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## Climate changes in the central Mediterranean and Italian vegetation dynamics since the Pliocene

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1 **Climate Changes in central Mediterranean and Italian vegetation dynamics since the**  
2 **Pliocene.**

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4 N., Combourieu-Nebout<sup>1,2</sup>, A., Bertini<sup>3</sup>, E., Russo-Ermolli<sup>4</sup>, O., Peyron<sup>5</sup>, S., Klotz<sup>6</sup>, V.,  
5 Montade<sup>5</sup>, S., Fauquette<sup>7</sup>, J., Allen<sup>8</sup>, F., Fusco<sup>9</sup>, S., Goring<sup>10</sup>, B., Huntley<sup>8</sup>, S., Joannin<sup>11</sup>, V.,  
6 Lebreton<sup>2</sup>, D., Magri<sup>12</sup>, R., Orain<sup>3</sup>, L., Sadori<sup>12</sup>

7

- 8 1. LSCE, UMR 8212 CNRS/UVSQ.CEA, Orme des merisiers, F-91198 Gif sur Yvette,  
9 France, [nathalie.nebout@lsce.ipsl.fr](mailto:nathalie.nebout@lsce.ipsl.fr)
- 10 2. Département de Préhistoire du Muséum national d'Histoire naturelle, UMR 7194  
11 CNRS, 1 rue René Panhard, F-75013 Paris
- 12 3. Dipartimento di Scienze della Terra, Università di Firenze - via G. La Pira 4, 50121  
13 Firenze, Italy
- 14 4. Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università di  
15 Napoli Federico II, Largo San Marcellino 10, 80138 Napoli, Italy
- 16 5. CBAE, UMR 5059 CNRS, Institut de Botanique, 163 rue A. Broussonet, 34090  
17 Montpellier, France
- 18 6. Geographisches Institut, Universität Tübingen, Rümelinstr. 19-23, 72070 Tübingen,  
19 Germany
- 20 7. ISE-M, UMR 5554 CNRS, Université Montpellier 2, Place Eugène Bataillon, 34095  
21 Montpellier cedex 05, France
- 22 8. Environmental Research Centre, University of Durham, Durham DH1 3LE, UK

- 23 9. LIPPIA, Laboratorio Indipendente di Palinologia Paleontologica, Investigativa ed  
24 Ambientale, viale G. Bovio 10, 65123 Pescara, Italy
- 25 10. Department of Geography, University of Wisconsin-Madison, Wisconsin 53706, USA
- 26 11. LGL. TPE, UMR 5276 CNRS, Université de Lyon1, 2 rue Dubois, 69622  
27 Villeurbanne Cedex, France
- 28 12. Dipartimento di Biologia Vegetale, Sapienza Università di Roma, P. le Aldo Moro 5,  
29 Roma, Italy

30

31

32

33 **Abstract**

34 Pollen records and pollen-based climate reconstructions from the Italian Peninsula (central  
35 Mediterranean) show clear signals of vegetation changes linked to variations in water  
36 availability in the Mediterranean basin over the past 5 million years. Profound vegetation  
37 changes occur in four major steps from the Pliocene to the present. The subtropical taxa that  
38 dominate Pliocene assemblages decline and then disappear between 3-2.8 and 1.6 Ma (at  
39 around 2.8 Ma in the North and later in the South), progressively replaced by temperate  
40 *Quercus* forests at mid altitude, with increasing *Quercus* development at around 1.4-1.3 Ma in  
41 the South and increasing *Fagus* proportions after 0.5 Ma. Conifer forest (*Tsuga* then *Abies*  
42 and *Picea*) expanded at high altitude, beginning at 2.8 Ma. Mediterranean-type forest, rare  
43 during the Early Pleistocene, develops and increases in diversity during the Middle and Early  
44 Pleistocene. Open landscapes, with higher abundances of steppic taxa, increase with the onset  
45 of Glacial/Interglacial cyclicity around 2.6 Ma and gradually enlarge during glacials. Climate  
46 reconstructions performed on selected southern Italy pollen records suggest declines winter  
47 temperature and annual precipitation. Specifically, both precipitation and winter temperature  
48 reconstructions suggest changes in interglacial maxima and glacial minima at around 3-2.8  
49 Ma, 2 Ma, 1.3-1.4 Ma and 0.5 Ma.

50 This critical review provides evidence that the North-South precipitation gradient, with drier  
51 conditions in the South, had been a consistent feature on the Italian peninsula since the  
52 beginning of the Pleistocene.

53

54 **Keywords: Mediterranean, vegetation, Climate, Plio-Pleistocene, Italy, palynology.**

55 **1. Introduction**

56 The Mediterranean basin is considered a global biodiversity hotspot (e.g. Médail and  
57 Quézel, 1997, 1999; Giorgi, 2006; Christensen et al., 2007). Given projections of future  
58 regional climate, and the particular importance of water resources in the region, the  
59 preservation of ecosystems within the basin is considered a key goal for governments (IPCC,  
60 2007). Indeed, given the importance of water resources within the basin, particularly in the  
61 south, both climate and growing demographic pressures in coastal zones are likely to place  
62 continued stresses on ecosystems across the region.

63 Water availability is a key factor limiting plant growth and is an important driver for  
64 vegetation composition (Daget, 1977; Venetier et al., 2010). The future composition of  
65 Mediterranean ecosystems is thus clearly tied to water availability. While modern vegetation  
66 data from the region provides an excellent baseline for understanding relationships between  
67 aridity and vegetation composition, paleoecological records provide support for understanding  
68 vegetation responses at longer time scales. Paleoecological records show that aridity had not  
69 been a persistent feature within the Mediterranean basin, appearing somewhat recently and  
70 gradually increasing up to the present time (Pons et al., 1995). Even during the Messinian  
71 salinity crisis, MSC (5.9 - 5.3 Ma), aridity did not play a major role in restructuring  
72 vegetation. Climate was dry in the southern Mediterranean before, during and after the MSC  
73 (Suc and Bessais, 1990; Bertini, 2006; Fauquette et al., 2006). Mediterranean-type taxa,  
74 sporadically present in the basin since the Paleocene, increase their importance in the course  
75 of the most recent time. The development of modern Mediterranean ecosystems seems to be  
76 linked to increasing dryness and seasonality focusing that dryness during summer times  
77 (Quézel and Médail, 2003; Pons et al, 1995).

