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Vegetation sensitivity to local environmental factors and global climate changes during the Middle Pleistocene in southern Italy—A case study from the Molise Apennines

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ABSTRACT

The Boiano sequence, in the Southern Apennines, delivers new pollen data concerning the local and regional vegetation response to climate changes during the Middle Pleistocene. Several local palaeoecological singularities have been highlighted in the Boiano basin record. The sequence is constrained by $^{40}Ar/^{39}Ar$ dating from MIS 13 to MIS 9, with a short gap at MIS 10. The evidence of an interglacial period, marked by singular associations of humid–temperate vegetation, constitutes the first MIS 11 record in Italy. Indeed, this pollen sequence contributes to fill the gap in the Quaternary environmental dynamics of the Italian Peninsula. The relative persistence of *Picea*, potentially located on the surrounding high relief, is recorded along the sequence together with the progressive development of *Fagus*. Concomitantly, the maintenance of local edaphic humidity benefited exigent taxa, such as *Carya*, which persists up to MIS 9. The edaphic characters and the basin physiography certainly favored the persistence of such floristic biodiversity, giving rise to the occurrence of an ecological refuge.

1. Introduction

Global climate changes since the Mid-Pleistocene Transition (MPT) are well documented into i) marine isotopic archives and ii) continental records, where they turn out to be conditioned by local peculiarities, depending on geographical location, physiographical setting and environmental conditions of investigated sites (i.e., Lisiecki and Raymo, 2005; Tzedakis et al., 2006; Joannin et al., 2011; Lang and Wolff, 2011). The change in climate rhythmicity from ca. 41 ka to ca. 100 ka cycles, which occurred during the MPT, strongly impacted the Mediterranean ecosystems, leading to the progressive impoverishment of the floristic biodiversity (Joannin et al., 2008, 2011; Bertini, 2010). Such impoverishment had already started in the Pliocene and intensified with the emergence of the climate cyclicity at around 2.6 Ma, emphasizing the North/South and East/West Mediterranean heterogeneity in vegetation composition (Suc et al., 1995; Tzedakis, 2005; Suc and Popescu, 2005;). In the central Mediterranean area, numerous continental Quaternary sequences located along the Italian Peninsula document the Pleistocene impoverishing trend through pollen analysis (Bertini, 2010) even if strong regional and local disparities are recorded (Bertini, 2010; Magri, 2010; Magri et al., 2010; Russo Ermolli et al., 2010a,b; Manzi et al., 2011). However, additional palynological records have to be found to fill gaps in the long term vegetation responses to climate changes during the whole Pleistocene (Bertini, 2010; Manzi et al., 2011). In this regard, the first pollen data from Boiano (Molise, southern Italy) clearly highlights the local response of vegetation to climate and environmental changes from Marine Isotopic Stages (MIS) 13 to 9 (Amato et al., 2011; 2014; Aucelli et al., 2011; Orain et al., 2012; 2013). The present study focuses on higher resolution palynological analysis of the Boiano infilling succession. It aims at refining the story of vegetation responses to climate changes during a poorly documented period of the Italian Pleistocene (Bertini, 2010; Manzi et al., 2011; Orain et al., 2012; 2013) and at delivering key issues on the overall environmental dynamics in Italy.

2. Geological setting

The Boiano basin (14°48′25″E–41°29′00″N; 490 m a.s.l.) is a 4 km wide and 20 km long tectonic intramontane depression in the Molise Apennines, located between the Matese carbonate massifs and the siliciclastic Sannio Hills (Fig. 1). It is orientated in the NW–SE direction and is drained by the Biferno river. The basin formed as a consequence of Miocene to Pliocene compression phases, followed by strike–slip tectonics and by extension since the Middle Pleistocene (Corrado et al., 1997a,b; Di Bucci et al., 2002; 2005; Amato et al., 2011; Aucelli et al., 2011).

