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Late Holocene forest dynamics in the Gulf of Gaeta (central Mediterranean) in relation to NAO variability and human impact

Federico Di Rita[a, *], Fabrizio Lirer[b], Sergio Bonomo[b, c], Antonio Cascella[d], Luciana Ferraro[b], Fabio Florindo[e], Donatella Domenica Insinga[b], Pontus Conrad Lurcock[e], Giulia Margaritelli[b, g], Paola Petrosino[f], Roberto Rettori[g], Mattia Vallefuoco[b], Donatella Magri[a]

[a] *Department of Environmental Biology, Sapienza University of Rome, Piazzale Aldo Moro, 5, 00185 Roma, Italy*
[b] *Istituto per l'Ambiente Marino Costiero (IAMC) – Consiglio Nazionale delle Ricerche, Calata Porta di Massa, Interno Porto di Napoli, 80133 Napoli, Italy*
[c] *Istituto di Biomedicina ed Immunologia Molecolare "Alberto Monroy" (IBIM), Consiglio Nazionale delle Ricerche, Via Ugo La Malfa 153, 90146 Palermo, Italy*
[d] *Istituto Nazionale di Geofisica e Vulcanologia, Via della Faggiola 32, 52126 Pisa, Italy*
[e] *Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy*
[f] *DiSTAR - Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse – Università degli Studi di Napoli "Federico II", Largo S. Marcellino 10, 80138 Napoli, Italy*
[g] *Dipartimento di Fisica e Geologia – Università di Perugia, Via Alessandro Pascoli, 06123 Perugia, Italy*

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ABSTRACT

A new high-resolution pollen record, spanning the last five millennia, is presented from the Gulf of Gaeta (Tyrrhenian Sea, central Italy), with the aim of verifying if any vegetation change occurred in the central Mediterranean region in relation to specific well-known global and/or regional climate events, including the 4.2 ka event, the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA), and to detect possible vegetation changes related to still under-investigated climate signals, for example the so-called "Bond 2" cold event around 2.8 ka BP. The vegetation dynamics of the Gaeta record shows a recurrent pattern of forest increase and decline punctuating the mid- and late Holocene. When the timing of these patterns is compared with the climate proxy data available from the same core (planktonic foraminifera assemblages and oxygen stable isotope record) and with the NAO (North Atlantic Oscillation) index, it clearly appears that the main driver for the forest fluctuations is climate, which may even overshadow the effects of human activity. We have found a clear correspondence between phases with negative NAO index and forest declines. In particular, around 4200 cal BP, a drop in AP (Arboreal Pollen) confirms the clearance recorded in many sites in Italy south of 43°N. Around 2800 cal BP, a vegetation change towards open conditions is found at a time when the NAO index clearly shows negative values. Between 800 and 1000 AD, a remarkable forest decline, coeval with a decrease in the frequencies of both *Castanea* and *Olea*, matches a shift in the oxygen isotope record towards positive values, indicating cooler temperatures, and a negative NAO. Between 1400–1850 AD, in the time period chronologically corresponding to the LIA (Little Ice Age), the Gaeta record shows a clear decline of the forest cover, particularly evident after 1550 AD, once again in correspondence with negative NAO index.

1. Introduction

The vegetation of the central Mediterranean Basin, at the interface between the two continents of Europe and Africa, is especially sensitive to the climate forcing from both the North Atlantic Oscillation (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, and consequently the development of forest vegetation. Recent paleoclimate reconstructions agree that during the entire Holocene the climate evolution of the Mediterranean region exhibits a strong spatial and temporal precipitation variability, often linked to seasonal mid-latitude and sub-tropical climate dynamics (Fletcher et al., 2013; Magny et al., 2013; Peyron et al., 2017).

The most prominent mode of climate variability influencing winter precipitations in the North Atlantic and Mediterranean regions is the NAO, coupled with the Arctic Oscillation (Hurrell, 1995; Wanner et al., 2001; Xoplaki et al., 2012). According to Olsen et al. (2012) when the NAO index is positive, Northern Europe and the Eastern United States are mild and wet, while a negative index is associated with the reverse pattern. Regarding the Mediterranean area, the NAO index signal often appears associated with regional hydrological regimes showing opposite patterns in different areas, and in turn opposite vegetation responses: under a positive NAO, the Mediterranean northern borderlands experience dry conditions, while the southern Mediterranean regions benefit from increasing precipitation

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[*] Corresponding author.
Email address: federico.dirita@uniroma1.it (F. Di Rita)

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as in NW Europe (Marshall et al., 2001; Dünkeloh and Jacobeit, 2003; Magny et al., 2013). Opposite patterns develop under negative NAO conditions. According to Magny et al. (2013), the boundary between the two opposite hydrological sectors of the Mediterranean may be affected by latitudinal fluctuations.

A further factor of climate variability is represented by orbitally-driven changes in insolation, producing latitudinal migrations of the Intertropical Convergence Zone (ITCZ), thus influencing the global-scale climate variability (Wanner et al., 2011). Latitudinal migrations of the ITCZ may affect the precipitation in the Northern Hemisphere summer monsoon area (Yan et al., 2015) and contribute to a reorganization of the atmospheric systems at middle latitudes (Wirth et al., 2013), possibly influencing the distribution of the vegetation in the central Mediterranean (Di Rita, 2013; Zanchetta et al., 2016).

The vegetation of southern Italy is particularly exposed to these different climatic signals and can rapidly respond to climate change, being developed in a complex physiographic system, enhancing high floristic richness and admixtures of xerophilous and mesophilous plant assemblages, often located close to each other (Magri et al., 2015). This pattern is the result of a long-term persistence of temperate, mediterranean and steppe plant communities, which coexisted throughout the glacial-interglacial cycles of the Quaternary (Magri et al., 2017).

This climatic, physiographic and vegetational complexity is well expressed in the Tyrrhenian coast of the Campania region (Fig. 1). We present a new detailed palaeovegetational reconstruction, extending back to 5.5 ka, from a shallow water marine core, recovered in the Gulf of Gaeta at the mouth of the Volturno River.

A previous study on this core (Margaritelli et al., 2016) provided a detailed reconstruction of the main climate oscillations over the last 4.5 ka, identifying nine time intervals associated with archaeological/cultural periods (top of Eneolithic ca. 2410 BC, Early Bronze Age ca. 2410 BC ca. 1900 BC, Middle Bronze Age Iron Age ca. 1900–500 BC, Roman Period ca. 500 BC - 550 AD, Dark Age ca. 550–860 AD, Medieval Climate Anomaly ca. 860–1250 AD, Little Ice Age ca. 1250–1850 AD, Industrial Period ca. 1850–1950 AD, Modern Warm Period ca. 1950 AD - present day). The good correspondence between climate oscillations and archaeological intervals underline the role exerted by climate change in determining rises and declines of civilizations. Within these time intervals, planktonic foraminifera and oxygen stable isotope data have allowed us to detect a series of past climate changes on decadal to millennial time scale, linked to dynamics of ocean-atmospheric coupling or to solar activity, such as the 4.2 ka event, four Roman solar minima, the Medieval Cold Period and the Maunder event. In addition, Margaritelli et al. (2016) suggest a strong modification in the climate system from the onset of the Roman Period up to the present-day documented by long-term trend and amplitude oscillations in the $\delta^{18}O_{G.\ ruber}$ signal, by the onset of main planktonic foraminiferal turnovers from carnivorous to herbivorous opportunistic species, and by consistent forest fluctuations in the pollen record. Moreover, the correlation between the NAO index and $\delta^{18}O_{G.\ ruber}$ signal suggests a global climate signature in the shallow water marine study record, pointing to a hemispheric scale atmospheric connection.

Climate reconstructions from planktonic foraminifera and oxygen stable isotopes offer the possibility to avoid circular argumentations when evaluating the responses of vegetation to climate change, and to disentangle the effects of human activity from changes in temperature and precipitation. For the same reason, special attention has been paid to independent evidence of the NAO index oscillations, which – as discussed above – undoubtedly influenced the regional vegetation dynamics (Gouveia et al., 2008).

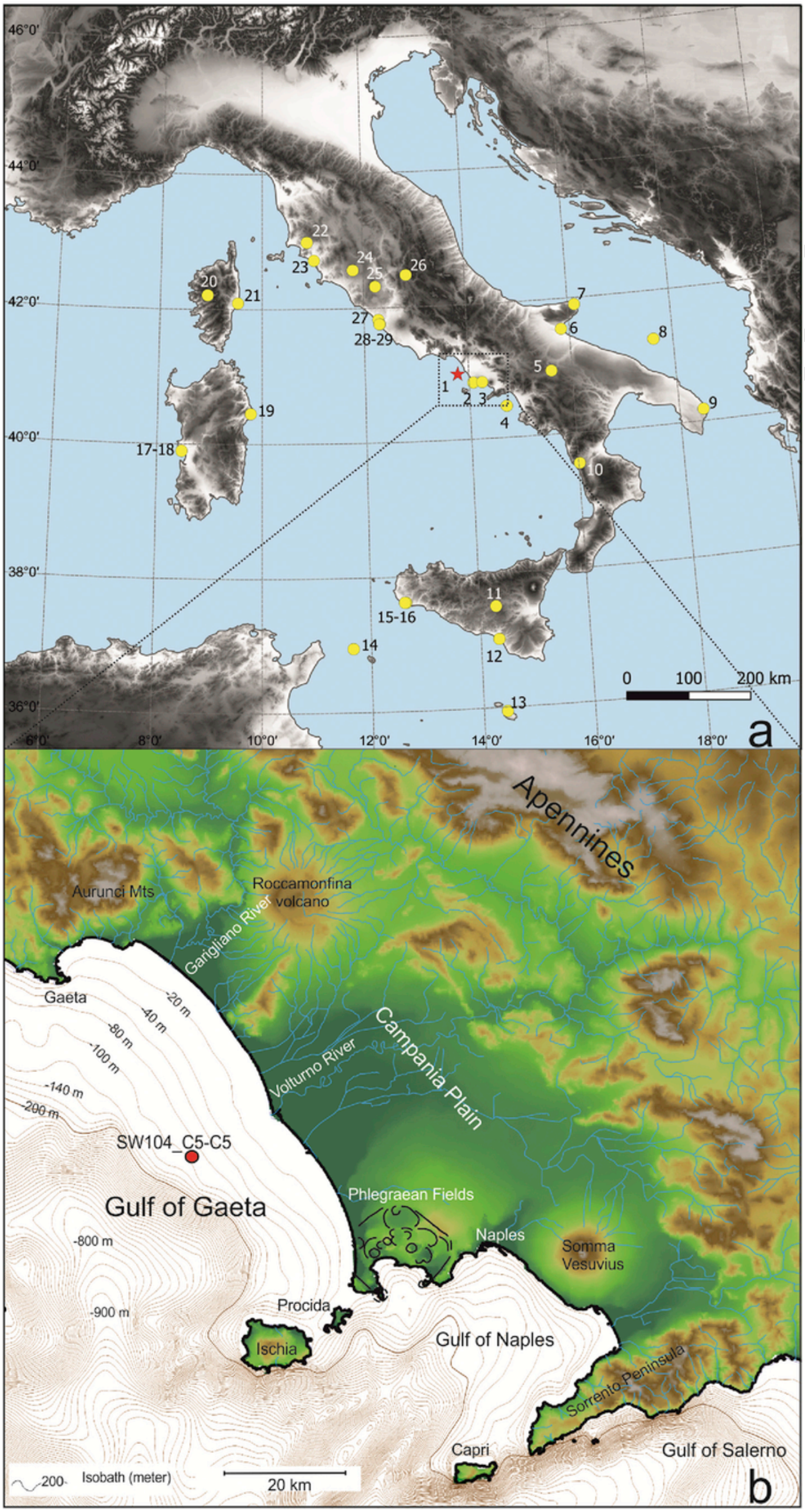
Based on these premises, the present study is aimed not only at providing a high-resolution vegetation record for the last five millennia, which is missing for this region, but also at defining possible responses of vegetation in the central Mediterranean to specific climate events detected in Margaritelli et al. (2016), which are in some cases relatively well known, for example the 4.2 ka event, but in other cases are still unclear, for example the 2.8 ka event, corresponding to the so-called "Bond 2" event (Bond et al., 2001), the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). In this paper, we discuss the role of human activities in the vegetation changes recorded at Gaeta in more detail with respect to Margaritelli et al. (2016), considering both pollen indicators and historical/archaeological sources, although a marine pollen record >10 km away from the shore may not be the best place to analyse local vegetation dynamics, including human impact related to crops and land use, which may be mitigated by the distance. On the whole, our pollen record appears especially suitable for tracing changes in the regional vegetation.