78           Researchers have documented the stepwise Pliocene-Pleistocene development of  
79 modern Mediterranean ecosystems and climate, even though sparse records have hindered  
80 basin-wide reconstructions (Pons et al., 1995; Sadori et al., 2013a). Given the limited number  
81 of available records, reconstructing long-term (5 Myr) vegetation changes on the Italian  
82 Peninsula will help to identify links between increasing dryness in the region and vegetation  
83 change. The Italian peninsula stretches across the centre of the Mediterranean basin along a  
84 northwest to southeast way. The Appenine Mountains running as a backbone in the  
85 peninsulageneratea heterogenous vegetation along elevation and latitudinal gradients. Several  
86 distinct climatic systems influence the climate in Italy: polar air masses from the North,  
87 tropical air masses from the South, Atlantic Westerlies and a monsoon system from the East  
88 (Lionello et al., 2006). This results in a climate gradient from North to South, with higher  
89 humidity in the North and increasing aridity to the South. Italy thus represents one of the most  
90 informative Mediterranean areas to (i) reconstruct the response of vegetation to various  
91 climatic stresses and (ii) assess the future behavior of Mediterranean plants. Furthermore,  
92 Italy's rich geological record makes it a significant source of information on the history of  
93 Mediterranean vegetation.

94           Given the uneven distribution of the pollen record in Italy, this paper will describe  
95 reconstructions from Northern and Southern Italy whose boundary was fixed in this paper at  
96 42.5°N, an isocline that approximately splits Italian peninsula according to the duration of the  
97 dry season, more or less than 3 months. This division allows us to describe continuous change  
98 in Mediterranean plant associations and the long and short-term climatic changes that have  
99 occurred in the Mediterranean basin during the last 5 million years.

## 100 **2. Present day Italian climate and vegetation**

101 Italy is a mountainous country, bounded in the North by the Alps, with the Apennine range  
102 running as a backbone from northwest to southeast. The Po Valley is a large plain situated in  
103 the north from the Ligurian Alps to the Adriatic Sea.

104 The Italian peninsula is located at the mid-latitudes and exhibits in some portions  
105 Mediterranean climate features, with mild winters and a pronounced drought during the  
106 warmest season (Fig. 1). The effects of the Mediterranean climate are markedly evident on the  
107 coasts and attenuated on the pre-Alpine chains. In the Apennines, the altitude increase  
108 produces a rapid transition towards less hot and dry summers, while in the Alps the  
109 continentality increases in going inward the mountain range (cold winters and hot summers),  
110 leading to strong temperature fluctuations. **The Po Valley, as a result of the isolation produced**  
111 **by the Apennine mountains to the sea, has a continental thermal regime.** It results therefore in  
112 an evident climatic gradient from the warm-temperate climate with a Mediterranean character  
113 to the cold-temperate climate of the Apennines or pre Alpine ranges, up to the cold and  
114 continental climate of the innermost Alps. Such a complex and diversified scenario, along  
115 with a strong north to south climatic gradient deeply affected the flora distribution and  
116 structure of vegetation. The actual state of knowledge of the Italian vegetation is stated in  
117 several reports (e.g. Ozenda, 1975, 1994; Tomaselli, 1973; Bonin, 1981; Pignatti, 1998;  
118 Quezel and Médail, 2003; Blasi, 2010). The European potential natural vegetation zones with  
119 the main physiognomic-ecological units for the Italian area have been summarized in Fig. 1  
120 (modified from Pignatti, 2011).



### 121 3. Material and methods

#### 122 3.1 Pollen records

123 This review is based on the available paleoecological literature for Italy based on  
124 palynology and paleobotanical information and 17 pollen records (Fig. 2, Table 1). These data  
125 help to reconstruct vegetation change in Italy, and its links to increasing dryness since the  
126 Pliocene. Pollen data is distributed unevenly across the region, and so each site has been  
127 assigned to either “Northern” or “Southern” Italy relative to the arbitrary latitude of 42.5°N,  
128 an isocline that approximately splits Italy according to the duration of the dry season (more or  
129 less than 3 months). Vegetation types from pollen records and the literature are plotted for  
130 glacial and interglacial periods within six key geological periods during the last 5 Myr:  
131 Zanclean-Piacenzian, Early Pleistocene (Gelasian, 2.588-1.806 Ma, and Calabrian, 1.806-  
132 0.781 Ma), Middle Pleistocene (“*Ionian*”, 0.781-0.126 Ma), Late Pleistocene (“*Tarantian*”,  
133 0.126-0.01 Ma) and the Holocene (Fig. 3a and b). Sites that combine long time series,  
134 coverage in key time periods and consistent age models (Table 1 in bold, Fig. 2 in red),  
135 provide the opportunity to develop a model of continuous vegetation change throughout Italy.  
136 The pollen diagrams of these selected sites have been plotted with Psimpoll (Bennett, 2008)  
137 with a subset of the total taxa to illustrate the major changes in the Italian vegetation since the  
138 Pliocene (Fig. 4a and b).

