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

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Abstract

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

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

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

1. Introduction

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

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

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

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

2. Present day Italian climate and vegetation

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

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

3. Material and methods

3.1 Pollen records

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

The term "Taxodiaceae" is used is quotations throughout this paper because many genera formerly assigned to Taxodiaceae are now grouped in subfamilies of Cupressaceae, for example Taxodioideae Endl. ex K. Koch (*Taxodium, Glyptostrobus*, and *Cryptomeria*) and Sequoioideae (Luerss.) Quinn (*Sequoia, Sequoiadendron*, and *Metasequoia*). The genus *Sciadopitys* is now generally placed in Sciadopityaceae (Brunsfeld et al., 1994; Farjon, 1998, 2005). However, the term "Taxodiaceae" has been commonly used in Italian records where it is commonly assumed to represent *Sciadopitys*, *Taxodium* type (which includes *Taxodium* cf. *distichum* and *Glyptostrobus*) and *Sequoia* type (which includes *Cryptomeria, Cunninghamia, Metasequoia glyptostroboides*, *Sequoiadendron giganteum* and *Sequoia sempervirens*, and). Because of the diversity of taxa represented by the term “Taxodiaceae” it is not easy to revisit the records and apply the new taxonomy. Thus we have chosen to keep the term “Taxodiaceae”, as used in older publications, but we will provide greater clarity when possible.

3.2 Climate reconstructions

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

This effort represents the first climate reconstruction spanning the entire Pleistocene for this region, a time of major change in vegetation composition, and for reconstructions isolating the cold and warm periods during the Middle and Late Pleistocene. Because temporal resolution is likely to be low, climate is presented as boxplots for temperature and/or precipitation within the chosen intervals. Box plots for reconstructions of four different climate parameters : mean temperature of the coldest month (MTCO), winter precipitation (PWIN), summer precipitation (PSUM) and mean annual temperature (TANN) during glacials and interglacials were calculated and plotted using R (R Core Team, 2012). The boxes represent the extent of the second and third quartiles, dotted delimited lines represent data extreme intervals. The median is indicated by a heavy line within the box.

3.3 chronology

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

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

4.1 Emergence of the Mediterranean vegetation communities in Italy

Climate in the Mediterranean had changed repeatedly at least since the Eocene when tropical, warm-humid conditions prevailed. The development of the Mediterranean climatic regime, punctuated by a dry season, occurred in the late Pliocene (Suc, 1984), a time when cooling is observed in marine records (Poore and Bergreen, 1975; Sprovieri et al., 2006). Glacial/Interglacial (G/I) cycles, beginning in the Pleistocene, have reinforced Mediterranean climate conditions by maintaining mesic interglacials and dry glacials (Pons et al., 1995)

