variability in Italy during the last two millennia. The interest of the palynological contribution to the project is increased by the scarcity of high-resolution pollen records in Italy in this time-frame and by the need to collect new detailed pollen data that may complement the other proxy records of the project.

The Laboratory of Palaeobotany and Palynology at Sapienza University of Rome has contributed to the project at different levels. First, a review of the published pollen records in Italy has produced a synthesis of the Holocene vegetation history, forming a comprehensive background on which the specific analysis of the last 2000 years could be founded (Magri & *alii*, 2015). Several aspects of plant population dynamics and vulnerability have been framed in a wider palaeoecological context, to better evaluate the role of human disturbance and biological processes (Magri & *alii*, 2017). Secondly, new detailed pollen analyses have been carried out on a marine sediment core from the Gulf of Gaeta (central Tyrrhenian Sea), within a multidisciplinary investigation (Margaritelli & *alii*, 2016; Di Rita & *alii*, 2018b). This record is complemented by new pollen data from the Campanian coast that allows distinction of regional and local aspects of vegetation dynamics (Di Rita & *alii*, 2018c). Thirdly, the reconstructed vegetation history has been interpreted in the context of the atmospheric circulation patterns acting over the central and western Mediterranean regions, to infer possible mechanisms responsible for regional palaeoenvironmental changes (Di Rita & *alii*, 2018a; Di Rita & Magri, 2019).

The present paper represents a further step in the analysis of the influence of climate and human activity on vegetation in the south-central Mediterranean during the last 2000 years. We integrate the published pollen record from the Gulf of Gaeta with new data of microcharcoal and Non-Pollen Palynomorphs (NPPs), with special attention to coprophilous fungi. Based on these data and on planktonic foraminifera and oxygen isotope records from the same marine site (Margaritelli & *alii*, 2016), as well as on the comparison with other Mediterranean pollen records, North Atlantic Oscillation (NAO) and solar sunspot curves, we examine the paleoclimatic and palaeoenvironmental features of a series of time intervals over the last 2000 years, whose specific social, cultural, and political characters may have been influenced by peculiar climate conditions (Carey, 2012; Holmgren & *alii*, 2016 and references therein; Mensing & *alii*, 2018). In particular, we focus on the climate effects on vegetation during periods corresponding to both cultural phases and known climate events (Roman Imperial Period, Dark Ages, Medieval Climate Anomaly (MCA), Little Ice Age (LIA) and Modern Period), also considering the effects of increasing human activity through agropastoral and silvicultural practices, forest clearance, fires and demographic increase.

## STUDY AREA

The south-central Mediterranean region has a complex vegetational configuration determined by a number of factors, including: (a) the long-term persistence of many taxa, which have found in this area suitable locations for survival during the unfavorable climatic phases of the Quaternary (Magri, 2010; Magri & *alii*, 2017); (b) the complex physiography of the region, determined by a long extent of coasts, high mountain chains (e.g., the Apennines), wide plains, and active volcanic areas; (c) a long-lasting impact of human presence, documented since the Lower Paleolithic (Manzi & *alii*, 2011), in the last millennia also enhanced by human populations from other Mediterranean regions with different agricultural practices; (d) the interplay of different climate modes acting on the Italian Peninsula and North Africa (Lionello & *alii*, 2006). This area, located at the interface between two large continents (Europe and Africa), is subject to climate forcing from both the NAO and the high-pressure conditions that dominate the Sahara. The balance between these two patterns of atmospheric circulation determines the amount and seasonality of moisture availability in the region, and consequently the development or contraction of the forest vegetation (Di Rita & *alii*, 2018a).

The pollen record from the Gulf of Gaeta (fig. 1), located in this key area at the interface between two different climate systems, is particularly suitable to investigate changes in atmospheric circulation patterns. At the same time, being collected >10 km away from the shore, it appears especially appropriate for tracing changes in the regional vegetation that were influenced by human activity, as local vegetation dynamics and human impact related to crops and land use are mitigated by the distance from the land.