139 The term “Taxodiaceae” is used in quotations throughout this paper because many genera  
140 formerly assigned to Taxodiaceae are now grouped in subfamilies of Cupressaceae, for  
141 example Taxodioideae Endl. ex K. Koch (*Taxodium*, *Glyptostrobus*, and *Cryptomeria*) and  
142 Sequoioideae (Luer. & Quinn) Quinn (*Sequoia*, *Sequoiadendron*, and *Metasequoia*). The genus  
143 *Sciadopitys* is now generally placed in Sciadopityaceae (Brunsfield et al., 1994; Farjon, 1998,  
144 2005). However, the term “Taxodiaceae” has been commonly used in Italian records where it

145 is commonly assumed to represent *Sciadopitys*, *Taxodium* type (which includes *Taxodium* cf.  
146 *distichum* and *Glyptostrobus*) and *Sequoia* type (which includes *Cryptomeria*, *Cunninghamia*,  
147 *Metasequoia glyptostroboides*, *Sequoiadendron giganteum* and *Sequoia sempervirens*, and).  
148 Because of the diversity of taxa represented by the term “Taxodiaceae” it is not easy to revisit  
149 the records and apply the new taxonomy. Thus we have chosen to keep the term  
150 “Taxodiaceae”, as used in older publications, but we will provide greater clarity when  
151 possible.

### 152 3.2 Climate reconstructions

153 Climate reconstruction using pollen records allow the reconstruction of the climate  
154 trends that have driven changes in Italian vegetation over the last 5 Ma. Depending on the  
155 period of interest we have used different methods for reconstructing climate. Annual  
156 precipitation and temperature have been reconstructed using (1) probability mutual climatic  
157 spheres (PCS), which use the modern climatic requirements of plants, transposed to plants  
158 assemblages (Klotz, 1999; Klotz et al., 2006) using 60 out of 110 taxa identified in the fossil  
159 pollen floras for reconstruction from Pliocene to Early Pleistocene (e.g. Klotz et al., 2006;  
160 Fauquette et al., 1999, 2007). This method is actually the best way to reconstruct climate  
161 parameters from old pollen records that contain vegetation association that are not found  
162 today over the world. From the Middle Pleistocene to the Holocene (2) the Modern Analogue  
163 Technique (MAT) was used (Guiot, 1990; Joannin et al., 2011; Combourieu-Nebout et al.,  
164 2013; Peyron et al., 2013). The mean temperature of coldest month (MTCO), summer  
165 precipitation (PSUM), winter precipitation (PWIN) and annual precipitation (PANN) are  
166 presented here for MAT reconstructions.

167 This effort represents the first climate reconstruction spanning the entire Pleistocene  
168 for this region, a time of major change in vegetation composition, and for reconstructions

169 isolating the cold and warm periods during the Middle and Late Pleistocene. Because  
170 temporal resolution is likely to be low, climate is presented as boxplots for temperature and/or  
171 precipitation within the chosen intervals. Box plots for reconstructions of four different  
172 climate parameters : mean temperature of the coldest month (MTCO), winter precipitation  
173 (PWIN), summer precipitation (PSUM) and mean annual temperature (TANN) during glacial  
174 and interglacials were calculated and plotted using R (R Core Team, 2012). The boxes  
175 represent the extent of the second and third quartiles, dotted delimited lines represent data  
176 extreme intervals. The median is indicated by a heavy line within the box.

### 177 **3.3 chronology**

178 Chronology from the pollen records have been compiled here according to their respective  
179 age models published in the literature. As appropriate for each period, age models are based  
180 on 14C datings, links to Greenland Ice core records and tephra layer data for the most recent  
181 series, and K/Ar datings, foraminifers zonation, links to oxygen isotope records from  
182 Mediterranean or Atlantic reference records and astronomical tunings for the oldest ones. The  
183 purpose is not to discuss the individual age model even if each one has their own limits. The  
184 proposed review intends to reconstruct the general pattern of the Italian vegetation changes  
185 that goes from the Pliocene to the present day one.

186

## 187 **4.The Italian vegetation : the outcome to the progressive drought increasing trend**

### 188 **4.1 Emergence of the Mediterranean vegetation communities in Italy**

189 Climate in the Mediterranean had changed repeatedly at least since the Eocene when  
190 tropical, warm-humid conditions prevailed. The development of the Mediterranean climatic

191 regime, punctuated by a dry season, occurred in the late Pliocene (Suc, 1984), a time when  
192 cooling is observed in marine records (Poore and Bergreen, 1975; Sprovieri et al., 2006).  
193 Glacial/Interglacial (G/I) cycles, beginning in the Pleistocene, have reinforced Mediterranean  
194 climate conditions by maintaining mesic interglacials and dry glacials (Pons et al., 1995)

195 Modern Mediterranean taxa were present, but only sporadically, in the Paleogene (Fig.  
196 5). Mediterranean taxa have been reported in the western Mediterranean since the Paleocene,  
197 even though diversification of Mediterranean flora followed the end of the Oligocene (Quézel  
198 and Médail, 2003). Oligocene fossils of Oleaceae (pollen and leaves) have been reported from  
199 Northern Italy (Sachse, 2001). However, the development of truly Mediterranean vegetation  
200 occurs later during the Miocene, with the weak onset of summer dryness favoring its  
201 establishment in Italy and throughout the Mediterranean basin.

202 Xerophytic taxa were reported in the north Mediterranean from deposits as early as the  
203 Miocene (e.g. de Saporta, 1889; Bessedik, 1985); nevertheless semi-arid associations were a  
204 minor component in the rich tropical vegetation that colonized the Mediterranean (e.g.,  
205 Bertini, 2006; Fauquette et al., 2006, 2007; Bertini and Martinetto, 2008, 2011). The MSC, as  
206 well, does not seem to have played a major role in restructuring vegetation, although in some  
207 periods (e.g. close to 5.5 Ma) aridity appears to have promoted the expansion of open  
208 vegetation including steppe plants such as *Lygeum* (Bertini, 2006). The expansion of semi-  
209 arid associations across the Mediterranean seems rather related to (1) the development of a  
210 Mediterranean climate during the Pliocene and (2) the periodic occurrences of aridity since  
211 the onset of the Pleistocene. Semi-arid plant communities develop during the Pliocene and  
212 expand at low to middle altitude during the middle Pleistocene.

## 213 4.2 The Pliocene, the starting picture

214 A rich, diverse Pliocene flora is found in Italian sites after the MSC. Pollen data in  
215 Northern Italy come from several sites, while in South Italy, only rare pollen data are  
216 available (Fig. 3a and b; Tab 1) making vegetation synthesis difficult across the peninsula  
217 (e.g. Bertini, 2010; Bertini et al., 2010 and reference therein).