2. Study area

The Gulf of Gaeta borderland has a typical Mediterranean climate, with annual precipitations of up to 1200 mm on the reliefs and ca. 850 mm along the coastal plains. The mean annual temperature varies between 9 °C and 16 °C. This area is characterized by the Garigliano and Volturno floodplains and the Campania Plain more inland; it is bordered on the North by the Aurunci mountains, on the East by the volcanic district of Roccamonfina and the limestone Southern Apennines, and on the South by the volcanic districts of Mt. Somma-Vesuvius and Phlegraean Fields (Fig. 1). This region represents the main source area of the pollen recorded in the Gulf of Gaeta pollen record.

A recent classification of Italy based on vegetational aspects includes this territory in the Southern Lazio and Western Campania ecoregion subsections (Blasi et al., 2014), which are mostly characterized by central Tyrrhenian pre-Apennine coastal sub-acidophilous *Quercus frainetto* series (*Mespilo germanicae-Querco frainetto* sigmetum), central Tyrrhenian pre-Apennine neutro-basophilous *Ostrya carpinifolia* series (*Mespilo germanicae-Ostryo carpinifoliae* sigmetum), Adriatic neutro-basophilous *Quercus cerris* and *Q. pubescens* series (*Daphno laureolae-Querco cerridis* sigmetum), peninsular neutro-basophilous *Quercus ilex* (*Cyclamino hederifolii-Querco ilicis* segmetum), and peninsular hygrophilous chain of series of the riparian zone (*Salicion albae*, *Populion albae*, *Alno-Ulmion*).

Both the climate and the modern vegetation of the Gulf of Gaeta borderlands appear to be strongly related to the inland orographic complexity and the proximity of the sea (Filesi et al., 2010). Sclerophyllous shrublands and *Quercus ilex* woodlands generally dominate the coastal promontories and the south-facing slopes at low altitudes (ca. 0–600 m), while mixed evergreen/deciduous and deciduous forest formations are more frequent at higher altitudes, favoured by orographic humidity. In the limestone massifs of the Ausoni and Aurunci mountains, for example, *Quercus pubescens* woodland is mostly distributed on the footslopes, whereas *Quercus cerris* dominates the bottom of the intra-montane karst plateaux. The north facing slopes of these mountains are rich in *Carpinus orientalis* and *Ostrya carpinifolia*, located in the hilly and montane zone, respectively. The highest altitudes of the montane zone are covered by *Fagus sylvatica* forests (Di Pietro, 2011). In the volcanic district of Roccamonfina, chestnut cultivations represent the main element of land cover (Croce and Nazzaro, 2012). Conifer forests have a restricted and patchy distribution in the land bordering the Gulf of Gaeta: stands of *Pinus pinea, P. halepensis* and *P. maritima* have been planted along the coast since 1955, when a nature reserve was established at the mouth of the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80 m
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-140 m
-200 m
Volturno River
Campania Plain
SW104_C5-C5
Gulf of Gaeta
-800 m
-900 m
Phlegraean Fields
Naples
Somma Vesuvius
Procida
Ischia
Gulf of Naples
Sorrento Peninsula
Capri
Gulf of Salerno
200 Isobath (meter)
20 km
b

Volturno River, currently designated as a Ramsar Site (www.ramsar.org). Agricultural areas, with arable lands and permanent orchards and olive groves, extensively cover the coastal plain and foothills. In the middle-late Holocene, the geomorphic configuration of the Garigliano and Volturno river floodplains underwent deep changes related to deltaic system evolution and coastal plain development (Sacchi et al., 2014; Bellotti et al., 2016; Alberico et al., 2017; Ruberti et al., 2017). Presumably, the vegetation also underwent major changes. A recently published pollen record from the Garigliano mouth (Bellotti et al., 2016) and still unpublished data collected from Lago Patria (13 km south the Volturno mouth) suggest that the local floodplain vegetation was mostly characterized by riparian *Alnus*-dominated and sedge-dominated swampy formations, intermixed with deciduous and evergreen semi-open woodlands.

Another landscape feature typical of the Campania region is the presence of volcanoes. The volcanic complex surrounding Naples and its province (Somma-Vesuvius, Phlegraean Fields and Ischia), is currently quiescent, but still active. The Roccamonfina volcano, in the northern part of Campania, is considered extinct, as its last eruption occurred ca. 50 ka BP (Radicati di Brozolo et al., 1988).

Despite the active volcanism in historic and prehistoric times, human presence in Campania is documented since the Palaeolithic. In many cases, pyroclastic materials have determined excellent conditions for the preservation of archaeological sites, such as in the well-known case of Pompeii. In the time-span considered by this paper, the last 5.5 ka BP, the Campania Region appears widely inhabited, although no prehistoric sites have been studied in the territory close to the mouth of the Volturno River. During the Eneolithic, traces of cultivated fields and ploughing have been identified just below the pyroclastic materials of the Agnano-Montespina eruption (4.42 ka BP), but no stable settlements have been recognized (Nava et al., 2007; Saccoccio et al., 2013). Several Bronze Age sites have been studied north of Naples and in the volcanic area of Somma-Vesuvius and Phlegraean Fields (Albore Livadie et al., 2005; Laforgia et al., 2009; Saccoccio et al., 2013; Di Vito et al., 2013), but the Bronze Age archaeological finds are rare in the coastal plain along the Gulf of Gaeta (Albore Livadie, 2007), where Iron Age settlements are completely missing (Nava et al., 2007). The first historical evidence of human settlements around the Volturno mouth, a colony by the Opici italic population, dates back to the 9th century BC. Starting in the 8th century BC the coast close to Naples was colonized by the Greeks, and in the 6th century inland areas were occupied first by the Etruscans and then by other Italic populations, including Samnites and Osci. The Etruscans also controlled the coastal areas of the Gulf of Gaeta, where they built the town of *Volturnum*, located at the mouth of the Volturno river, in the territory occupied by the ancient Opici settlement. *Volturnum* became an important trade point on the road to Capua. At the beginning of the 3rd century BC the region was occupied by the Romans, who considered Campania the most prosperous region of the Italian Peninsula (*Campania felix*) because of its beauty and the fertility of soils. In 194 BC, *Volturnum* became a Roman colony with the main purpose of controlling the lower course of the Volturno river. From the beginning of the 2nd century BC to the 5th century AD, the coastal plain south of the Volturno river mouth hosted another important Roman colony named *Liternum*, built on a rocky basement on the southern side of the Lake Patria (*Literna Palus*). *Liternum* was chosen as a residence by Scipio Africanus, who died there in 183 BC. In Imperial times, the inland area of the *Liternum* territory was exploited for olive, grape and cereals cultivations (Camodeca, 2010). In 455, the town was plundered and destroyed by Genseric, king of the Vandals. Starting in the 6th century AD, the region was progressively occupied by Lombards, and in the 11th century by the Normans. The 11th century also coincided with a phase of expansion of the Benedictine monasticism in Campania. A large marsh south of the Volturno river mouth was controlled by the Benedictine Monastery of San Lorenzo d'Aversa. From the 13th to the 16th century the region was under the rule of the Angevin and Aragonese, followed by the Spanish domination until 1734, when the Bourbons established the new kingdom of Naples and Sicily. In 1860 the Campania region was annexed to Italy.

3. Materials and methods

The composite record described in the present paper (hereafter called Gaeta record) was obtained from two shallow marine sedimentary cores: the SW104_C5 core (40°58′24,993″N, 13°47′03,040″E; 108 cm long) and the C5 core (40°58′24.953″N, 13°47′02,514″E; 710 cm long), recovered in the Gulf of Gaeta (central Tyrrhenian Sea) at 93 m below sea level, onboard the R/V Urania-CNR in 2013 (Fig. 1). The stratigraphic correlation of the two cores was based on magnetic susceptibility signals and was allowed by the recognition of a distinct common peak in magnetic susceptibility of the two cores, found in SW104_C5 core and C5 core at 61 and 48 cm depth, respectively, corresponding to the tephra layer of the Vesuvius eruption dated at 1906 AD (for details see Margaritelli et al., 2016). Our pollen analysis improves the detail of a previous pollen record, published in Margaritelli et al. (2016), and extends the analysis back to 5.12 mbsf of the composite sequence, mostly composed of fine-grained light grey hemipelagic sediments.