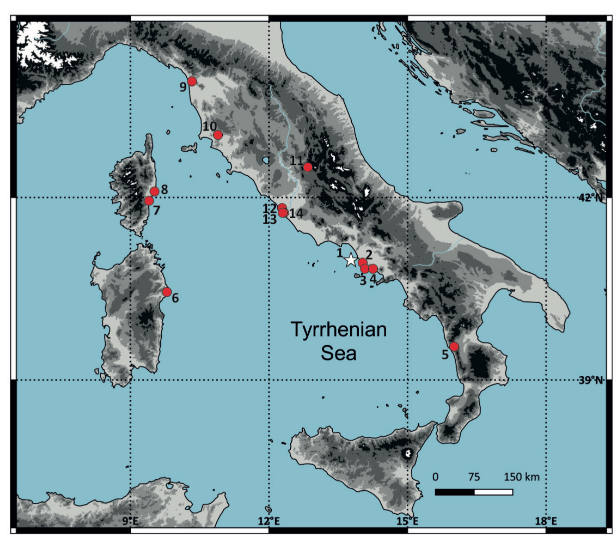


Fig. 1 - Location of the pollen sites mentioned in the text (circles). 1. Golfo di Gaeta: Margaritelli & *alii* (2016), Di Rita & *alii* (2018a, b) (star); 2. Lago Patria: Di Rita & *alii* (2018c); 3. Lago d'Averno (Grüger & Thulin, 1998); 4. Neapolis harbour: Allevato & *alii* (2010, 2016); 5. Lago Trifoglietti: Joannin & *alii* (2012); 6. Sa Curcurica: Beffa & *alii* (2016); 7. Palo: Revelles & *alii* (2019); 8. Aleria del Sale: Currás & *alii* (2017); 9. Lago di Massaciuccoli: Colombaroli & *alii* (2007); 10. Lago dell'Accesa: Vannière & *alii* (2008); 11. Lago Lungo: Mensing & *alii* (2015, 2016, 2018); 12. Lingua d'Oca-Interporto: Di Rita & *alii* (2010); 13. Ostia C5: Bellotti & *alii* (2011); 14. Fiume morto: Pepe & *alii* (2016).

## MATERIALS AND METHODS

The composite paleoenvironmental record of the Gulf of Gaeta was obtained from the shallow marine sedimentary cores SW104_C5 (40° 58′ 24.993″ N, 13° 47′ 03.040″ E; 108 cm long) and C5 (40° 58′ 24.953″ N, 13° 47′ 02.514″ E; 710 cm long), recovered close to each other at 93 m below sea level (fig. 1). The two cores were stratigraphically correlated by means of magnetic susceptibility, which allowed to recognize a distinct common peak corresponding to the tephra layer of the Vesuvius eruption dated at 1906 AD (for details see Margaritelli & *alii*, 2016).

The chronology of the Gaeta record is based on $^{210}Pb$ and $^{137}Cs$ radionuclide measurements, for the uppermost 60 cm, and on the identification of the following five tephra layers: Vesuvius (1906 AD at 53 cm depth), Vateliero-Ischia (2.6-2.4 ka BP, 319 cm), Capo Miseno (3.9-3.7 ka BP, 403 cm), Astroni 3 (4.3-4.1 ka BP, 414 cm) and Agnano Monte Spina (4.42 ka BP, 437 cm). The age-depth model takes into consideration a few additional time-constrained biostratigraphical and magnetostratigraphical events. Details on the age-deph model are reported in Margaritelli & *alii* (2016).

The pollen record of the last 2000 years includes 60 samples that were chemically treated with HCl (37%), HF (40%) and NaOH (20%), following the standard procedure summarized in Magri & Di Rita (2015). No heavy liquids were used during sample preparation. Pollen grains were identified by means of a light microscope at x400 and x640 magnifications, with the help of both atlases of pollen morphology (Reille, 1992; Beug, 2004) and the reference collection of the Laboratory of Palaeobotany and Palynology at Sapienza University of Rome.

In this paper, a new NPPs record is presented, with special attention to coprophilous fungi, in order to improve the palaeoenvironmental reconstruction. The identification and paleoecological interpretation of NPPs were based on several specific papers and monographs (e.g., Manzano & *alii*, 2017; Florenzano, 2019, Læssøe & Petersen, 2019; Miola, 2012; van Geel & *alii*, 2011). Micro-charcoal analysis was carried out in order to reconstruct the fire history of the area and the vegetation responses to fire. The concentration of microcharcoal in each sample was determined using the Clark (1982) point count method in 150 fields of view, excluding fragments <5 µm. *Lycopodium* spores, added to known weights of sediments, were used to estimate pollen, NPPs and micro-charcoal concentrations. The computer program Psimpoll 4.27 (Bennett, 2009) was used to plot the pollen diagram.

## RESULTS

The new results of the NPPs and microcharcoal analyses from the Gaeta core are subdivided in time intervals representing cultural or climate phases. They can be summarized as follows (fig. 2):

0-550 AD (hereafter "Roman Period"): NPPs are represented by modest concentrations of *Glomus*, *Trichodelitschia* type, *Sordaria* type, *Sporormiella*, and *Podospora* type. No NPP type exceeds 500 spores/gram sediment. The microcharcoal data shows an increasing trend from 0.4 to 3.5 cm²/g sediment.

550-850 AD (hereafter "Dark Ages"): there is a general decrease of NPPs, marked by a temporary disappearance of *Trichodelitschia* type and *Sporormiella*, and by the complete disappearance of *Podospora* type. *Cercophora* type shows its first appearance. The microcharcoal curve drops, with a minimum between 600 and 700 AD (0.3 cm²/g sediment).

850-1300 AD (hereafter "Medieval Climate Anomaly"): NPPs show a general increase, especially marked in *Sordaria* type (>1800 spores/g sediment), *Podospora* type (>700 spores/g), *Trichodelitschia* type (>700 spores/g) and *Sporormiella* (>850 spores/g). *Gelasinospora* and *Delitschia* type appear for the first time. Between 850 and 1200 AD, the microcharcoal record shows a fluctuating increase, up to 2.8 cm²/g, then it shows a temporary drop to 0.6 cm²/g.