218 Pliocene forests in the north were composed of rare tropical to common subtropical taxa  
219 such as *Taxodium*-type mixed with temperate trees (Bertini, 2001; Fauquette and Bertini,  
220 2003; Zheng and Cravatte, 1986; Zheng 1990) (Fig. 3a; Fig. 4a). Swamp environments were  
221 widespread and herbs were a minor component of the vegetation (Fig. 6a and b). After 3 Ma,  
222 following marine cooling, an altitudinal forest developed, with major increases in *Picea*  
223 followed by *Cedrus* and *Tsuga* while *Taxodium*-type forest declined (Bertini, 2001, 2010).

224 In southern Italy, vegetation records are provided in few areas. Thus, in Sicily which is the  
225 southernmost part of Italy at Punta Piccola (Combourieu-Nebout et al., 2004) and Capo  
226 Rossello (Guerrera et al., 1984; Bertoldi et al., 1989; Bertoldi, 1985a; Suc et al., 1995) open  
227 herbaceous vegetation had already expanded although steppic taxa were still sporadic.  
228 *Quercus* forest was here restricted to mountains, and contained relicts of subtropical taxa.  
229 Further information would be useful to conclude on what really happened to the southern  
230 Italian vegetation during this period and how was the open vegetation exactly expanded at this  
231 time.

232 This contrast between the north and southern-south supports the early occurrence of a  
233 north-to-south climate gradient in Italy during the Pliocene, similar to the broader  
234 Mediterranean climate at this time (Fauquette et al., 2007). It adds to an evident west-east  
235 gradient also suggested out by palynological records since the Neogene in the entire  
236 Mediterranean area (Suc et al., 1995; Bertini, 2006, 2010; Fauquette et al., 2006, 2007).

237 During the early Pliocene, climate conditions were prevalently sub-tropical with year-round  
238 moisture and warm temperature (e.g. Fauquette and Bertini, 2003). Mean annual temperatures  
239 were between 12 and 20°C in northern Italy while they exceeded 22°C in Sicily (Fauquette et  
240 al., 1999, 2007). Annual precipitation was between 1100 and 1400 mm in the North and  
241 decreasing down to ~600 mm in the South (Fauquette et al., 1999, 2007). Although the extent  
242 of seasonality is unknown, mean values are similar to modern ones.

### 243 **4.3 The Pleistocene: onset of recurrent drought pressure and influence on the** 244 **Mediterranean ecosystems**

#### 245 4.3.1 The Early Pleistocene (EP, 2.588-0.781 Ma, Gelasian and Calabrian) and the 246 regression of subtropical trees

247 The development of the Arctic ice cap at the beginning of Pleistocene had significant  
248 impacts on global climate. The Early Pleistocene corresponds to the initiation of the  
249 glacial/interglacial (G/I) alternations that had largely driven the millennial-scale climate  
250 variability as well depicted in  $\delta^{18}\text{O}$  records (for the Mediterranean Sea, see Lourens et al.,  
251 1996, 2004) (Fig. 4a). In the Mediterranean, especially in Italy, geological processes, such as  
252 Apennine uplift and sea level change further modified the larger cyclic processes and resulted  
253 in changes in vegetation composition and structure. Several records have illustrated the  
254 occurrence and dynamic of climate cycles during this period (Combourieu-Nebout, 1993,  
255 1995, Combourieu-Nebout et al., 2000; Fusco, 1996, 2007; Bertini, 2001, 2003, 2010, 2013;  
256 Capraro et al., 2005, Joannin et al., 2007; Bellucci et al., 2014). The start of G/I cycles and  
257 especially the occurrences of the cold glacial periods had favored a rise in steppic taxa, that  
258 had continued their expansion throughout the Pleistocene up until the present time. At the  
259 same time, forest diversity declined as a result of the progressive decline and loss of sub-  
260 tropical taxa during the Early and Middle Pleistocene (Fig. 3a). As noted above, the North-

261 South climate gradient, marked by increasing dryness towards the South, was already well  
262 established at this time (Fig. 3a and Fig 4a) (Fusco, 2007).

263 During the Early Pleistocene (EP), Mediterranean taxa (mainly *Quercus ilex*  
264 accompanied by *Olea*, *Pistacia*, and *Cistus*) were present in assemblages, especially in  
265 southern and central Italy, but were infrequent (e.g. Combourieu-Nebout et al., 1995; Magri et  
266 al., 2010; Corrado and Magri, 2011). These taxa were not a major component of the  
267 vegetation during either interglacial or glacial periods in the EP. Indeed, they probably  
268 developed only at low altitude or near the coast. They may have also been scattered through  
269 the warm-temperate forest where they persisted during the glacial phases.

270 In the North, moist conditions along the Po valley, the paleo-gulf enabled the  
271 persistence of swamp environments during interglacial periods, with *Taxodium*-type. These  
272 swamps were also occasionally present during glacials as well, up to the end of the Early  
273 Pleistocene (Fusco, 1996, 2007; Fig. 3a, see event A in Fig. 4a, 6a and b). At higher  
274 elevations, conifer forests with *Picea* and *Tsuga* developed (Fig. 6a; e.g. Fusco, 2010 and  
275 references therein). Declines in subtropical swamp forest began around 2.8 Ma, at the same  
276 time of the first expansion of high altitude conifer forest (Fig.4a see event A). This expansion  
277 is marked by *Picea* and observed at sites such as Stirone (Bertini, 2001), but also in central  
278 Italy, in the Upper Valdarno (Bertini, 2010, 2013). The expansion of conifers in the North  
279 marks cooling, but not a drastic decrease of moisture, given the sparse presence of open  
280 vegetation during peak glacial phases. Expansion and contraction of the conifer forests mimic  
281  $\delta^{18}\text{O}$  variations (Fusco, 2010). In Central Italy, however, the glacial phases show significant  
282 expansion of steppe taxa especially *Artemisia* (e.g. Bertini, 2010, 2013).