The chronology of the study record is based on ^{210}Pb and ^{137}Cs radionuclide measurements, for the uppermost 60 cm, and the identification of five tephra layers at the depths of 53, 319, 403, 414 and 437 cm, namely: Vesuvius (1906 AD), Vateliero-Ischia (2.6–2.4 ka BP), Capo Miseno (3.9–3.7 ka BP), Astroni3 (4.3–4.1 ka BP), and Agnano Monte Spina (4.42 ka BP), respectively (Margaritelli et al., 2016). The age-depth model (Fig. 2) takes also into account additional reliable time-constrained events, such as the peak in abundance of *Globorotalia truncatulinoides* left coiled (1718 ± 10 yr AD, Lirer et al., 2013, 2014) and the acme interval of *Globigerinoides quadrilobatus* (base 3.7 ± 0.048 ka BP, top 2.7 ± 0.048 ka BP, Lirer et al., 2013), the $\delta^{18}O_{G.ruber}$ comparison with the C90 core from the Gulf of Salerno (Lirer et al., 2014), and palaeomagnetic inclinations measured on the composite core (Margaritelli et al., 2016). Details for the

Fig. 1. (a): Location map of the pollen sites mentioned in text: 1. Gulf of Gaeta (Margaritelli et al., 2016); 2. Lago d'Averno (Grüger and Thulin, 1999); 3. Neapolis harbour (Allevato et al., 2010, 2016); Russo Ermolli et al., 2014); 4. C106 (Russo Ermolli and di Pasquale, 2002); Di Donato et al., 2008); 5. Lago Grande di Monticchio (Allen et al., 2002); 6. Lago Salso (Di Rita et al., 2011); 7. Lago Battaglia (Caroli and Caldara, 2007); 8. MD 90–917 (Combourieu-Nebout et al., 2013); 9. Lago Alimini Piccolo (Di Rita and Magri, 2009); 10. Lago Trifoglietti (Joannin et al., 2012); 11. Lago di Pergusa (Sadori and Narcisi, 2001); 12. Biviere di Gela (Noti et al., 2009); 13. Burmarrad (Djamali et al., 2013); 14. MD04-2797 (Desprat et al., 2013); 15. Gorgo Basso (Tinner et al., 2009); 16. Lago Preola (Calò et al., 2012); 17. Mistras (Di Rita and Melis, 2013); 18. Tirso Plain (Melis et al., 2017); 19. Sa Curcurica (Beffa et al., 2016); 20. Lac de Creno (Reille et al., 1999); 21. Aleria Del Sale (Currás et al., 2017); 22. Lago dell'Accesa (Drescher-Schneider et al., 2007); 23. Ombrone (Biserni and van Geel, 2005); 24. Lagaccione (Magri, 1999); 25. Lago di Vico (Magri and Sadori, 1999); 26. Lago Lungo (Mensing et al., 2015, 2016); 27. Lingua d'Oca-Interporto (Di Rita et al., 2010); 28. Ostia C5 (Bellotti et al., 2011); 29. Fiume morto (Pepe et al., 2016). (b): bathymetric map of the study area with the location of the study core and the hydrographic grids of the Garigliano and Volturno rivers.

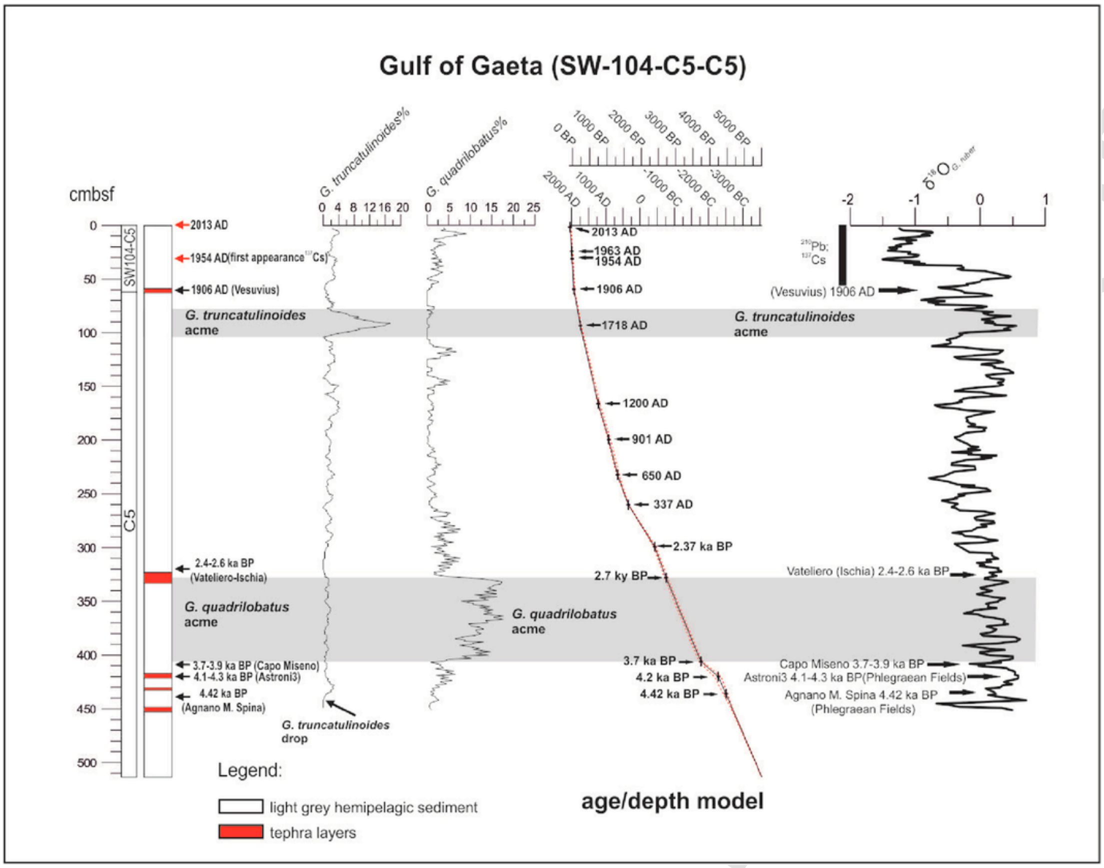

Fig. 2. Age-depth model of the composite core from the Gulf of Gaeta (SW104—C5–C5) modified from Margaritelli et al. (2016). The distribution patterns of planktonic foraminifers *Globorotalia truncatulinoides*, *Globigerinoides quadrilobatus* and the δ^{18}O$_{G.\ ruber}$ record are plotted with a 5- point points moving average in the depth domain. The black arrows are the tie-points used in Margaritelli et al. (2016) for the construction of the age-depth profile of the composite core here adopted.

construction of the age model are reported in Margaritelli et al. (2016).

Pollen analysis was successfully carried out on 100 samples that were chemically treated with HCl (37%), HF (40%) and NaOH (20%), following the standard procedure (Magri and Di Rita, 2015). Pollen concentration values were estimated by adding *Lycopodium* tablets to known weights of sediment. No heavy liquids were used during sample preparation. Pollen grains were identified by means of a light microscope at 400 and 640 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 of Sapienza University of Rome. The main percentage sum is based on terrestrial pollen excluding pollen of aquatics and non-pollen palynomorphs (NPPs). The computer program Psimpoll 4.27 (Bennett, 2009) was used to plot the pollen diagrams and subdivide them into eleven local assemblage zones, numbered from the base upward.

4. Results

The results of pollen analysis are presented as a detailed percentage diagram with the records of the single pollen taxa plotted against age (Fig. 3), and a synthetic diagram including cumulative percentages of conifers, riparian trees, deciduous trees, evergreen trees and shrubs, anthropogenic indicators, Arboreal Pollen (AP + Anthropogenic trees) percentages, paleoclimate proxies of Bond events and NAO index variability, δ^{18}O$_{G.\ ruber}$ and the percentages of *Globigerinoides* total and *Turborotalita quinqueloba* from the same core in the Gulf of Gaeta (core SW104—C5–C5) (Fig. 4).

The pollen record includes 14 new samples in addition to those described in Margaritelli et al. (2016). These have been added at the base of the record and between 5000 and 3000 years BP, to increase the average resolution of the record to ca. 55 years. Excluding pollen of aquatics, fern spores and other non-pollen palynomorphs (NPPs), an average number of ca. 200 pollen grains per sample was counted. These represent a statistically reliable number of grains to undertake a reconstruction of the vegetation history, especially considering the low pollen concentrations (1300–7000 pollen grains/g sediment) and the fraction of analysed sample (often >10%). The pollen taxa diversity is represented by 84 terrestrial pollen types, including 39 arboreal and 45 non-arboreal taxa.

The vegetation history depicted by the pollen records can be schematized as follows:

- Zone GdG-1 (5500-4750 cal BP; 3550–2800 BC): the forest cover (AP>80%) was composed of mixed deciduous and evergreen taxa, dominated by evergreen (45%) and deciduous *Quercus* (20%), accompanied by several woody taxa with frequencies >2%: *Pinus*, *Alnus*, *Ostrya*/*Carpinus orientalis*, *Fagus*, *Ulmus*, and Ericaceae.
- Zone GdG-2 (4750-4100 cal BP; 2800–2150 BC): a forest decline, culminating around 4200 cal BP, was mainly related to a decrease in evergreen *Quercus* (25%). It was accompanied by a remarkable increase in herbaceous taxa (>40%), Cichorioideae (17%), Chenopodiaceae (7%), Poaceae (5%), and *Artemisia* (4%) being the most abundant.