1300-1850 AD (hereafter "Little Ice Age"): NPPs show generally high values, particularly marked in *Sordaria* (>2500 spores/g around 1770 AD), *Sporormiella* (up to >1400 spores/g around 1450 AD), and *Trichodelitschia* type (>1000 spores/g around 1400 AD). After 1640 *Glomus* type shows appreciable values (>200 spores/g). Microcharcoals show a generally decreasing trend, with a minimum around 1725 AD (0.3 cm²/g).

1850 AD-present day (hereafter "Modern Period"): NPPs are always present, *Glomus* type being especially abundant (almost 1600 spores/g around 1910 AD). After 1950 AD there is a moderate change in the composition and abundance of NPPs. For example, *Sporormiella* and *Podospora* type decrease abruptly, while *Trichodelitschia* type increases. At the same time, microcharcoals show high values (up to 2.9 cm²/g).

## DISCUSSION

The Gaeta pollen record, complemented by the new NPPs and microcharcoal data, is used here as a reference to reconstruct regional vegetation, land use, and climate changes in central Tyrrhenian Italy during the last 2000 years. A number of other pollen, microcharcoal and NPPs records have been considered for comparison (fig. 1). In addition, regional-scale correlation with marine records over the Mediterranean area is considered.

### *Roman Period (0-550 AD)*

In the Gulf of Gaeta, the first three centuries of the Roman Imperial Period correspond to a phase of forest expansion suggesting relatively wet climate conditions (fig. 2). The pollen record shows significant values of evergreen oaks (>20%), deciduous oaks (>15%), and *Pinus* (>10%), which are coeval to positive NAO index values. During this time interval, the progressive decrease in abundance of warm planktonic foraminifera *G. ruber* white variety, associated with *T. quinqueloba - G. glutinata* gr. increase, occurs in a phase with more positive values in the $\delta^{18}O_{G.\ ruber}$ record, suggesting a marked Mediterranean seasonality with mild/dry climate conditions during the summer season and cold/humid conditions during late winter/early spring.