283 Deciduous trees and conifers begin to dominate forests in the North at 2 Ma, marking a  
284 second step-change (e.g. Fusco, 2007). Interglacials in the Alps are marked by the presence of

285 Juglandaceae (mainly *Carya*) at around 1.4 Ma, representing increased humidity during  
286 interglacials (e.g. Ravazzi and Rossignol Strick, 1995; Fusco, 2007).

287 Subtropical forests in the South expanded during interglacials at low to mid-elevations, with  
288 deciduous *Quercus* forests. Conifer forests continue to develop at high altitudes, while herbs  
289 are limited to coastal fringes (Fig. 6b; Combourieu-Nebout et al., 2000). During glacials,  
290 steppic taxa colonized low altitudes, subtropical and deciduous forest were patchy at middle  
291 elevations and conifer forests dominated at high altitudes, expanding from mountain sites  
292 (Fig. 6b). Mountain elevations were still too low to permit the development of alpine tundra  
293 (Fauquette and Combourieu-Nebout, 2013). Climate oscillations were the major (but not  
294 exclusive) drivers of vegetative change (e.g. Bertini 2003; Capraro et al., 2005; Bertini, 2010)  
295 as shifts between forest and open vegetation clearly follow G/I cycles driven by obliquity  
296 (Figs. 4a, 6a and b; Combourieu-Nebout et al., 1990; Combourieu-Nebout and Vergnaud  
297 Grazzini, 1991; Combourieu-Nebout, 1993, 1995; Fusco, 2007; Leroy, 2007; Tzedakis, 2007).  
298 Subtropical trees still represent the main forest component during the Early Pleistocene.  
299 “Taxodiaceae” progressively decline with the decline of *Taxodium*-type at the  
300 Pliocene/Pleistocene boundary followed by *Sequoia*-type at the middle Calabrian (Fig. 3a, see  
301 A and B events in Fig. 4a, Fig. 6a). The onset of decline in *Sequoia*-type in southern Italy at  
302 around 2.45 Ma coincides with the intensification of sea surface cooling in the Mediterranean,  
303 marked by recurrent increases in  $\delta^{18}\text{O}$  values (see B event in Fig 4a; Lourens et al., 1996).  
304 Successive cold intervals at the beginning of the Pleistocene likely stressed sub-tropical trees  
305 resulting in their progressive decline. Subtropical trees persist in some localities until at least  
306 1.6 Ma (e.g. *Cathaya*; Combourieu-Nebout and Vergnaud Grazzini, 1991; Combourieu-  
307 Nebout et al., 1990; Bellucci et al., 2014) and possibly even later (Capraro et al., 2005;  
308 Corrado and Magri, 2011)(Fig 4a see changes from events B to B’). Today, in China, where  
309 *Cathaya* and “Taxodiaceae” including *Sequoia*-type (e.g. *Metasequoia*) are living in the same



310 areas, they are found in two distinct altitudinal belts, with *Cathaya* higher in elevation than  
311 “Taxodiaceae” (Wang, 1961; Wang, 1986). Thus, *Cathaya* development at the expense of  
312 “Taxodiaceae” clearly expresses a progressive cooling of the interglacial optima  
313 (Combourieu-Nebout and Vergnaud Grazzini, 1991). This result matches the increase of  
314 interglacial  $\delta^{18}\text{O}$  values in the marine environments marking cooler sea surface temperatures  
315 during interglacial optima (see the Oxygen isotope record in Fig. 3a). At the beginning of the  
316 Pleistocene, conifers were probably confined to high altitude sites in the southern Italy  
317 mountains, with *Abies*, *Picea*, *Cedrus* and *Tsuga*. *Tsuga* increases during the Calabrian and  
318 *Cathaya* declines around 1.6 Ma (Combourieu-Nebout and Vergnaud-Grazzini, 1991;  
319 Combourieu-Nebout et al., 1990). Today, *Tsuga* is found at higher elevations than *Cathaya*  
320 when both are found in the same region (Wang, 1961). Thus, as with Taxodiaceae and  
321 *Cathaya*, vegetation indicates a cooling of interglacial optima and coincides with increases in  
322 interglacial  $\delta^{18}\text{O}$  values. Vegetation is again re-organized during the middle Calabrian, around  
323 1.3-1.4 Ma, with the expansion of *Quercus* mixed forest (see event C and D in Fig. 4a and b).  
324 Altitudinal forests with *Tsuga* persist and Ericaceae increases in parallel with herbs while  
325 *Carya* declines rapidly after 1.3 Ma (see event D and E in Fig. 4b; e.g. Joannin et al., 2007,  
326 2008; Dubois et al., 2001; Corrado and Magri, 2011).

327 Early Pleistocene climate reconstructions from sites in southern Italy indicate a  
328 subtropical climate. Winters were mild during glacials and interglacials with mean  
329 temperatures above 5 °C (Klotz et al., 2006 and this paper). Glacial values were slightly  
330 cooler and drier than interglacials (Fig. 7, box plots 52-76 and 81-100). A temperature decline  
331 occurred around 2 Ma (Fig. 7) associated to a slight cooling during interglacial winters and  
332 sharp declines in precipitation during glacials (between box plot 52-76 and 81-100) and  
333 interglacials (between box plots 43-79 and 81-101).. Between 1.4 and 1.3 Ma climate  
334 reconstructions indicate another cooling period in winter temperatures for both interglacial

335 maxima (Fig. 7, see difference between boxplot 41-43 and 41-79) and glacial minima (Fig. 7,  
336 see difference between boxplot 42-46 and 52-78). During the same period, annual  
337 precipitation declines in interglacial and glacial periods (Fig. 7).