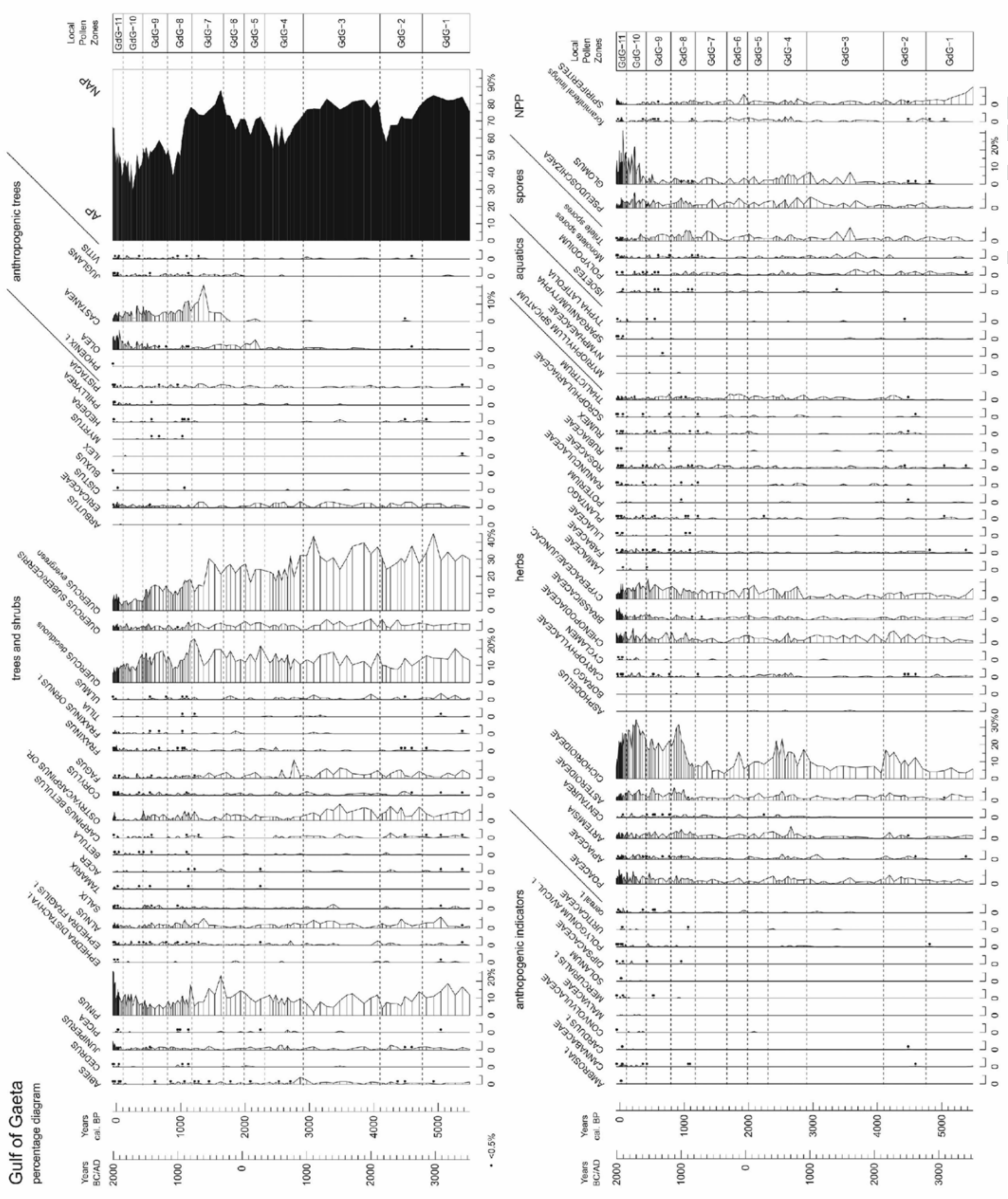

Fig. 3. Pollen percentage diagram from the Gulf of Gaeta.

- Zone GdG-3 (4100-2900 cal BP; 2150–950 BC): a remarkable increase in evergreen *Quercus* (>40%), but also in deciduous elements such as *Quercus* (18%), *Ostrya*/*Carpinus orientalis* (10%), and *Fagus* (6%), is reflected in the AP percentages, surpassing 80% and indicating that extensive forests covered both the coastal plain, with evergreen elements, and the inland reliefs, with mixed deciduous oak and beech forest. Significant values of Chenopodiaceae (5%) and Cichorioideae (8%) are still recorded.
- Zone GdG-4 (2900-2300 cal BP; 950–350 BC): the forest vegetation shows a new decline, as indicated by the AP percentages, reaching three minima of about 55% between 2900 and 2600 cal BP. Once again, evergreen *Quercus* (17%) were the trees most affected by this deforestation event. Almost all the herbaceous taxa significantly increased, including Cichorioideae (23%), Asteroideae (5%), Cyperaceae/Juncaceae (6%), Poaceae (4%), and *Artemisia* (7%).
- Zone GdG-5 (2300-2000 cal BP; 350 BC-50 BC): the pollen diagram shows a moderate forest expansion. This was also favoured by a significant increase in *Olea* (6%) in the 2nd century BC. For the first time *Castanea* exceeds 1%.
- Zone GdG-6 (2000-1650 cal BP; 50 BC-300 AD): the AP shows an oscillating trend. *Juglans* shows a continuous curve with values of almost 2%, certainly in relation to the cultivation of this tree.
- Zone GdG-7 (1650-1150 cal BP; 300–800 AD): a considerable increase in trees (max AP 88%) is largely imputable to a marked increase in *Castanea* (>20%), clearly due to cultivation. *Olea*,

Juglans, and *Vitis* show continuous curves and testify to intense agricultural activity in the region. This increase in cultivated trees corresponds to a decline in evergreen *Quercus*, which progressively decrease until the present time.

- Zone GdG-8 (1150-800 cal BP, 800–1150 AD): the AP percentages show a marked forest drop, with AP values < 40% during the phase of maximum reduction of trees, involving both evergreen and deciduous elements. A clear increase in the diversity of herbaceous taxa is recorded, including various anthropogenic indicators, such as Cannabaceae, *Mercurialis* type, *Polygonum aviculare* type, and Urticaceae.
- Zone GdG-9 (800-400 cal BP; 1150–1550 AD): a moderate development of forest vegetation is mostly related to a temporary expansion of oak-dominated woodlands, while many anthropogenic taxa (e.g., Cannabaceae) are clearly reduced. However, cereal pollen shows a slight increase.
- Zone GdG-10 (400-100 cal BP; 1550–1850 AD): a new marked drop in forest vegetation causes AP% to decrease to <35%. *Olea*, *Castanea*, *Juglans* and *Vitis* are always well represented, together with Cannabacae, cereals and several other anthropogenic indicators, except for a short interval between 1650 and 1720 AD (Fig. 3). Interestingly, pollen of *Solanum* is found in some layers.
- Zone GdG-11 (100 cal BP-present; 1850 AD-present): a new expansion of arboreal vegetation (max 67%) is mostly related to an increase in conifers dominated by *Pinus*, especially in the last 50 years, also in relation to the plantations of *P. pinea*, *P. halepensis* and *P. maritima* along the coast. The last century is also marked by increasing frequencies of cultivated taxa. Three taxa are found for the first time: *Buxus* and *Phoenix*, which may have been introduced for ornamental purposes, and *Ambrosia*, which may correspond to an invasive ragweed.

5. Vegetation development in the Gulf of Gaeta

In the Gaeta record it is difficult to disentangle the influence of the local vegetation from the regional vegetation. The low frequencies of riparian trees, important floristic elements of the floodplain forests in central-southern Italy (Colombaroli et al., 2007; Di Rita et al., 2010; Melis et al., 2017), suggest that the Gaeta record reflects a mixed-up airborne regional pollen rainfall, even though in some cases pollen in nearshore marine sediments can be mainly transported by rivers (Brown et al., 2007 and references therein). The main phases of vegetation history are here discussed in relation to other pollen records in central and southern Italy (Fig. 1), taking into account the marked differences in physiography, ecology, and human impact among regions. Few other pollen records are available from the Campania region; they include a marine record from the Gulf of Salerno outlining the main vegetation changes of the last 35 ka (Russo Ermolli and di Pasquale, 2002; Di Donato et al., 2008), a record from Lago d'Averno (15 km West of Naples), spanning from the 6th cent.

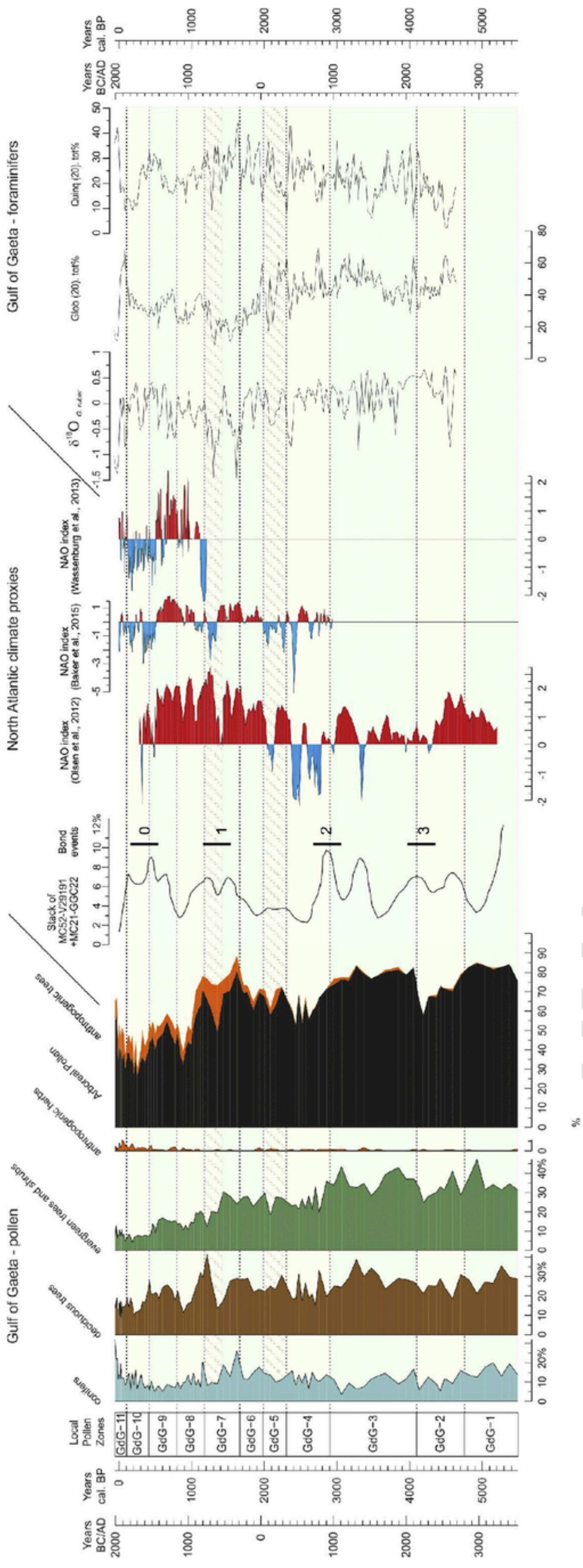

Fig. 4. Summary pollen percentage diagram including the cumulative percentages of conifers (mostly represented by *Pinus*, *Juniperus*, and *Abies*), riparian trees (*Alnus*, *Salix*, *Populus*, and *Tamarix*), deciduous trees (mostly deciduous *Quercus*, *Corylus*, *Fagus*, *Ostrya*/*Carpinus orientalis*, *Carpinus betulus* and *Ulmus*), evergreen trees and shrubs (evergreen *Quercus*, Ericaceae, *Phillyrea*, and *Pistacia*), anthropogenic indicators (including *Castanea*, *Olea*, and other cultivated and anthropochore taxa such as *Juglans*, *Vitis*, cereals, etc.), Arboreal Pollen (Arboreal Pollen + Anthropogenic trees), $\delta^{18}O_{G.\ ruber}$, the *Globigerinoides* total % and *Turborotalita quinqueloba* % plotted with 5-point moving average from the Gulf of Gaeta (SW104—C5–C5), chronologically correlated with proxies of the "Bond events" (Bond et al., 2001), and the NAO index reconstructed by Olsen et al. (2012), Wassenburg et al. (2013), and Baker et al. (2015).