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

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

4.2 The Pliocene, the starting picture

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

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

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

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

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

4.3 The Pleistocene: onset of recurrent drought pressure and influence on the Mediterranean ecosystems

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

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

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

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

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

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

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

Subtropical forests in the South expanded during interglacials at low to mid-elevations, with deciduous *Quercus* forests. Conifer forests continue to develop at high altitudes, while herbs are limited to coastal fringes (Fig. 6b; Combourieu-Nebout et al., 2000). During glacials, steppic taxa colonized low altitudes, subtropical and deciduous forest were patchy at middle elevations and conifer forests dominated at high altitudes, expanding from mountain sites (Fig. 6b). Mountain elevations were still too low to permit the development of alpine tundra (Fauquette and Combourieu-Nebout, 2013). Climate oscillations were the major (but not exclusive) drivers of vegetative change (e.g. Bertini 2003; Capraro et al., 2005; Bertini, 2010) as shifts between forest and open vegetation clearly follow G/I cycles driven by obliquity (Figs. 4a, 6a and b; Combourieu-Nebout et al., 1990; Combourieu-Nebout and Vergnaud Grazzini, 1991; Combourieu-Nebout, 1993, 1995; Fusco, 2007; Leroy, 2007; Tzedakis, 2007). Subtropical trees still represent the main forest component during the Early Pleistocene. “Taxodiaceae” progressively decline with the decline of *Taxodium*-type at the Pliocene/Pleistocene boundary followed by *Sequoia*-type at the middle Calabrian (Fig. 3a, see A and B events in Fig. 4a, Fig. 6a). The onset of decline in *Sequoia*-type in southern Italy at around 2.45 Ma coincides with the intensification of sea surface cooling in the Mediterranean, marked by recurrent increases in $\delta^{18}O$ values (see B event in Fig 4a; Lourens et al., 1996). Successive cold intervals at the beginning of the Pleistocene likely stressed sub-tropical trees resulting in their progressive decline. Subtropical trees persist in some localities until at least 1.6 Ma (e.g. *Cathaya*; Combourieu-Nebout and Vergnaud Grazzini, 1991; Combourieu-Nebout et al., 1990; Bellucci et al., 2014) and possibly even later (Capraro et al., 2005; Corrado and Magri, 2011)(Fig 4a see changes from envents B to B’). Today, in China, where *Cathaya* and “Taxodiaceae” including *Sequoia*-type (e.g. *Metasequoia*) are living in the same areas, they are found in two distinct altitudinal belts, with *Cathaya* higher in elevation than "Taxodiaceae" (Wang, 1961; Wang, 1986). Thus, *Cathaya* development at the expense of "Taxodiaceae" clearly expresses a progressive cooling of the interglacial optima (Combourieu-Nebout and Vergnaud Grazzini, 1991). This result matches the increase of interglacial $\delta^{18}O$ values in the marine environments marking cooler sea surface temperatures during interglacial optima (see the Oxygen isotope record in Fig. 3a). At the beginning of the Pleistocene, conifers were probably confined to high altitude sites in the southern Italy moutains, with *Abies*, *Picea*, *Cedrus* and *Tsuga*. *Tsuga* increases during the Calabrian and *Cathaya* declines around 1.6 Ma (Combourieu-Nebout and Vergnaud-Grazzini, 1991; Combourieu-Nebout et al., 1990). Today, *Tsuga* is found at higher elevations than *Cathaya* when both are found in the same region (Wang, 1961). Thus, as with Taxodiaceae and *Cathaya*, vegetation indicates a cooling of interglacial optima and coincides with increases in interglacial $\delta^{18}O$ values. Vegetation is again re-organized during the middle Calabrian, around 1.3-1.4 Ma, with the expansion of *Quercus* mixed forest (see event C and D in Fig. 4a and b). Altitudinal forests with *Tsuga* persist and Ericaceae increases in parallel with herbs while *Carya* declines rapidly after 1.3 Ma (see event D and E in Fig. 4b; e.g. Joannin et al., 2007, 2008; Dubois et al., 2001; Corrado and Magri, 2011).

Early Pleistocene climate reconstructions from sites in southern Italy indicate a subtropical climate. Winters were mild during glacials and interglacials with mean temperatures above 5 °C (Klotz et al., 2006 and this paper). Glacial values were slightly cooler and drier than interglacials (Fig. 7, box plots 52-76 and 81-100). A temperature decline occured around 2 Ma (Fig. 7) associated to a slight cooling during interglacial winters and sharp declines in precipitation during glacials (between box plot 52-76 and 81-100) and interglacials (between box plots 43-79 and 81-101).. Between 1.4 and 1.3 Ma climate reconstructions indicate another cooling period in winter temperatures for both interglacial maxima (Fig. 7, see difference between boxplot 41-43 and 41-79) and glacial minima (Fig. 7, see difference between boxplot 42-46 and 52-78). During the same period, annual precipitation declines in interglacial and glacial periods (Fig. 7).

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

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

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

Deciduous forest also dominates in the South during MP interglacials and *Fagus* begins to increase in proportion. Subtropical trees are absent. *Tsuga* is present sporadically as a relic of the older vegetation (Figs 4b see event F, 5a and b). *Carya* and *Pterocarya* are still found, but rarely, possibly in refuge areas (e.g. Orain et al., 2013). Conifers became established at higher altitudes with *Abies* and expanded during glacial periods (Fig. 4 see event G, Fig 6b)(Orain et al., 2013). During the longer, colder and drier glacial periods herbs colonized lower elevations and land was exposed by dropping sea levels. Steppe proportions increased during the glacial period after 0.3-0.2 Ma as a signal of drought's increase (Fig. 4b see after event H).