338 4.3.2. The middle Pleistocene (MP - 0.781-0.126 Ma, *Ionian*) and the development of  
339 deciduous and altitudinal forest

340 The 41kyr climate cycles of the EP extended to 100 kyr during the MP, and the length  
341 of glacial periods increased (Leroy, 2007; Tzedakis, 2005, 2007; Tzedakis et al., 2012). This  
342 change is evident in several Italian records (e.g. Follieri et al., 1988; Russo-Ermolli et al.,  
343 1995, 2010; Russo-Ermolli and Cheddadi, 1997; Magri, 1999; Magri and Sadori, 1999;  
344 Muttoni et al., 2007, Ravazzi et al., 2009; Fusco, 2010; Magri, 2010; Magri and Palombo,  
345 2013; Orain et al., 2013). Plant communities in the MP were very different from those of late  
346 Calabrian, with deciduous *Quercus* forest across the Peninsula during the interglacial and  
347 increasing herbaceous cover during glacials. Mediterranean taxa are present with *Quercus ilex*  
348 as the main component and they increase in representation during the interglacials.

349 Deciduous forests dominate in the North and Central Italy during the MP. The  
350 increasing length and severity of glacial periods effectively extirpate subtropical taxa from the  
351 region and support the expansion of conifer forests in the Alps (e.g. Muttoni et al., 2007,  
352 Ravazzi et al., 2009) (Figs 4b, 5a and b). Conifers expanded downslope during cold periods  
353 while at lower elevations there was an open herbaceous vegetation mixed with steppic  
354 elements (Fig. 4b see event F). Ericaceae were now a non-negligible part of the open  
355 vegetation (Fig. 6a).

356 Deciduous forest also dominates in the South during MP interglacials and *Fagus*  
357 begins to increase in proportion. Subtropical trees are absent. *Tsuga* is present sporadically as  
358 a relic of the older vegetation (Figs 4b see event F, 5a and b). *Carya* and *Pterocarya* are still

359 found, but rarely, possibly in refuge areas (e.g. Orain et al., 2013). Conifers became  
360 established at higher altitudes with *Abies* and expanded during glacial periods (Fig. 4 see  
361 event G, Fig 6b)(Orain et al., 2013). During the longer, colder and drier glacial periods herbs  
362 colonized lower elevations and land was exposed by dropping sea levels. Steppe proportions  
363 increased during the glacial period after 0.3-0.2 Ma as a signal of drought's increase (Fig. 4b  
364 see after event H).

365         Pollen-inferred climate indicates low temperatures in both glacial and interglacial  
366 periods. Maxima for MP interglacial periods are near the lowest values observed during the  
367 LP glacials. MP glacial periods experience much lower temperatures (Fig. 7). Cool  
368 interglacials that are longer than previous interglacials (Tzedakis, 2007, Tzedakis et al., 2012),  
369 may explain the increase in conifers, the expansion of *Quercus* forest at mid altitude and the  
370 increase in *Fagus* (e.g. Russo-Ermolli and Cheddadi, 1997; Russo-Ermolli et al., 1995, 2010;  
371 Magri, 1999; Magri and Sadori, 1999). The increases in Ericaceae and herbs in southern Italy  
372 may also be related to the cooler and longer glacial periods (Figs 6a and b). Polleninferred  
373 climate reconstructions show annual precipitation values near to modern during interglacials  
374 while glacials are dry. Precipitation seasonality exists during the interglacials (Fig. 7).  
375 Although, pollen inferred reconstructions exhibit climate oscillations with warm/humid  
376 interglacials and cold/dry glacials, during the MP, some interglacials seem to experience  
377 cooler winters than glacials, especially stage 11 (Fig. 7). Precipitation at stage 11 appears  
378 lower during winter and higher in summer. Reconstructed values for isotope stage 11 are the  
379 lowest of the interglacial MTCO box plot series while precipitation appears higher than in  
380 preceding periods. The Stage 11 reconstructions come from assemblages in the Boiano  
381 section, and such needs to be confirmed by more analyses on other series as it is not a  
382 common feature in G/I alternation. The Boiano basin may be a refuge for vegetation during  
383 Stage 11, potentially biasing estimates because of the presence of taxa such as *Carya* that

384 persist at this site, while regional climate may be less suited to their presence (Orain et al.,  
385 2013). Younger G/I cycles show the standard pattern of opposition between interglacial and  
386 glacial values, although contrast appears low between the two. The lowest glacial MTCO  
387 values are recorded during stages 6-8 (Fig.7).

388

#### 389 4.3.3. The Late Pleistocene (LP - 0.125-0.01 Ma, *Tarantian*) and the Sustainability of 390 drought

391 Several pollen records capture the Late Pleistocene (LP) in Italy (e.g. Mullenders et  
392 al., 1996; Follieri et al., 1998; Magri, 1999; Magri and Sadori, 1999; Ravazzi, 2002; Kent et  
393 al., 2002; Allen et al., 1999; Allen and Huntley, 2000, 2009; Brauer et al., 2007b; Pini et al.,  
394 2009a, b) and demonstrate the extent, duration and recurrence of drought through the regular  
395 expansion of steppe/semi desert over large areas in Italy, increasing after isotope Stage 11.  
396 The last LP interglacial/glacial cycle is expressed through a deciduous forest - steppe  
397 alternation in the North as in the South (Fig. 4b). Mediterranean taxa are well represented  
398 during the warm interglacial periods and restricted during the last glacial period.

399 In the North, the proportion of conifers increases from the Po valley towards the Alps  
400 (Fig. 3a and b; e.g., Mullenders et al., 1996; Pini et al., 2009a, b). *Picea* and *Abies* occupy  
401 upper elevations and are mixed with deciduous *Quercus* at middle to low altitude during the  
402 last interglacial (Ravazzi, 2002). Herbaceous and steppic vegetation occupy northern valleys  
403 during glacial periods. Mediterranean taxa are rarely present in the North even if they may be  
404 considered in the regional vegetation.