BC to the 6th cent. AD (Grüger and Thulin, 1998), and a pollen-wood analysis at the Neapolis harbour (4th cent. BC-6th cent. AD) (Allevato et al., 2010; Russo Ermolli et al., 2014). Palaeovegetational changes were also compared with the climate oscillations documented by planktonic foraminifera and oxygen stable isotope data from the same Gaeta record (Margaritelli et al., 2016), and curves of NAO-index reconstruction (Olsen et al., 2012; Wassenburg et al., 2013; Baker et al., 2015) (Fig. 4). The human impact on vegetation related to cultivation, pastoral practices and human demographic increase was interpreted considering also the history of human frequentation of the area, as attested by archaeological sites and historical documents.

5.1. 5500 - 4750 cal BP (3550–2800 BC)

A widespread forest vegetation, characterized by the dominance of Mediterranean evergreen *Quercus* accompanied by extensive temperate deciduous forest communities, confirms the vegetation features found in the pollen sites of Apulia (Caroli and Caldara, 2007; Di Rita and Magri, 2009; Di Rita et al., 2011) and Sicily (Sadori and Narcisi, 2001; Noti et al., 2009; Tinner et al., 2009; Calò et al., 2012), especially those located in the evergreen vegetation belt (Fig. 1). In the pollen records from Apulia, high percentages of local evergreen vegetation are coupled with high frequencies of deciduous elements, reflecting either mesophilous vegetation stands in nearby montane sectors (Caroli and Caldara, 2007; Di Rita et al., 2011), or pollen transport from the Balkan Peninsula (Di Rita and Magri, 2009). In the pollen records from Sicily, the forest conditions were mostly related to widespread *Quercus ilex* and *Pistacia*-dominated woodlands (Tinner et al., 2009; Calò et al., 2012; Noti et al., 2009; Sadori et al., 2013). According to Djamali et al. (2013), the evergreen forest formations in Sicily and Malta developed consistently with a migration of the ITCZ starting around 7000 cal BP. This atmospheric process may have favoured the eastward movement of the North Atlantic cyclonic systems, conveying humid air masses into the central and eastern Mediterranean through the westerlies. Very high AP percentages (>90%), were also found at Lago Grande di Monticchio, in southern Italy (Allen et al., 2002). A stable warm and humid climate, described in the pollen record of the Adriatic marine core MD 90–917, was associated with high frequencies of *Quercus* pollen (Combourieu-Nebout et al., 2013), comparable to the Gulf of Gaeta.

The considered time interval, showing the development of a dense forest in the Gaeta record, chronologically corresponds to a phase of NAO positive values (Fig. 4), associated with mild and wet winters in northern Europe (Olsen et al., 2012) and in the southern Mediterranean (Magny et al., 2013).

5.2. 4750 - 4100 cal BP (2800–2150 BC)

The forest decline profiled in the Gaeta record can be included in a wider deforestation pattern culminating around 4200 cal BP, mostly involving evergreen vegetation, which was recorded in many pollen sites south of 43°N in the central Mediterranean (Sadori and Narcisi, 2001; Di Rita and Magri, 2009; Noti et al., 2009; Tinner et al., 2009; Di Rita et al., 2011; Desprat et al., 2013; Combourieu-Nebout et al., 2013). Di Rita and Magri (2009) suggest that the atmospheric mechanism underlying the 4.2 ka deforestation process was a northward displacement/expansion of a semi-permanent high-pressure cell from North Africa, determining dry climate conditions mostly affecting the evergreen vegetation, which generally represents the dominant vegetation type in southern-central Mediterranean sites where this pattern is recorded.

The occurrence of extra-regional pollen grains, suggesting the direction of dominant winds, supports the hypothesis of an anticyclone clock-wise atmospheric circulation in the southern regions of the central Mediterranean: *Cedrus* pollen at Lagaccione (Magri, 1999) and Lago di Vico (Magri and Sadori, 1999) suggests an incidence of dominant winds from Africa towards the western (Tyrrhenian) sectors of Italy (Magri and Parra, 2002), while the record of *Picea* pollen at Lago Alimini Piccolo (Di Rita and Magri, 2009) suggests dominant winds from the Balkan Peninsula towards the eastern (Ionian) sectors of Italy. This picture is enriched by recent pollen evidence from Sardinian sites, where the occurrence of *Cedrus* pollen between 4600 and 4000 cal BP confirms a dominance of African winds (Di Rita and Melis, 2013). In Sardinian pollen records (Di Rita and Melis, 2013; Beffa et al., 2016; Melis et al., 2017), *Betula* is present before and after this time interval, but absent during it. This absence may be interpreted as the establishment of a sort of atmospheric blocking against northern winds crossing Corsica, where *Betula* was present (Reille et al., 1999; Currás et al., 2017). In the Gaeta record, while the forest decline is consistent with the deforestation pattern described by Di Rita and Magri (2009), no occurrence of pollen of extra-regional origin was found in this time interval, possibly because the Gulf of Gaeta was central in the envisioned high-pressure cell, whereas winds tends to circulate with their maximum strength at the fringes of the cell.

The forest decline recorded in the central Mediterranean was probably a regional manifestation of the globally known 4.2 ka event, a centennial-scale climate oscillation recorded in many paleoclimate and palaeoenvironmental records from Africa, Mediterranean, Middle East, India, and as far as China, related to complex processes of atmospheric circulation of supra-regional amplitude (Walker et al., 2012). This climate event was also documented by the $\delta^{18}O_{G.ruber}$ signal of the Gaeta core (Margaritelli et al., 2016).

In the central Mediterranean, the atmospheric variability of this time period can be attributed to a complex climate process related to both changes in the NAO index polarity and the latitudinal position of the ITCZ (Di Rita and Magri, 2009; Magny et al., 2013; Zanchetta et al., 2016). In the NAO index reconstruction proposed by Olsen et al. (2012), this interval corresponds to a phase of declining positive values, culminating around 4250 cal BP with a NAO index inversion towards negative values (Fig. 4). This coincides with a forest decline at Gaeta and in other records of the region, caused by a decrease in precipitations in central-southern Italy.

Dry phases in the central Mediterranean are also inferred from the activity peaks of Central Tunisian rivers (Zielhofer and Faust, 2008), in the pollen record of Palavas (Azuara et al., 2015) and in pollen records of marine cores MD 90–917 (Combourieu-Nebout et al., 2013) and MD04-2797 (Desprat et al., 2013). This aridification phase coincides with a cooling of North Atlantic surface waters, known as Bond “event 3”, one of the coldest events detected in the North Atlantic (Bond et al., 2001; Walker et al., 2012). The increase in abundance of planktonic foraminifera *Globigerina bulloides* and *Globigerinoides quadrilobatus*, over this interval of the study core (Margaritelli et al., 2016), suggest the occurrence of cold late winter/early spring climate conditions and warm-dry periods in summer/fall seasons. This latter feature is also supported by a shift toward positive values in the $\delta^{18}O_{G.ruber}$ signal (from 0‰ to 0.5‰) (Margaritelli et al., 2016). Even though dryness seems to have been generally more effective than cold temperatures in limiting tree growth in the central Mediterranean during the late Holocene, it is not excluded that a cold late winter/early spring climate underlying the Bond events may have contributed to a decrease in trees.

As to human impact, the Gaeta pollen diagram displays very low frequencies in the curves of cultivated plants (Figs. 3–4). Single grains of *Olea* and *Vitis* seem more related to natural populations than to cultivation, while in the curve of anthropogenic plants scattered grains of Rubiaceae, *Polygonum aviculare* type and *Carduus* may be accounted for by the presence of disturbed lands destined for agriculture and pastures. Surprisingly, there is no pollen evidence of cereal cultivation, despite the archaeological finds of agrarian field systems in the Campanian Plain (Saccoccio et al., 2013) before and after the chronological divide represented by the massive Pomici di Avellino eruption dated to ca. 3945 cal BP (Sevink et al., 2011). It is worth noting, however, that a reliable representation of cereal pollen in marine pollen records is complicated by its low dispersal masking the real amount of regional cereal cultivation (Vuorela, 1973). High percentages of Cichorioideae, found all along the Gaeta record, probably represent open habitats and grasslands typical of Mediterranean dry environments, often corresponding to extensive pastures (Desprat et al., 2013; Florenzano et al., 2015).

5.3. 4100 - 2900 cal BP (2150–950 BC)

A new forest expansion is evidenced by high frequencies of deciduous trees and a remarkable and rapid recovery of evergreen trees (Fig. 3). *Fagus* often surpasses 5%, which is a relatively high value in a fully mediterranean environment. *Abies* shows a continuous presence, with frequencies of up to 4%. Wood remains of *Fagus* and *Abies* from the wetland site of Longola Poggiomarino (Di Pasquale et al., 2014 and references therein), a late Bronze Age-Iron Age settlement (1700–700 BC) in the Campania region not far from Mt. Vesuvius, confirm that these taxa lived locally on the slopes of the inland reliefs mixed with broadleaved trees (Di Pasquale et al., 2010).