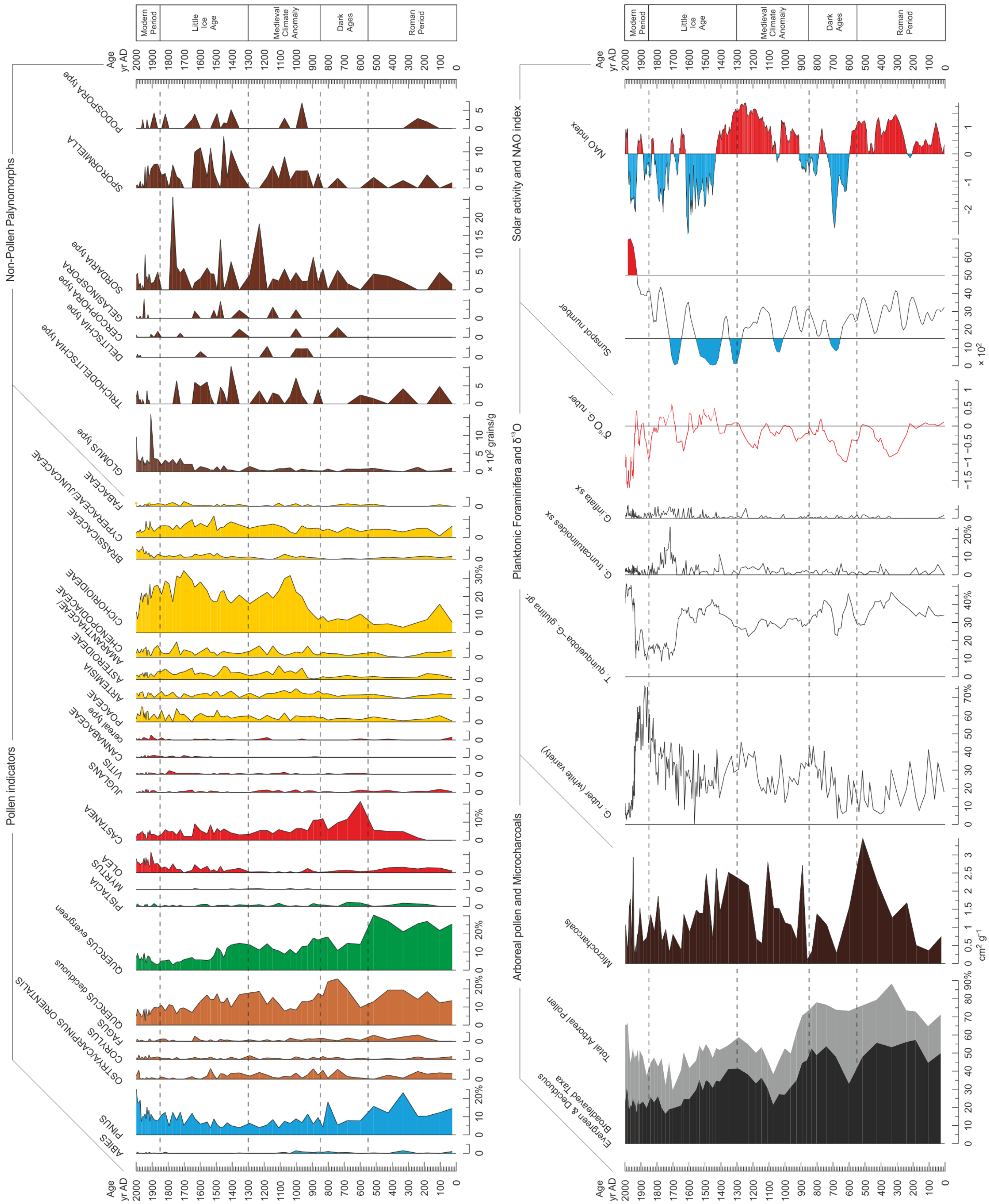


FIG. 2 - Summary pollen record from the Gulf of Gaeta spanning the last 2000 years, including microcharcoals and NPPs. Oxygen isotope and planktonic foraminifera curves from the same core (Margaritelli & *alii*, 2016), grand minima (blue) and maxima (red) of solar activity reconstructed by Usoskin & *alii* (2007), and NAO index reconstructed by Baker & *alii* (2015) are also shown.

A peak in Arboreal Pollen percentages (AP=88%) around 350 AD corresponds to a rapid shift towards negative values in the oxygen isotope record (fig. 2), indicating increased temperatures. This temporary rise in woody taxa may suggest an increase in water availability, but it was mainly due to *Pinus*, probably related to an influence of human activities. *Pinus* was partly native and partly planted by the Romans in many Tyrrhenian coastal areas. It is documented in northern Etruria by low numbers of charcoal of *Pinus halepensis/pinea* (Di Pasquale & *alii*, 2014). Besides, several historical documents report the presence of a strip of dense natural forest mostly dominated by pines and holm oaks along the coastal area between the Volturno River mouth and the Phlegraean Fields, named *Sylva Gallinaria*, whose existence is documented in the pollen record from Lago Patria (Di Rita & *alii*, 2018c). During the Roman Imperial Period, pine plantations were widespread at Lago d'Averno and Naples, in coastal areas of Campania, as *Pinus* was locally employed in shipyards (Grüger & Thulin, 1998; Allevato & *alii*, 2010, 2016). A connection of pine plantations with important Roman harbors is documented also by the development of *Pinus* at the Tiber river mouth near the port cities of Ostia and Portus (Di Rita & *alii*, 2010; Bellotti & *alii*, 2011, 2018; Pepe & *alii*, 2016), as well in the Turkish harbour of Elaiussa Sebaste (Melis & *alii*, 2015).

Between 350 and 450 AD, during the cold event Roman III at the end the Roman Period (Lirer & *alii*, 2014; Margaritelli & *alii*, 2016), the forest cover along the Gulf of Gaeta decreased (AP around 80%) mostly in relation to a drop in *Pinus* suggesting the demise of local pine plantations during the decline of the Roman Empire (fig. 2). At the same time, there is a slight decrease in the abundance of high-productivity planktonic foraminiferal indicators *T. quinqueloba -G. glutinata* gr., probably associated to low temperatures and reduced runoff. In addition, the observed distributional pattern of *G. ruber* pink variety, the occurrence of *G. scitula - N. pachyderma* gr. and the strong decrease in abundance of *T. quinqueloba - G. glutinata* gr. suggest relatively wetter conditions during summer and cold-dry winters (fig. 2) (Margaritelli & *alii*, 2016). This winter dryness may have contributed to the decline of the forest cover, which is visible also further north along the Tyrrhenian coast, in the pollen records at the Tiber delta mouth.

Clear evidence of human impact on the landscape is documented in all pollen records of Roman age along the Tyrrhenian coast (Stoddart & *alii*, 2019; Di Rita & Magri, 2012 and references therein). It is especially witnessed by the increase of cultivated plants, including cereals, *Castanea*, *Olea*, and *Juglans* (Mercuri & *alii*, 2013). However, the presence of a constant low concentration of *Sporormiella* in the Gulf of Gaeta record suggests a modest stockbreeding activity (stock-rearing, cattle raising), similarly to the site of Sa Curcurica, in E Sardinia (Beffa & *alii*, 2016) and Palo in E Corsica (Revelles & *alii*, 2019). In these records a moderate stock-rearing activity corresponds to an increase in forest. In contrast, in the Basilicata region the joint record of pollen pasture indicators and spores of coprophilous fungi suggests that continuous and intense pastoral activities have been practiced in the territory and have highly influenced its landscape (Florenzano, 2019). These results suggest regional differences in the land use during the Roman times.

The microcharcoal data from the Gaeta record shows an increasing trend in the course of the Roman Period. This is consistent with high forest biomass, documented by high AP percentage values, especially evergreen oaks. Moderately high values of microcharcoal in increasingly forested landscapes are also recorded along the Latium coast (Di Rita & *alii*, 2010). However, it is likely that part of the fires affecting deciduous vegetation between 450 and 550 AD were related to human-induced openings of the forest in favour of chestnut plantations.

*Dark Ages (550-850 AD)*

The first centuries of the Dark Ages show a considerable complexity both in climate fluctuations and in historical events.