405 In Southern Italy, the last interglacial is marked by the development of deciduous  
406 *Quercus* forest at mid altitudes, with strong rise in *Fagus* (Figs. 3 and b, 4b see after event H,  
407 6b, 8; e.g. Watts et al, 1996, 2000; Magri and Sadori, 1999; Follieri et al., 1998, Allen et al.,

408 2000, 2002; Brauer et al., 2007). In fact, *Abies* and *Fagus* increased at higher altitudes in the  
409 Apennines, while at low altitudes Mediterranean communities expanded. Herbs and steppic  
410 taxa were probably restricted to the coast. Chenopodiaceae increased in importance within the  
411 open vegetation assemblages, especially during glacial periods, probably spreading out in an  
412 edaphic fringe near the coast and over the land opened by the sea level lowering (Figs 4b, 6b;  
413 e.g. Magri and Sadori, 1999; Follieri et al., 1998; Allen et al., 1999; Allen and Huntley, 2000,  
414 2009; Brauer et al., 2007b). A steady Mediterranean forest was established at mid altitude,  
415 especially south to 43°N. During glacial phases, and especially during Isotopic Stage 3, peaks  
416 of steppic elements regularly indicate changes in vegetation associated with arid periods  
417 (Allen et al., 1999; Fletcher et al., 2011) recognized from the western Mediterranean and  
418 concurrent with North Atlantic Heinrich events as observed at the same time in the western  
419 Mediterranean (e.g. Combourieu Nebout et al., 2002; Sanchez-Goni et al., 2002). This clearly  
420 indicates the ability of vegetation in the central Mediterranean to respond quickly to abrupt  
421 climate events.

422 Pollen inferred reconstructions performed on the South Italian sites show that MTCO in  
423 Isotopic Stage 5e is nearly as warm as the EP interglacials (Fig. 7). Nevertheless annual  
424 precipitation remains low with respect to the older interglacials. During the glacial period,  
425 climate values are all very low and correspond to the lowest values obtained in the whole  
426 boxplot record (Fig.7). This is probably linked to recurrent Mediterranean cooling, along with  
427 increased aridity induced by the global climate effects of Heinrich event discharges in the  
428 North Atlantic (e.g. Combourieu-Nebout et al., 2002; Sanchez Goni et al., 2002).

429 4.3.4. The Last deglaciation and Holocene: the installation of the Mediterranean climate  
430 seasonnality and human pressure on the Mediterranean environments.

431 The last deglaciation and Holocene in Italy is well described by pollen records. These  
432 records show the step-wise development of deciduous *Quercus* forests in Northern Italy (e.g.  
433 Joannin et al., 2013) and of Mediterranean mixed forests in Southern Italy (e.g. Rossignol-  
434 Strick et al, 1992; Zonneveld, 1996; Combourieu-Nebout et al., 1998, 2013; Magri and  
435 Sadori, 1999; Allen et al., 2002; Rossignol Strick and Planchais, 1989; Oldfield, 2003,  
436 Drescher Schneider et al., 2007; Sadori et al., 2011, 2013b; Di Rita and Magri, 2012; Joannin  
437 et al., 2012, di Rita and Magri 2012; di Rita et al., 2013 and references therein,) (Fig. 3a and  
438 b, Fig. 4b; Fig. 8). The early Holocene Maximum is marked by a humid event, expressed by  
439 increases in Po discharges in the Adriatic Sea and increases in high elevation forests (e.g.  
440 Combourieu-Nebout et al., 1998, 2013). After 4.2 kyr, pollen records show increasing  
441 dryness, expressed as an expansion of herbs and Mediterranean taxa. After the 4.2 kyr event  
442 we begin to see the onset of present-day precipitation seasonality and increases in human  
443 impacts, through deforestation and agriculture (e.g. di Rita and Magri, 2009; Sadori et al.,  
444 2011, 2013b; Combourieu-Nebout et al., 2013). Thus pollen inferred reconstructions show the  
445 modern Mediterranean climate regime setting up with an inversion of the winter and summer  
446 precipitation trends after 4.2 kyr, well illustrated in the regional record from the marine MD  
447 90-917 core (Fig.7; Combourieu-Nebout et al., 2013). Italian precipitation regime  
448 modifications and aridification fit to the scenario of Mediterranean Holocene climatic changes  
449 outlined in Pons and Quezel (1985) and Jalut et al (2000, 2009). Forever drastic until today all  
450 two drove the recent vegetation changes in Italy and, will influence simultaneously with  
451 human impact the behavior of Mediterranean ecosystems in the future.

## 452 **5. Conclusion**

453 Pollen records are used to show the step-wise change in vegetation patterns on the  
454 Italian peninsula over the past 5 million years. These pollen records show the relationships

455 between successive vegetation changes and climate variations (temperature and precipitation)  
456 in the Mediterranean:

- 457 – A North-South gradient exists on the peninsula at least from the Pliocene based on  
458 vegetation composition. After a warm and humid Pliocene, the Early Pleistocene,  
459 characterized by the beginning of G/I cycles, experiences a progressive decline in  
460 subtropical taxa, *Taxodium*-type (~3-2.8 Ma), then *Sequoia*-type (~2 Ma) and then  
461 *Cathaya* (after 1.6 Ma), while steppic associations occur cyclically, expanding during  
462 glacial periods. This marks first step-wise declines in humidity and winter  
463 temperature, around 2 Ma and 1.4-1.3 Ma.
- 464 – During the Middle and Late Pleistocene, new vegetation associations occur, marked  
465 by the expansion of conifer forest in the north and of deciduous *Quercus* forest, with  
466 *Fagus* and *Betula*, in the south. At the same time herbs and steppic taxa expand over a  
467 large area, especially during glacial periods. The next cooling step occurs at 0.4-0.5  
468 Ma, with a decline in precipitation and winter temperature during glacials, although  
469 interglacials stay relatively humid.
- 470 – The modern Mediterranean summer drought is finally established after 4.2 kyr, during  
471 the Holocene, following a humid climatic optimum (especially in summer).

472

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477

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1156 **Figure Captions**

1157 Figure 1: Present-day vegetation and climate in Italy (modified from Pignatti, 2011). A  
1158 selection of climatic (ombrothermic) diagrams illustrate the modern North/South climate  
1159 gradient calculated with the NewLocClim software (Gieser et al., 2006).