These vegetation features correspond to a progressive increase in *Globigerinodes* tot. abundance (Fig. 4), indicative of warm and oligotrophic surface water in summer (e.g., Sprovieri et al., 2003 and reference therein). In addition, high frequencies of the herbivorous-opportunistic species *Turborotalita quinqueloba* occur, indicating high surface water productivity, strong seasonality, and the presence of continental runoff due to increased precipitations during late winter/early spring (e.g., Margaritelli et al., 2016).

This climate scenario corresponds to a long-lasting phase of positive NAO index circulation producing mild and wet winter climate conditions in Northern Europe (Olsen et al., 2012) (Fig. 4). At the same time, a general increase in arboreal vegetation is observed in many coastal and inland pollen sites of the south-central Mediterranean (Di Rita and Magri, 2012 and references therein), especially those affected by the 4.2 ka aridification process, confirming a general increase in precipitation also in this region.

The main pollen evidence of human activity in the Gaeta record is represented by the presence of the first finds of cereal pollen, testifying to quite widespread agricultural practice in the Campanian Plain (Saccoccio et al., 2013; and references therein). Pollen occurrences of *Olea* and *Vitis*, especially between 3400 and 3000 cal BP, may indicate practices of management and exploitation, as also recorded in other sites of the central Mediterranean during the recent Bronze Age (Di Rita and Magri, 2012). However, compared to the *Olea* record in Apulia (Caroli and Caldara, 2007; Di Rita and Magri, 2009) and Sicily (Sadori and Narcisi, 2001; Noti et al., 2009; Tinner et al., 2009), the distribution of *Olea* appears very reduced along the Campanian coast (Magri et al., 2015), where the cultivation of olive trees appears very late, being probably enhanced only after the Greek colonization.

5.4. 2900 - 2300 cal BP (950–350 BC)

The pollen record from Gaeta shows a new decline of forest vegetation coupled with an increase in herbaceous taxa (Cichorioideae) and xeric elements (e.g., *Artemisia* and *Ephedra fragilis*) after a single peak of *Fagus* (11%), coeval with a drop in evergreen *Quercus* (Fig. 3). This vegetation change towards open conditions, centred at 2.8 ka BP, does not find clear correspondence in the foraminiferal record, although positive values in the oxygen isotope curve may account for a cooler oscillation (Fig. 4).

In the central Mediterranean region, the effect of this climate change on vegetation appears rather unclear. At Lake Trifoglietti a forest decline is clearly recorded between 3000 and 2500 cal BP, but is not associated with any climate change (Joannin et al., 2012). Instead, Joannin et al. (2012) relate a drying phase, observed from both lake level and annual precipitation records between 2500 and 1800 cal BP, to a well-known cooling phase which occurred around 2700–2500 cal BP at the Subboreal-Subatlantic transition (van Geel et al., 2000), marked by glacier advances in the Alps (Deline and Orombelli, 2005; Ivy-Ochs et al., 2009) and Apennines (Giraudi et al., 2011). At Lago di Ledro, in Northern Italy, between 2800 and 2600 cal BP, there is a decrease in flood frequencies and a temporary drop in lake levels, possibly pointing to dry climate, coupled with a decrease in anthropogenic indicators in the pollen record between 2700 and 2500 cal BP (Vannière et al., 2013). A vegetation change was also found in the estuarine pollen site of the Ombrone River in Tuscany (Biserni and van Geel, 2005), where an increase in chenopods and other herbaceous taxa starting around 2800 cal BP was related to cool and wet climate conditions, associated with a decrease in solar activity. However, landscape archaeological investigations have shown that the same area, close to the Etruscan harbour of *Rusellae*, was occupied by saltworks in Roman times, which may have caused the increase in salt-tolerant chenopod communities. The same increase in chenopods was also documented in other records from coastal sites near Rome, used as saltworks since ca. 2600 cal BP (Di Rita et al., 2010; Bellotti et al., 2011; Pepe et al., 2016).

Clear vegetation changes recorded in other lakes from the central Mediterranean between 2900 and 2300 cal BP have never been adequately discussed in climatic terms, being more or less explicitly explained by human impact. For example, at Lago Battaglia a clear drop in forest vegetation was attributed to an enhancement in cereal exploitation (Caroli and Caldara, 2007). At Lago Alimini Piccolo, a phase of forest degradation starting around 2700 cal BP, characterized by a progressive decline in evergreen *Quercus* forests which were replaced by an evergreen scrubland, was chronologically correlated with the onset of the Greek domination in the Salento region (Di Rita and Magri, 2009). All the same, the Greek domination in Sicily was considered responsible for the disruption of the original evergreen forest recorded in the pollen sites of Gorgo Basso, at ca. 2800 cal yr BP (Tinner et al., 2009), and Biviere di Gela at ca. 2600 cal BP (Noti et al., 2009).

In the Gaeta record, the human impact was a possible factor contributing to the forest decline at 2900-2300 cal BP, especially considering that the Campania Plain was largely inhabited during the Etruscan/Greek phase, as testified by important cities like Cuma and Dicearchia (the modern Pozzuoli). In this period the coastal area surrounding the Volturno river mouth was occupied by the Etruscan colony of *Volturnum*, which certainly exerted an impact on the natural coastal vegetation, although hardly detected from anthropogenic pollen indicators. In fact, in our pollen record cultivated trees and cereals are almost absent in this phase, and the anthropogenic sum

(<1%) is only composed of secondary anthropogenic indicators, such as *Polygonum aviculare* type and *Urtica* (Figs. 3–4). In the planktonic foraminiferal assemblages of the Gaeta record, *Globigerinoides* tot. shows a decline in abundance which corresponds to an increase of *T. quinqueloba* (Fig. 4), documenting a reduction of warm–dry conditions during summer and a dominant high productivity in surface water/increase in run-off during late winter/early spring (e.g., Margaritelli et al., 2016 and references therein) (Fig. 4). The increase in run-off suggested by foraminiferal assemblages is confirmed by an increase in *Glomus* and *Pseudischizaea* (Fig. 3), indicating soil erosion and downwash, probably related to the general deforestation of the territory.

The reduced evidence of human activity in the Gaeta record in the time interval 2900-2300 cal BP stimulates a re-interpretation of the forest decline observed in Southern Italy and Sicily, also in the light of recent reconstructions of the NAO index, which clearly shows negative values (Olsen et al., 2012; Baker et al., 2015). As in the case of the NAO negative index of the 4.2 ka event, this forest decline may correspond to a decrease in winter precipitation in the Southern Mediterranean (Fig. 4). Evidence of a climate change in the central-southern Mediterranean is also provided in Benito et al. (2015), showing a strong decrease in floods and fluvial activity in Southern Italy and Tunisia. Magny et al. (2013) point to a possible atmospheric change in the Mediterranean, consistent with the latitudinal migration of the limit between the northern and the southern hydrological sectors. This time interval matches the "Bond event 2" cold event recorded in the North Atlantic (Bond et al., 2001), and corresponds to a decrease in insolation around 2.8 cal BP (van Geel et al., 1996; Steinhilber et al., 2009; Martìn-Puertas et al., 2012). Considering that decreases in solar activity may cause southward migrations of ITCZ (Haug et al., 2001), this configuration of NAO, solar activity and ITCZ may have produced an atmospheric circulation pattern similar to the 4.2 ka event, although possibly less effective and partially masked by the contemporaneous increase in human activity.

In summary, it appears that between 2900 and 2300 cal BP the vegetation in the central Mediterranean shows a response to a climate signal, whose nature, intensity, duration, and geographical expression needs to be better defined and separated by the masking effects of human activity.

5.5. 2300 to 2000 cal BP (350 BC-50 BC)

From here on, the discussion of the vegetation history will make use of BC/AD years, for ease in comparison with historical events.

Between 350 and 50 BC, the pollen diagram shows a phase of moderate forest development, although there are still xeric taxa like *Artemisia*. This transitional character is also reflected in the NAO curves, which suggest rather unstable conditions (Fig. 4). The NAO index reconstruction by Olsen et al. (2012) fluctuates from positive to negative values, while Baker et al. (2015) point to a negative NAO index, which is associated with cool and dry climate in the southern Mediterranean regions. This discrepancy may reflect dating uncertainties or limitations in the NAO proxy calibrations (Baker et al., 2015), possibly exacerbated by rapidly fluctuating conditions.

A clear increase in *Olea* (up to 6%) started at the beginning of the 2nd century BC, when the *Liternum* colony was founded, at approximately the same time of the record from Lago d'Averno, located 30 km southeast of the Gaeta record (Grüger and Thulin, 1998). On the other hand, in the harbour of Naples, 15 km east of Lago d'Averno, the recovery of only sparse finds of *Olea* macroremains and pollen suggests that olive cultivation was mostly a local activity in the region (Russo Ermolli et al., 2014; Allevato et al., 2016). Interestingly, several pollen records from Apulia and Sicily with considerable amounts of *Olea* during the Bronze Age, show only modest values of olive in the last two centuries BC, indicating that this time period was not especially favourable for the cultivation of *Olea* in southern Italy (Magri et al., 2015).

5.6. 2000 to 1150 cal BP (50 BC-800 AD)

In Roman Imperial times, from ca. 50 BC to 300 AD (zone GdG-6), there is a moderate increase in evergreen oaks, *Pinus*, *Ostrya*/*Carpinus orientalis*, and *Ulmus*, suggesting a slow recovery of woody taxa, corresponding to a positive fluctuation of the NAO index (Fig. 4). This abundance of evergreen *Quercus* may be considered a signal of a relatively reduced human impact along the coast of the Gaeta Gulf. In fact, at Lago d'Averno it has been shown that dense stands of *Quercus ilex* developed when human activity was reduced (Grüger and Thulin, 1998). Conversely, in the densely-populated area of the Neapolis harbour, evergreen oaks were relatively scarce and the vegetation cover around the city was mainly dominated by deciduous forests and fields (Russo Ermolli et al., 2014). A continuous curve of *Juglans*, which was sporadically represented since the beginning of the Gaeta record, testifies to the cultivation of walnut since the early 1st century AD. *Juglans* was a native species in southern Italy (Pollegioni et al., 2017) and was widely used in Campania since Roman times for both timber and food (Allevato et al., 2010; Russo Ermolli et al., 2014). It was certainly cultivated on the slopes of Lago d'Averno between the 1st and 4th century AD (Grüger and Thulin, 1998). During this time interval, the progressive decrease in abundance of *Globigerinoides* tot. associated with the increase in *T. quinqueloba* occur during positive NAO index and in phase with more positive value of $\delta^{18}O_{G.ruber}$ record, suggesting the occurrence of mild/dry climate conditions during the summer season and cold/humid ones during late winter/early spring (Fig. 4).