The vegetation dynamics along the Gulf of Gaeta was strongly influenced by a combination of climate conditions and impact of human activities. Between 550 and 700 AD, a decline in the values of trees documents a reduction of the natural forest cover, especially determined by a rapid decrease in evergreen broadleaved taxa, as well as in conifers, but balanced by a marked expansion of cultivated *Castanea* that contributed to keep stable the overall forest cover (fig. 2). Human-induced fires for chestnut cultivation probably contributed to keep high microcharcoal curve, despite its remarkable decrease between 550 and 600 cal. BP.

The planktonic foraminiferal record suggests warm climate conditions until 700 AD, evidenced by negative $\delta^{18}O_{G.\ ruber}$ values and an increase in warm water species *G. ruber* white variety (Margaritelli & *alii*, 2016). A shift from positive to negative values of NAO index in correspondence to "Bond event 1", around 550 AD (Bond & *alii*, 1997), may have caused a reduction of water availability, affecting the development of the natural tree populations, which were already managed in favour of chestnut forestry (Di Rita & *alii*, 2018a). Despite its cultivation, *Castanea* was not widely diffused in ancient Campania during the Roman period, whereas it became a common timber from the 5$^{th}$ century AD. It provided the most commonly used wood in Campania around the 6$^{th}$ century AD, as suggested by anthracological data from Cumae (Di Pasquale & *alii*, 2010), which is consistent with the spread of chestnut in the Gulf of Gaeta record.

The pollen study from the Rieti Plain in central Italy indicates that the time interval 550-750 AD was characterized by substantially humid climate conditions (Mensing & *alii*, 2015), which contrasts with the Gaeta record, where wet climate conditions occurred only between 700 and 850 AD, when a new natural forest recovery was recorded (fig. 2). A trend toward cooler climate conditions, culminating around 800 AD during the cold 'Roman IV event', is documented by the foraminiferal record from Gaeta and is recognized in other palaeoclimate proxy records of the Mediterranean (Lirer & *alii*, 2014; Margaritelli

& *alii*, 2018). However, the published palaeovegetational and paleoclimatic evidence from the Italian Peninsula still appears too scarce to outline a well-defined climate scenario for the Dark Ages.

The microcharcoal curve drops, with a minimum between 600 and 700 AD, when deciduous oaks recover and *Castanea* declines, at a time when the NAO index is negative and sunspots decrease. Considered altogether, these data suggest that a climate change may have favoured a recovery of the mixed oak forest, which also corresponds to a temporary reduced silvicultural and agropastoral activity, as documented by the disappearance of *Sporormiella* type. Few other microcharcoal and NPPs records are available from the Tyrrhenian coast. They generally agree with the Gaeta record. At Lingua d'Oca-Interporto (Di Rita & *alii*, 2010) and at Sa Curcurica (Beffa & *alii*, 2016) a decline in microcharcoal is found after 600 AD, when at Sa Curcurica *Sporormiella* type temporarily disappears. In contrast, during the Dark Ages a general increasing trend in the microcharcoal curve is observed at Massaciuccoli, with no significant drop at 600 AD, possibly in relation to the establishment of a shrubby macchia (*Phillyrea* and *Erica*) (Colombaroli & *alii*, 2007).

A new increase in *Castanea* is found during the 9$^{th}$ century AD. It corresponds to the Carolingian domination in northern and central Italy, which is considered a period of chestnut tree management for fruit production (Buonincontri & *alii*, 2015).

*Medieval Climate Anomaly (850-1300 AD)*

The Medieval Climate Anomaly was characterized by the combined effect on the landscape of human activity and two climate oscillations recognized by independent climate proxy records.

Between 850 and 1100 AD, in the Gaeta record there was a remarkable decline in natural broadleaved forest, especially deciduous trees, and a considerable corresponding increase in herbaceous taxa, especially Cichorioideae, which document a rapid and widespread establishment of open areas (fig. 2). At the onset of this phase, the NAO index reconstruction from speleothems in Scotland (Baker & *alii*, 2015) points to a general negative index circulation pattern (fig. 2), consistent with a change in the atmospheric circulation of the central Mediterranean that may have triggered the vegetation change. Planktonic foraminifera document generally temperate climate conditions, as testified by the coexistence of warm and cold species (Margaritelli & *alii*, 2016). However, a reduction in abundance of warm water species *G. ruber* white variety from ca. 1000 to ca. 1100 AD associated with a slight increase in *G. ruber* pink and to a shift of the oxygen isotope record towards positive values, suggests less temperate and humid conditions (Margaritelli & *alii*, 2016). The Oort minimum of solar activity (1040-1080 AD), which may have influenced the vegetation towards open landscapes, complements this information on climate change.

The following phase of the Gaeta record, between 1100 and 1300 AD, is characterized by a new forest recovery, mostly related to an increase in both deciduous and evergreen arboreal taxa. Montane taxa like *Fagus* and *Abies* decline, while mediterranean elements like *Myrtus* and *Pistacia* slightly increase, together with evergreen *Quercus*, as a possible effect of enhanced Mediterranean climate conditions. As to human impact, no clear signs of change in land use are evident from the anthropogenic pollen indicators, apart from a moderate increase in cereal pollen. The expansion of broadleaved populations was possibly triggered by a new atmospheric circulation change, evidenced by positive values in the NAO index (fig. 2). A marked shift in $\delta^{18}O_{G.\ ruber}$ signal towards negative values, associated with a strong increase in *G. ruber* white abundance (Margaritelli & *alii*, 2016), document the warmest interval of the medieval period, namely the MCA, which may explain the increase in mediterranean thermophilous taxa.