1160 Figure 2: Selected Italian sites : 1) Azzano Decimo; 2) Lago di Ledro; 3) Piànico-Sèllere,  
1161 Leffe, Fornaci di Ranica; 4) Fimon; 5) Venice; 6) Pianengo; 7) Rio Ca' Viettone; 8)  
1162 Villafranca RDB; 9) Stirone, Castell'Arquato (Campile), Monte Falcone-Rio Crevalesse; 10)  
1163 Compiano; 11) Aulla-Vallescura; 12) Monticino 1987, Lamone composite section; 13)  
1164 Sarzana; 14) Cava di Villanova; 15) Castel d'Appio; 16) Val Marecchia; 17) Lower Valdarno  
1165 basin: San Quintino, Ponte a Elsa and other sections; 18) Upper Valdarno basin: Santa  
1166 Barbara, Rena Bianca and other composite sections; 19) Maccarone; 20) Gubbio; 21) Lago  
1167 dell'Accesa; 22) Pietrafitta, Tiberino basin: Fosso Bianco, Cava Toppetti and other composite  
1168 sections; 23) Colle Curti - Cesi composite section; 24) Leonessa; 25) Lagaccione, Lago di  
1169 Vico; 26) Marine core RF 93-30; 27) Madonna della Strada; 28) Corvaro, Borgorose and  
1170 Marano de' Marsi; 29) Valle di Castiglione, Valle Ricca; 30) Lago Battaglia; 31) Sessano, La  
1171 Pineta-Isernia; 32) Boiano; 33) Marine core MD 90-917, Marine core AD 91-17, Marine core  
1172 KET 82-16, Marine core KET SA 03-1, Marine core IN 68-9; 34) Saticula (Sant'Agata de'  
1173 Goti - BN); 35) Acerno; 36) Monticchio; 37) Salerno marine core C106; 38) Vallo di Diano;  
1174 39) Montalbano Jonico, Sant'Arcangelo; 40) Lago Alimini; 41) Camerota; 42) Mercure; 43)  
1175 Lago di Trifoglietti; 44) core KET8003; 45) Valle di Manche; 46) Semaforo and Vrica  
1176 sections, Santa Lucia; 47) Bianco; 48) Monte Singa; 49) Canolo Nuovo; 50) Le Castella; 51)  
1177 Lago di Preola; 52) Lago di Pergusa; 53) Punta Piccola, Capo Rossello composite section; 54)  
1178 Monte San Giorgio; 55) Monte San Nicola (Gela); 56) marine core MD 01-2797. Sites used  
1179 for pollen diagrams (Fig. 3 and 8) and pollen based climate reconstructions (Fig.7) are



1180 indicated in red. The orange dotted line represents the 42°5N latitude limit between Northern  
1181 and Southern Italy.

1182

1183 Figure 3a: Dominant vegetation during warm (interglacial, squares) and cold (glacial, stars)  
1184 periods in Italy for the six main stages from Pliocene to Early Pleistocene. Orange line  
1185 corresponds to the latitudinal limit of 42°5N

1186 Figure 3b: Dominant vegetation during warm (squares) and cold (stars) periods in Italy for the  
1187 six main stages from the middle Pleistocene to modern. Orange line corresponds to the  
1188 latitudinal limite of 42°5N

1189 Figure 4a: Vegetation changes in Northern and Southern Italy using representative pollen  
1190 diagrams from 5 Ma to 0.9 Ma.

1191 A: decrease in *Taxodium* type and increase in altitudinal trees, B: onset of decrease in  
1192 “Taxodiaceae” (*Sequoia* type) and increase in steppic vegetation, B’; extinction of  
1193 “Taxodiaceae” and development of *Cathaya*, C extinction of tropical forest and *Cathaya*,  
1194 development of *Tsuga* and *Quercus*, D: increase in *Quercus* forest and development of  
1195 Ericaceae. E increase in herbs.

1196

1197 Figure 4b: Vegetation changes in North and South Italy using representative pollen diagrams  
1198 from 1.2 Ma to 0 Ma.

1199 D: increase in *Quercus* forest and development of Ericaceae. E: increase in herbs, F increase  
1200 in *Quercus* and extinction of *Tsuga*, G: development of *Abies* and *Picea*, H: increase in  
1201 *Fagus*, development of Mediterranean forest, expansion of open vegetation and steppic  
1202 vegetation.

1203

1204 Figure 5: The onset of the Mediterranean flora and climate in the Mediterranean area  
1205 (modified from Quézel et al., 2003 and Sadori et al., 2013).

1206 Figure 6a: Vegetation profiles from the Pliocene to the Holocene at latitude above 42°5N.

1207 Figure 6b: Vegetation profiles from the Pliocene to the Holocene at latitude below 42°5N.

1208 Figure 7: Climate changes in South Italy from Early Pleistocene to present day. Results are  
1209 presented as boxplots summarizing time periods for interglacials: Holocene (Hol), stage 5e,  
1210 stage 7-9, stage 11, stages 13-15, stages 23-27, stages 41-43, stages 45-79, stages 81-101; and  
1211 for glacials: stages 2-4, stages 6-8, stages 12, stages 14-16, stages 22-28, stages 40-46; stages  
1212 52-78, stages 80-100. Interglacials are plotted in red and glacials in blue in two separate  
1213 diagrams. On the right, for the whole time series; on the left, for the last cycle in Monticchio  
1214 and for the Last deglaciation and Holocene for core MD 91-917.

1215 Bold lines represent the median, fine lines connect the means. The dotted line marks the  
1216 extreme values interval (interquartile range no more than 1.5) and outliers are indicated by  
1217 small empty circles.

1218 Figure 8: Representative vegetation changes during the last climate cycle in Northern and  
1219 Southern Italy. Same legend as Fig. 4 a and b.

1220

1221 **Table caption**

1222 Table 1. List of the sites used in this paper with their location, sediment type (C, continental  
1223 sites; L, lacustrine sites; M, marine cores), the time slice covered and the main related  
1224 bibliography references (in bold with palynology included, in italic, other references).