Between 300 and 450 AD (zone GdG-7), a marked increase in AP, especially evergreen *Quercus* matches a positive NAO index (Fig. 4). A contemporary increase in *Pinus*, strongly contributing to the high AP values, is difficult to interpret: in the Gaeta record, in contrast to all the other sites along the Tyrrhenian coast (e.g., Grüger and Thulin, 1998; Russo Ermolli and di Pasquale, 2002; Di Rita et al., 2010, 2015; Bellotti et al., 2011) significant percentages of *Pinus* (10–20%) are found since the mid-Holocene, suggesting a possible natural development of coastal stands of pine along the Gaeta Gulf, similar to the woodlands of *P. halepensis* along the eastern coast of the Gargano Promontory (Caroli and Caldara, 2007). However, these high percentage values of *Pinus* may also be the result of overrepresentation after long buoyancy of bisaccate grains in water (Magri et al., 2015). The Gaeta pollen diagram does not show a clear increase in *Pinus* pollen in the 1st century AD as a result of plantations by the Romans, as is distinctly observed in many pollen records from central and southern Italy (Grüger and Thulin, 1998; Russo Ermolli and di Pasquale, 2002; Di Rita and Magri, 2009; Di Rita et al., 2010; Bellotti et al., 2011), as well as from macrofossils from the harbour of Naples, documenting the local cultivation of *Pinus pinea*, *P. halepensis*, and *P. pinaster*, which were employed in the naval shipyards of Naples and for human nutrition (Allevato et al., 2010, 2016).

Other cultivated trees in the time interval 300–450 AD (zone GdG-7) include *Olea*, *Juglans*, and *Castanea*, the latter documented by percentages around 5%. A clear chestnut expansion was also recorded during the Roman period at Lago d'Averno (Grüger and Thulin, 1998). Although pollen of *Castanea* was rather sparse around Neapolis from the 1st century BC to the 5th century AD (Russo Ermolli et al., 2014), a massive use of chestnut timber throughout the entire Vesuvius area is reported between the 1st century BC and the 4th century AD (Di Pasquale et al., 2010; Allevato et al., 2012).

In the Gaeta record, the maximum development of *Castanea* (21%) is found around 600 AD, at a time when the natural forest vegetation, composed of mixed evergreen and deciduous communities, temporarily declined (Fig. 4). This decline is coeval with the cold climate shift corresponding to Bond "event 1" (Bond et al., 2001). Thus, it seems that these complex vegetation processes were caused by a combination of climate change and human activity. From 600 to 800 AD *Castanea* decreased together with *Olea* and *Juglans* in correspondence to a drop in evergreen oaks and an increase in deciduous oaks. The marine proxies from the Gaeta core indicate for this interval, corresponding to the cold event Roman IV (Margaritelli et al., 2016), a high abundance of the cold *Globorotalia scitula–Neogloboquadrina pachyderma* group and a decrease in warm water species (Margaritelli et al., 2016), matching negative NAO index values (Baker et al., 2015) and positive values of $\delta^{18}O_{G.ruber}$ (Fig. 4). Interestingly, also the time intervals corresponding to Bond event 3 (ca. 4.2 ka BP) and 2 (ca. 2.8 ka BP) coincided with a decline in evergreen oaks along the Gaeta Gulf.

Altogether, this period, which corresponds to the "Dark Ages", shows a considerable complexity both in climate fluctuations and in historical events, marked by successive invasions of barbarian populations reaching also the Campanian plain. In the central Mediterranean, the published palaeovegetational evidence appears too scarce to outline a defined climate scenario for the Dark Ages, which needs to be implemented with detailed analyses from additional pollen sites. For example, recent studies from central and southern Italy indicate that the time interval 450–750 AD was characterized by substantially humid climate conditions (Sadori et al., 2016; Mensing et al., 2015), which is not apparent in the Gaeta record. Interestingly, Mensing et al. (2016) suggest that during the Early Middle Ages the agricultural and sylvicultural practices, associated with the development of the Benedictine monastic estates, led to intense vegetational landscape conversions especially in the upland environments. The high values of *Castanea* found at Gaeta depict a similar situation. Consistently, starting around 600 AD, the pollen record from Gaeta shows the establishment of extensive vineyards, documented by the continuous finds of *Vitis* pollen. In Imperial times and until at least 450 AD, an industrial production of wine, documented in the Pompeii area and in the Phlegraean Fields, was destined not only for local consumption, but also for exportation towards the borders of the Empire (Allevato et al., 2012). This huge production is not attested by the pollen record from the Gaeta core, where the continuous presence of *Vitis* is documented only since the Early Middle Ages, after the occupation of the Lombards.

5.7. 1150 cal BP (800 AD) to present day

In the time period spanning from ca. 800 AD to the present day, the forest vegetation experienced a new general decline due to both a reduction in *Castanea*, probably testifying to slowdown of the sylvicultural practices, and a general decreasing trend in natural broadleaved vegetation. The Gaeta record highlights two main phases of forest decline, 800 to 1050 AD and 1550 to 1850 AD, interrupted by a temporary forest recovery from 1050 to 1550 AD (Figs. 3–4). Although the human impact has exerted an ever-increasing pressure on the natural landscape, these fluctuations in the forest vegetation appear strongly cadenced by two well-known climate fluctuations of the last two millennia, namely the Medieval Climate Anomaly (ca. 850–1300 AD) and the Little Ice Age (ca. 1300–1800 AD).

Between 800 and 1150 AD (zone GdG-8), a remarkable forest decline is represented in the Gaeta record, coeval with a decrease in the frequencies of both *Castanea* and *Olea*. A strong increase in Cichorioideae, which in this case does not appear connected to selective pollen preservation, may indicate the establishment of extensive open areas, partly favoured by pastoral practices (cf. slight increase in *Plantago*). The oxygen isotope record from the Gaeta core (Fig. 4) shows a shift towards positive values indicating cooler temperatures. Consistently, in the foraminiferal record, a reduction in the total abundance of *Globigerinoides* confirms less temperate climate conditions. In correspondence with this forest decline at Gaeta, the NAO index reconstructions from speleothems in Scotland (Baker et al., 2015) and Morocco (Wassenburg et al., 2013) point to a negative index circulation pattern between ca. 800 and 1100 AD, which was associated with the establishment of cold and dry climate in southern Mediterranean.

In the central Mediterranean, the effects of this climate phase on vegetation have been interpreted in a rather inhomogeneous way. For example, at Palavas in Southern France, a strong decrease in AP percentages, matching the evidence of decreased storm activity frequencies (Sabatier et al., 2012), was documented between 750 and 1150 AD (Azuara et al., 2015), but the authors recognize an arid climate only between 650 and 850 AD, on the basis of a turnover from *Fagus* to *Quercus*-dominated vegetation. A minimum in AP percentages is also recorded in the pollen diagram of Pergusa between 750 and 1000 AD, but it is not discussed as a possible period of decreased humidity (Sadori et al., 2016). At Lago Lungo, in central Italy, the most extensive degradation of the environment occurred during the Medieval Period (~870–1390 AD), when forest cover was greatly reduced, and herbs and ferns increased (Mensing et al., 2015). The initiation of forest cutting throughout the Rieti Basin was interpreted as mainly due to socioeconomic changes, as indicated by agricultural (increase in cereals) and pastoral (increase in *Sporormiella*) intensification, although the successful expansion of agriculture was also attributed to warmer than average temperatures combined with drier than average climate (Mensing et al., 2015).

Between 1150 and 1550 AD (zone GdG-9), the forest vegetation in the Gaeta record partly recovered. Montane taxa like *Fagus* and *Abies* appear reduced, while mediterranean elements like *Myrtus* and *Phillyrea* slightly increase, together with evergreen *Quercus*. 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 (Fig. 3). Between 1220 and 1250 AD a marked shift in the $\delta^{18}O_{\ G.\ ruber}$ signal towards negative values, associated with a strong increase in *Globigerinoides* total abundance, points to the warmest interval of the Medieval Warm Period (MWP). The inferred NAO index records (Fig. 4) highlight positive values, possibly determining a change toward warmer and more humid climate. At Lago di Pergusa, in Sicily, after a forest expansion between ca. 950 and 1100 AD, an opening of the forest was found between around 1100 and 1350 AD (Sadori et al., 2016), which does not match the general increase in forest conditions found in the Gaeta record during the MWP.

In the interval between 1400 and 1850 AD, chronologically corresponding to the Little Ice Age (LIA), both the decrease in total abundance of *Globigerinoides* and the $\delta^{18}O_{\ G.\ ruber}$ isotopic signal, clearly represented by more positive values associated with abrupt shift *vs* more negative ones, indicate a change towards a cooler climate (Fig. 4). These features are well documented in other marine records of Tyrrhenian Sea (Lirer et al., 2014; Margaritelli et al., 2016). The pollen record shows a clear decline in the forest cover, particularly evident after 1550 AD, once again mainly at the expense of the evergreen forest belt, while *Pinus* slightly increases. The decrease in AP had a maximum during the Maunder minimum of solar activity, around 1700 AD, and persisted until ca. 1750 AD. At the same time, human activities related to olive, chestnut and cereal cultivation appear strongly diminished, probably related to a demographic reduction in human population following the plague that in 1656 affected the Kingdom of Naples (Alfani, 2013). A marked increase in *Glomus*, accompanied by *Pseudischizaea* (Fig. 3), indicates soil erosion and downwash, which is expected during a phase of general deforestation. The increase in planktonic foraminifer *T. quinqueloba* (Fig. 4), suggesting an increase of nutrients in sea surface water, may be consistent with this process of soil erosion. Summarizing, the LIA in the Gaeta pollen record is characterized by a rather forested landscape until approx. 1550 AD, replaced by open vegetation (1550–1750 AD), followed by a new increase in trees after 1750 AD. These oscillations may reasonably reflect rather unstable climate conditions. During the LIA, effects of climate cooling on vegetation development are also reflected in other pollen records from the central Mediterranean. At Lago Lungo, in central Italy, a development of forest vegetation from 1400 to 1800 AD was related to both the 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, in turn leading to rapid reforestation of previously productive land (Mensing et al., 2016). At Pergusa, the LIA was associated with humid climate conditions that resulted in forest expansion, while a clear reduction in anthropogenic pollen indicators, between 1600 and 1700 AD, was tentatively related to the end of local large-scale livestock rearing activities, although there was also a plague outbreak in the seventeenth century (Sadori et al., 2016). At Lake Ledro, in northern Italy, the LIA coincides with a phase of forest development, accompanied by a reduction in anthropogenic pollen indicators (Joannin et al., 2013). This was interpreted as a combination of humid climate and a decline in local human population. However, the NAO index shows negative values, similarly to the 4.2 ka event, which is unanimously considered a dry period in the southern Mediterranean (Fig. 4). Therefore, the remarkable forest decline recorded at Gaeta appears in good agreement with the NAO pattern, suggesting that the LIA had a mainly dry character in the southern Italian Peninsula.