Pollen-inferred climate indicates low temperatures in both glacial and interglacial periods. Maxima for MP interglacial periods are near the lowest values observed during the LP glacials. MP glacial periods experience much lower temperatures (Fig. 7). Cool interglacials that are longer than previous interglacials (Tzedakis, 2007, Tzedakis et al., 2012), may explain the increase in conifers, the expansion of *Quercus* forest at mid altitude and the increase in *Fagus* (e.g. Russo-Ermolli and Cheddadi, 1997; Russo-Ermolli et al., 1995, 2010; Magri, 1999; Magri and Sadori, 1999). The increases in Ericaceae and herbs in southern Italy may also be related to the cooler and longer glacial periods (Figs 6a and b). Polleninferred climate reconstructions show annual precipitation values near to modern during interglacials while glacials are dry. Precipitation seasonality exists during the interglacials (Fig. 7). Although, pollen inferred reconstructions exhibit climate oscillations with warm/humid interglacials and cold/dry glacials, during the MP, some interglacials seem to experience cooler winters than glacials, especially stage 11 (Fig. 7). Precipitation at stage 11 appears lower during winter and higher in summer. Reconstructed values for isotope stage 11 are the lowest of the interglacial MTCO box plot series while precipitation appears higher than in preceeding periods. The Stage 11 reconstructions come from assemblages in the Boiano section, and such needs to be confirmed by more analyses on other series as it is not a common feature in G/I alternation. The Boiano basin may be a refuge for vegetation during Stage 11, potentially biasing estimates because of the presence of taxa such as *Carya* that persist at this site, while regional climate may be less suited to their presence (Orain et al., 2013). Younger G/I cycles show the standard pattern of opposition between interglacial and glacial values, although contrast appears low between the two. The lowest glacial MTCO values are recorded during stages 6-8 (Fig.7).

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

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

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

In Southern Italy, the last interglacial is marked by the development of deciduous *Quercus* forest at mid altitudes, with strong rise in *Fagus* (Figs. 3 and b, 4b see after event H, 6b, 8; e.g. Watts et al, 1996, 2000; Magri and Sadori, 1999; Follieri et al., 1998, Allen et al., 2000, 2002; Brauer et al., 2007). In fact, *Abies* and *Fagus* increased at higher altitudes in the Appenines, while at low altitudes Mediterranean communities expanded. Herbs and steppic taxa were probably restricted to the coast. Chenopodiaceae increased in importance within the open vegetation assemblages, especially during glacial periods, probably spreading out in an edaphic fringe near the coast and over the land opened by the sea level lowering (Figs 4b, 6b; e.g. Magri and Sadori, 1999; Follieri et al., 1998; Allen et al., 1999; Allen and Huntley, 2000, 2009; Brauer et al., 2007b). A steady Mediterranean forest was established at mid altitude, especially south to 43°N. During glacial phases, and especially during Isotopic Stage 3, peaks of steppic elements regularly indicate changes in vegetation associated with arid periods (Allen et al., 1999; Fletcher et al., 2011) recognized from the western Mediterranean and concurrent with North Atlantic Heinrich events as observed at the same time in the western Mediterranean (e.g. Combourieu Nebout et al., 2002; Sanchez-Goni et al., 2002). This clearly indicates the ability of vegetation in the central Mediterranean to respond quickly to abrupt climate events.

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

4.3.4. <u>The Last deglaciation and Holocene: the installation of the Mediterranean climate seasonnality and human pressure on the Mediterranean environments.</u>

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

5. Conclusion

Pollen records are used to show the step-wise change in vegetation patterns on the Italian peninsula over the past 5 million years. These pollen records show the relationships between successive vegetation changes and climate variations (temperature and precipitation) in the Mediterranean:

- A North-South gradient exists on the peninsula at least from the Pliocene based on vegetation composition. After a warm and humid Pliocene, the Early Pleistocene, characterized by the beginning of G/I cycles, experiences a progressive decline in subtropical taxa, *Taxodium*-type (~3-2.8 Ma), then *Sequoia*-type (~2 Ma) and then *Cathaya* (after 1.6 Ma), while steppic associations occur cyclically, expanding during glacial periods. This marks first step-wise declines in humidity and winter temperature, around 2 Ma and 1.4-1.3 Ma.

- During the Middle and Late Pleistocene, new vegetation associations occur, marked by the expansion of conifer forest in the north and of deciduous *Quercus* forest, with *Fagus* and *Betula*, in the nouth. At the same time herbs and steppic taxa expand over a large area, especially during glacial periods. The next cooling step occurs at 0.4-0.5 Ma, with a decline in precipitation and winter temperature during glacials, although interglacials stay relatively humid.

- The modern Mediterranean summer drought is finally established after 4.2 kyr, during the Holocene, following a humid climatic optimum (especially in summer).

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Figure Captions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table caption

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