In the pollen records from lacustrine sites in the central Mediterranean, these climate oscillations appear largely obliterated by the impact of human activity on the landscape (Di Rita & Magri, 2012). For example, in the Rieti Basin a strong reduction of forest cover between approx. 870-1390 AD, accompanied by an increase in herbs and ferns, was interpreted as mainly due to socioeconomic changes, as indicated by agricultural and stock-breeding intensification (increase in cereals and *Sporormiella*), although the successful expansion of agriculture was also attributed to warmer than average temperatures combined with drier than average climate (Mensing & *alii*, 2015).

Between 850 and 1100 AD, the microcharcoal record from the Gaeta core shows a general increase corresponding with the decline of the forest culminating at 1050 AD, which suggests an intentional opening of the landscape, possibly favored by a temporary climate change towards cooler and dryer climate conditions, as suggested by an inversion of the NAO index (Di Rita & *alii*, 2018b). During the Oort solar minimum (1040-1080 AD) (Usoskin & *alii*, 2007), when the forest was largely opened, *Olea* appears strongly reduced, and cereals disappear. This opening of the forest allowed extensive pastoral activities, as evidenced by the contemporary increase in *Sporormiella*, Cichorioideae, and other herbs of disturbed meadows (e.g., Fabaceae, Brassicaceae, and Amaranthaceae/Chenopodiaceae). These data altogether indicate a complex interaction of climate, fires, and agropastoral activities in setting the open landscapes.

After 1100 AD microcharcoals are generally high, despite the forest increase, indicating that fires did not affect the development of forest, probably favored by the climate shift towards warm and wet conditions corresponding to the Medieval Warm Period (Lüning & *alii*, 2019). When forest expansion reached its maximum, around 1250 AD, *Sporormiella* temporarily disappeared, suggesting a reduction of pastoral activities.

At Sa Curcurica, microcharcoals show a slight increase at around 1000 AD, when both *Sporormiella* and cereals decrease (Beffa & *alii*, 2016). This pattern seems related to a possible enhancement of regional fires, and a coeval decline of local agro-pastoral activities.

At Massaciuccoli, microcharcoals increase up to ca. 950 AD, mostly due to regional fire activities and possibly also in relation to clearance events for agricultural practices, as suggested by the pollen signal of *Secale* and other cereals (Colombaroli & *alii*, 2007).

*Little Ice Age (1300-1850 AD)*

The LIA is clearly documented in the main paleoclimate proxy records of the Gulf of Gaeta core. The vegetation was distinctly affected by the LIA climate change. In the pollen record this phase was characterized by a rather forested landscape until approx. 1550 AD, then by open vegetation (1550-1750 AD), followed by a new increase in trees after 1750 AD. The deforestation process affected especially the deciduous and evergreen broadleaved taxa, whose curves show the lowest percentage values of the entire sequence between 1650 and 1750 AD, in correspondence with the Maunder solar minimum (fig. 2) (Usoskin & *alii*, 2007), suggesting particularly cold and dry climate conditions. Solar grand minima including the Maunder of the LIA, the above-mentioned Oort minimum in Medieval times, and the Homeric minimum around 800 BC (Martin-Puertas & *alii*, 2012), may have had a significant role in the forest declines recorded in Gaeta (Di Rita & *alii*, 2018a), supporting the hypothesis of an influence of solar activity on vegetation development in the south-central Mediterranean (Di Rita, 2013).

The high-resolution $\delta^{18}O_{G.\ ruber}$ record appears to respond to four cold climatic oscillations related to solar activity minima: Wolf, Spörer, Maunder and Dalton (Margaritelli & *alii*, 2016). A shift to cooler climate conditions, during the LIA, was clearly indicated by a significant decrease in the warm water species *G. ruber* white especially during the Wolf and Spörer solar minima, and an increase of cool water planktonic foraminiferal species *Globorotalia inflata* left coiled and *G. truncatulinoides* left coiled, peaking during the Maunder minimum that represented the coldest interval of this phase (Margaritelli & *alii*, 2016).

During the LIA, the NAO index shows negative values, indicating a new change in the dominant atmospheric circulation with respect to the MCA. This is consistent with the establishment of atmospheric blocking suggested by changes in foraminifera assemblages and opening of the forest (Margaritelli & *alii*, 2016).

To some extent, also human activities may have contributed to produce deforestation during the LIA, enhancing the effects of climate change. Starting around 1500 AD, a new general increase in Cichorioideae, Brassicaceae, and Fabaceae parallels the increase in *Sporormiella* and other fungal genera with cophrophilous species (e.g. *Podospora*, *Cercophora*, and *Trichodelitschia*), which altogether point to an intensification of the stock-rearing activity. The records of cultivated plants, such as *Olea*, *Juglans*, *Vitis*, Cannabaceae and cereals, suggest enhanced sylvicultural and crop-farming practices compared to the Medieval period. However, during the Maunder solar minimum (ca. 1645 to 1715 AD) human activities related to olive, chestnut and cereal cultivation appear strongly diminished, partly due to a possible decrease in water availability and cold climate conditions, and partly because of the dramatic demographic decline related to a plague disease that in 1656 affected the Kingdom of Naples (Alfani, 2013). The evidence of a decrease in human impact is also supported by an abrupt disappearance of *Sporormiella* and a drop in other fungal spores. Microcharcoal concentrations, which parallel the trend of the forest biomass, show an overall decline culminating with a minimum centered at the Maunder minimum, which suggests that limited regional fires were related to cold climate conditions.