From the end of the Little Ice Age (ca. 1850 AD) to the present day, the Gaeta record shows a general increase in cultivated plants, especially *Olea*, attaining 11%, *Juglans* (2%), *Vitis*, *Corylus*, Cannabaceae, and cereals, accompanied by increased frequencies of anthropogenic indicators. Plants planted for ornamental purposes are also found, such as *Buxus* and *Phoenix*, as well as *Juniperus* type, which may suggest the presence of *Cupressus* in urbanized areas. An increase in *Pinus* reflects the plantations of *P. pinea*, *P. halepensis*, and *P. pinaster* documented since the 1950s. Unexpectedly, elements of the natural mixed oak forest also increase, as well as the evergreen trees and shrubs belonging to the *macchia*, resulting in an overall rise in AP (67% at the top of the record). A similar picture emerges also from Lago Lungo (Mensing et al., 2015), Lago Trifoglietti (Joannin et al., 2012), and Lago di Pergusa (Sadori et al., 2016), while in the Sicilian coastal sites of Gorgo Basso (Tinner et al., 2009), Lago Preola (Calò et al., 2012) and Biviere di Gela (Noti et al., 2009), no signs of forest recovery are visible.

In summary, the time period spanning from ca. 800 AD to the present day shows many fluctuations in vegetation that correspond quite well with climate changes indicated by the foraminifera record and the oscillations of the NAO index (Fig. 4), but contrast with the sequence of forest fluctuations recorded in the few detailed pollen records available from the central Mediterranean. This discrepancy may depend on chronological uncertainties, or on different vegetational responses to the ever-increasing human impact, which may have been particularly severe at local scales. In fact, it should be kept in mind that the Gaeta record, obtained from a marine core, mostly represents regional vegetation changes and therefore may mostly reflect climate oscillations at the scale of the central Mediterranean, which may have been different from central Europe.

6. Conclusions

The high-resolution pollen record from the Gulf of Gaeta adds new information on both the late Holocene vegetation dynamics in the Mediterranean region, and the timing and development of cultivations in southern Italy. In addition, it provides novel insights into the vegetation response to climate variability, and raises new questions about the mechanisms of past atmospheric circulation patterns in the central Mediterranean Basin.

The main vegetation type in the Gulf of Gaeta borderlands during the mid-to late Holocene was a mixed broadleaved forest composed of both evergreen and deciduous elements, mainly oaks, accompanied by a large number of other tree taxa. It is worth noting that deciduous and evergreen oaks display different dynamics through time: deciduous *Quercus* show only moderate fluctuations, possibly because they represent regional inland vegetation, while evergreen *Quercus* is subject to significant changes, due to a mostly local distribution or a greater sensitivity to climate change, especially winter aridity and cold temperatures.

Fagus, which is now distributed on the reliefs of the Apennines, was certainly located at much lower elevations during the late Holocene, as demonstrated by percentages in some cases surpassing 10%. This result confirms the picture provided by macrofossil finds of *Fagus* on the northern slopes of Vesuvius until the 5th century AD (Allevato et al., 2012). *Abies* was also locally present in the region, although in very low amounts, as documented by macrofossils (Di Pasquale et al., 2014). *Olea*, *Castanea*, *Juglans* and *Vitis* appear to be native in Peninsular Italy (Mercuri et al., 2013) and in the borderlands of the Gulf of Gaeta. Their intensive cultivation started at different times: a clear increase in *Olea* is found in the 2nd century BC; a continuous curve of *Juglans* testifies to the cultivation of walnut since the early 1st century AD; *Castanea* shows values indicating local cultivation only around 300 AD and reaches its maximum expansion around 600 AD, at a time when also *Vitis* becomes continuously present. In general, the age of cultivation of these taxa appears rather late compared to other areas in Italy. For example, *Olea* was widespread and probably managed in Apulia and Sicily already during the Bronze Age (Di Rita and Magri, 2009; Magri et al., 2015). *Castanea* was abundant in central Italy already at the time of the Etruscans (Magri and Sadori, 1999; Drescher-Schneider et al., 2007; Mercuri et al., 2013). In Campania, at Pompeii and Naples (Allevato et al., 2016) the presence of *Olea*, *Castanea*, *Juglans* and *Vitis* is documented well before the Gaeta record, suggesting that agricultural practices were not especially developed in the marshy area of the Volturno mouth, compared to the very fertile Phlegraean Fields and Vesuvius slopes. A clear increase in agricultural practices is found in the Gaeta record especially after the extensive reclamation works of the last century, when the effects of a massive human activity are clear, although not devastating. In particular, plantations of *Pinus* and ornamental species like *Buxus* and *Phoenix* appear only in the last decades. A special mention is due to the sparse pollen grains of *Solanum*, found in the Gaeta record since the 17th century. Although it cannot be demonstrated, we like to advance that this could be the start of the cultivation of tomatoes that has made the "Neapolitan pizza" famous all over the world.

One peculiar aspect in the vegetation dynamics of the Gaeta record is the recurrent pattern of forest increase and decline punctuating the mid- and late Holocene. When the timing of these patterns is compared with the climate proxy data available from the same core and with the NAO index, it clearly appears that the main driver for the forest fluctuations is climate, which may even overshadow the effects of human activity. During the last millennia, several vegetation fluctuations may have been produced by climate changes in the Mediterranean, but the expression, geographical range, and intensity of these climate events is still to be assessed. For this reason, and because of the location of the Gaeta record in a climatically very sensitive region, the forest fluctuations found in our pollen record are a very valuable source of information on past atmospheric circulation over the central Mediterranean.

We have found a clear correspondence between phases with negative (positive) NAO index and forest declines (increases). This suggests that in the southern-central Mediterranean negative NAO conditions are associated with cold/dry events, and vice-versa (Fig. 4). In particular, we have found the following openings of vegetation coeval with climate changes reported by independent proxies:

- Around 4200 cal BP, a drop in AP, especially evergreen oaks, in the Gaeta record confirms the forest decline recorded in many sites in Italy south of 43°N, and parallels a phase of declining NAO values, culminating around 4250 cal BP. This may correspond to decreasing winter precipitations, determining a reduction of evergreen vegetation.
- Around 2800 cal BP, a vegetation change towards open conditions is found in the Gaeta record, which is not clearly discussed in other pollen records from the region, although vegetation changes are visible in several sites. The NAO index clearly shows negative values. As in the case of the 4.2 ka event, this phase may correspond to a decrease in winter precipitation in the central-southern Mediterranean, matching the "Bond 2" cold event recorded in the North Atlantic (Bond et al., 2001). This time interval corresponds also to a decrease in solar activity (Martìn-Puertas et al., 2012).
- Between 800 and 1000 AD, a remarkable forest decline is represented in the Gaeta record, coeval with a decrease in the frequencies of both *Castanea* and *Olea.* The oxygen isotope record from the Gaeta core shows a shift towards positive values indicating cooler temperatures. The NAO index reconstructions (Wassenburg et al., 2013; Baker et al., 2015) once again point to a generally negative index circulation pattern.
- Between 1400–1850 AD, in the time period chronologically corresponding to the LIA, the Gaeta record shows a clear decline of the forest cover particularly evident after 1550 AD, mainly at the expense of the evergreen forest belt, suggesting dry climate conditions. In the same core, both the planktonic foraminifera assemblages and the oxygen stable isotope indicate a change towards a colder climate. As in the preceding openings of the forest, the NAO index shows negative values.

In addition to these main phases of forest decline, a clear decrease in evergreen oaks between 550 and 800 AD may be associated with a spell of negative NAO index values, leading to a reduction in winter precipitation. This matches Bond "event 1" (Bond et al., 2001).

Phases with positive NAO index values generally match periods of forest expansion (Fig. 4). In particular, between 4100 and 2900 cal BP there is a remarkable increase of both evergreen and deciduous trees. Similar extensive forests are also found in many other sites in the Central Mediterranean (Di Rita and Magri, 2012 and references therein). A second time interval with forest expansions matching a positive NAO index, from ca. 50 BC to 600 AD, includes the Roman Imperial period and the beginning of the Middle Ages. In spite of massive human activity, witnessed also by abundant anthropogenic indicators in the pollen record, stable forest conditions were probably favoured by a humid climate. A third period with a relative forest development within a generally open anthropogenic landscape is found between approx. 1050 and 1550 AD, at a time when all NAO index reconstructions indicate positive values (Olsen et al., 2012; Wassenburg et al., 2013; Baker et al., 2015).

The forest fluctuations recorded at Gaeta in some cases correspond very well to other pollen records from southern Italy, for example in the 4.2 ka event. In other cases, for example around 2.8 ka BP, our record highlights changes in the forest cover that have not been adequately discussed, or have been merely ascribed to human activity, in spite of the evidence for climate change provided by independent proxies. During the MCA and the LIA, the forest fluctuations detected at Gaeta correspond quite well with climate changes indicated by the foraminifera record and the oscillations of the NAO index, but contrast with previous interpretations of the vegetation changes recorded in other pollen sites from the central Mediterranean. While it is clear that during the last two thousand years the human impact has been increasingly important in determining a progressive opening of the forest at Gaeta, as documented in the central Mediterranean (Di Rita and Magri, 2012) and European records (Fyfe et al., 2015), the most marked forest fluctuations in the Gulf of Gaeta appear in clear correspondence with the main historical climate fluctuations and NAO index oscillations.

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Uncited references

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