During the LIA, effects of a climate cooling on the vegetation are also reflected in other pollen records from the central Mediterranean. At Lago Lungo, in central Italy, around 1600 AD arboreal pollen declines from 89% to about 60%, *Juglans* and *Olea* temporarily disappear, and *Sporormiella* is reduced during a phase of establishment of a wetter climate and a rapid change of settlement pattern of the montane human populations, consistent with the abandonment of areas at high elevations in favour of an enhancement of fortified settlements (Mensing & *alii*, 2016). A decrease in forests, at a time of low fire frequency is also detected at Lago dell'Accesa (Vannière & *alii*, 2008) and at Massaciuccoli, where *Olea* declines (Colombaroli & *alii*, 2007). In the Sardinian site of Sa Curcurica (Beffa & *alii*, 2016) and in the Corsican site of Palo (Revelles & *alii*, 2019) pollen analysis, despite low resolution, confirm a decrease in arboreal taxa, including *Olea*, and of *Sporormiella*, in a period characterized by low values of charcoal influx. A temporary disappearance of *Olea* after 1500 AD is confirmed by the pollen record from Aleria Del Sale in Corsica (Currás & *alii*, 2017).

*Modern Period (1850 AD-present)*

From the end of the Little Ice Age (ca. 1850 AD) to the present day, despite increased human activity in the landscape, the pollen record from Gaeta points to a general forest recovery, related to both mixed oak forest and evergreen trees and shrubs belonging to the *macchia*, suggesting wetter and warmer climate conditions. The palaeoclimate proxy records of the Gaeta core point to the occurrence of a warm climate, which is highlighted by an increase in warm species *G. ruber* pink and *G. ruber* white and the absence of cold planktonic foraminiferal taxa *G. truncatulinoides* left coiled and *G. inflata* left coiled (Margaritelli & *alii*, 2016). Over the last decades, the contemporary abrupt decrease in *G. ruber* white variety (Margaritelli & *alii*, 2016) and the most prominent negative shift of $\delta^{18}O_{G.\ ruber}$ signal of the last two millennia, suggests a significant climate warming consistent with the ongoing worldwide climate change.

Cultivated trees, such as *Olea*, *Juglans*, and *Corylus*, contributed to enhance the woody vegetation. In addition, during the last decades a remarkable increase in arboreal vegetation, dominated by *Pinus*, reflects extensive plantations of *P. pinea*, *P. halepensis*, and *P. pinaster* in the coastal areas of the Gulf of Gaeta, documented also by administrative papers since the 1950s. The human impact on the natural ecosystems, evidenced by increasing values of *Sporormiella* until the 1950s and of *Sordaria* until present, is confirmed by the record of herbaceous anthropogenic indicators, pointing to increasing cultivations of cereals and hemp and open meadows devoted to farming activities and cattle breeding. This intensive use of land is corroborated by the remarkable increase in *Glomus*. A similar scenario is confirmed by the pollen records of Lago di Massaciccoli (Colombaroli & *alii*, 2007), Lago dell'Accesa (Vannière & *alii*, 2008), Lago Lungo (Mensing & *alii*, 2015), Lago Patria (Di Rita & *alii*, 2018), and Lago Trifoglietti (Joannin & *alii*, 2012). At Sa Curcurica (Beffa & *alii*, 2016) and Palo (Revelles & *alii*, 2019) in addition to a marked increase in *Olea* and *Pinus*, a slight increase of coprophilous fungi documents an intense human activity in the territory.

## CONCLUSION

The pollen data from Tyrrhenian Italy indicates that a succession of forested and more or less open landscapes alternated during the last 2000 years. In the Gaeta record, the phases with declining forests generally correspond to negative NAO oscillations (fig. 2), which determine a marked change in atmospheric circulation resulting in a weakening of storm tracks conveyed by westerlies (Hurrel, 1995). Irrespective of the societal cultural phase, this atmospheric configuration may have induced dry climate, and in turn forest decline. Evidence from other proxy records suggests that this process involved a wide region of the south-central Mediterranean, which had an opposite pattern compared to the south-west Mediterranean and the north Mediterranean regions (Di Rita & *alii*, 2018 a, 2018 b). Besides, decreases in precipitation recorded in the south-central Mediterranean, determining forest declines, are often coeval to solar grand minima (fig. 2), that generally correspond to negative phases of both East Atlantic (EA) pattern and NAO (Sánchez-López & *alii*, 2016). In addition, solar activity influences latitudinal shifts of the InterTropical Convergence Zone (ITCZ), which may have played an indirect influence in the reorganization of the climate synoptic systems over the Mediterranean. During the last 2000 years, the southernmost position of the ITCZ was reached in the Maunder Minimum (1645-1715 AD), which coincides with important atmospheric modifications in Europe (Shindell & *alii*, 2001) and corresponds to a forest decline and a marked decrease of anthropogenic indicators in the Gaeta record (fig. 2). More in general, during the solar activity minima, the interplay between ITCZ and NAO may have determined a decrease in temperature and precipitation over the south-central Mediterranean, as also suggested by the forest decline centered around 1050 AD in the Gaeta record, which coincides with the Oort minimum. Another possible explanation for the aridity phases in the south-central Mediterranean involves the extension and location of the North African anticyclone, inducing torrid temperatures and dryness especially in summer, which can determine drought events in the more southern areas of the Italian Peninsula (Di Rita & Magri, 2019). This may be also related to southward latitudinal shifts of the ITCZ, as documented during the LIA (Sachs & *alii*, 2012).

In synthesis, in the last 2000 years, in the south-central Mediterranean during phases characterized by low solar irradiance (solar gran minima), a combination of low latitudinal position of ITCZ with both negative NAO and EA circulations may have determined repeated decreases in precipitation caused by a weakening of the westerlies combined with the displacement of North African high pressures. This may have been the main mechanism determining the reductions in forest extent, such as during the Oort and Maunder minimum. In contrast, during phases characterized by high solar irradiance, high latitudinal position of ITCZ and positive NAO and EA circulations, higher precipitations may have occurred over the south-central Mediterranean, inducing forest recovery even in historical periods characterized by demographic increase and expected high human impact on the territory, such as during the Roman Imperial times.

In this scenario, microcharcoal and NPPs provide complementary information about fire dynamics and human pressure on the landscape that can help to disentangle human-induced variations from natural climate oscillations. In the Gaeta record, NPPs show a general increasing trend through time, visible in *Glomus*, *Podospora* type, *Gelasinospora*, and especially *Sporormiella*, consistent with a progressive increase of human pressure on the territory, also supported by the general decreasing trend of forests. In particular, the record of *Sporormiella*, combined with the pollen and microcharcoal records, can be used to distinguish six main phases of stock-breeding activity:

1. During the Roman times and the Early Dark Ages until approx. 850 AD a modest livestock farming activity is detected. In contrast, agricultural and silvicultural practices were well developed, as documented by high values of *Olea* until the fall of the Roman Empire and by a strong increase of *Castanea* values peaking around 600 AD during the Dark Ages.

2. In the time-interval 850-1150 AD, the increase of *Sporormiella* and pollen of disturbed meadows point to an intensification of breeding activity. Contemporarily, high values of microcharcoal concentration are found at the time of a marked opening of the forest, culminating during the Oort solar minimum and an inversion of a NAO index. It appears that human and climate factors concurred in determining extensive landscapes changes.

3. Between 1150 and 1300 AD, during a temporary disappearance of *Sporormiella*, indicators of disturbed meadows drop, which corresponds to a reduction of stock-rearing activities during a new forest expansion. High microcharcoal values suggest that despite frequent fires the development of the forest was not affected, being driven by the warm and wet climate conditions corresponding to the Medieval Warm Period.

4. In the time-interval 1300-1650 AD, *Sporormiella* attains high values testifying a new increase of human activities related to stock-breeding, confirmed by a development of Brassicaceae, Fabaceae and Cichorioideae. A clear turnover in plant cultivation is characterized by a decline of *Juglans* and cereals (until 1500 AD) and a development of *Olea* and *Castanea* orchards.

5. In correspondence with the Maunder minimum (ca. 1645-1715 AD), *Sporormiella* disappears, suggesting a marked reduction/change in farming practices. A general decline of human activities is also revealed by a drop of cultivated plants, such as *Olea*, *Castanea*, and cereals, and a reduction in microcharcoal concentration.

6. Since the 18$^{th}$ century, a new intensification of human impact related to agropastoral activity is testified by increasing values of both *Sporormiella* and pollen indicators of open meadows. An intense land use for farming activities is also witnessed by a remarkable increase in *Glomus* type and in microcharcoal concentrations. Besides, there is a development of hemp, cereals and olive cultivations. Despite the anthropic pressure, there is a spread of forested environment, favored by high temperatures and precipitations, as documented by independent palaeoclimate proxies.

The general good agreement between forest cover and microcharcoal concentration suggests that the frequency of fire events was mostly related to the availability of forest biomass. In many cases, there is no direct correspondence between the human impact expected from the cultural, demographic and technological development of society and the change of vegetational landscapes. For example, extensive forests and low concentration values for NPPs related to cattle raising occurred during the Roman Imperial age, corresponding to a time of considerable societal development. In contrast, at the transition between the final part of the Roman Period and the the first part of the Dark Ages a remarkable decline in natural broadleaved forest, still accompanied by frequent fires and evidence of modest stock-breeding activity, is recorded by pollen, microcharcoal and NPPs. These discrepancies suggest that while human impact produced a general and progressive decline of forest vegetation over the last 2000 years, other factors concurred in determining the main oscillations in forest cover at a regional scale, especially the climate oscillations known in historical times and confirmed by a variety of independent data.

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