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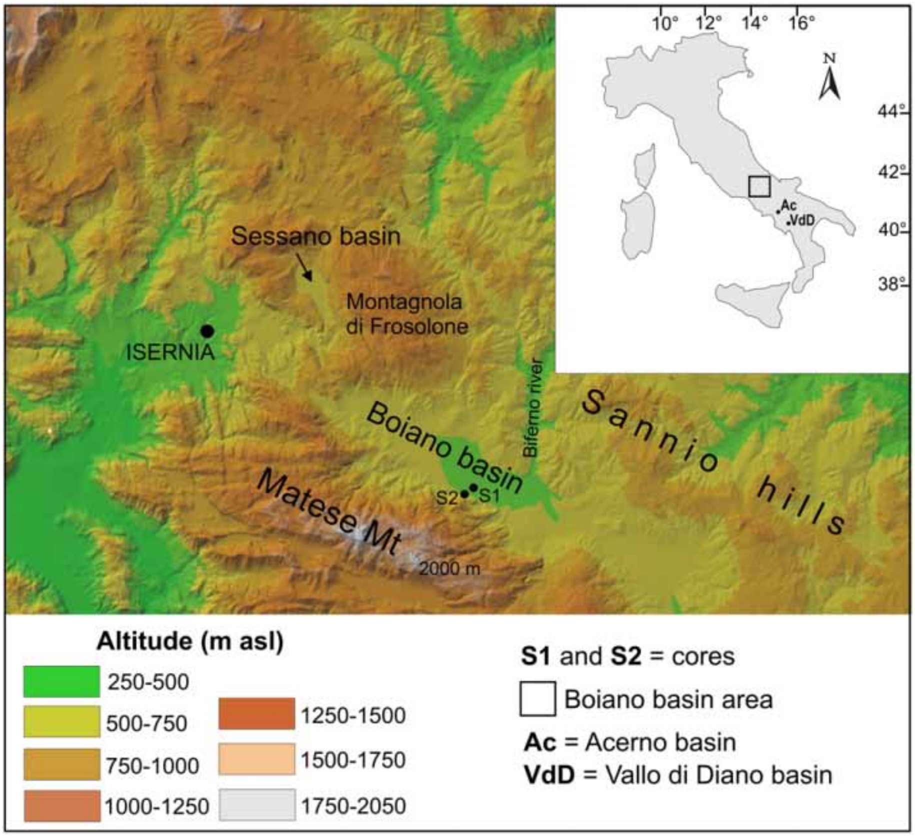

Fig. 1. Geographical location of the Boiano basin and position of the investigated core.

During the Middle Pleistocene, the basin was filled in with thick sedimentary successions of alternating lacustrine, palustrine and fluvial environments. Two boreholes (S1-158 m depth, S2-72 m depth), drilled in the southern sector of the Boiano basin (Fig. 1), give insight into the nature of the infilling. In particular, sedimentation proved to be discontinuous, with hiatuses and erosion surfaces (Fig. 2), while lithology is heterogenous, with alternations of gravels, sands and fine sediments of lacustrine, palustrine and fluvial facies (Fig. 2; Amato et al., 2014). Several tephra layers are intercalated in the succession giving the opportunity to directly date the sediments. The different sediment thickness recorded in the two cores was ascribed to the presence of a fault separating two sectors of the basin with differential subsidence rates (Amato et al., 2014). ^{40}Ar/^{39}Ar dating, tephrostratigraphic correlation and preliminary pollen analysis allowed the beginning of sedimentation in the Boiano basin to be considered older than ca. 440 ka on the basis of the ^{40}Ar/^{39}Ar age obtained on the deepest tephra layer. The interglacial phase recorded below this level, and down to the base of the cored succession, has tentatively been ascribed to MIS 13 even if its attribution to an older interglacial (MIS 15) cannot be excluded (Aucelli et al., 2011; Orain et al., 2012; Amato et al., 2014).

3. Materials and methods

Pollen analysis was realized on the sediments of core S1 (Fig. 2). This core, recovered in the sector of the Boiano basin with higher sedimentation rates (Fig. 1), preserves a thicker sedimentary record (158 m) with respect to core S2 (72 m), which has already been analyzed (Fig. 2; Orain et al., 2012). Two hundred and twelve samples were collected along the core with a resolution varying from 50 to 25 cm. Five grams of sediment were treated following a standard procedure (Fægri and Iversen, 1989). Pollen were calculated by adding two calibrated *Lycopodium* tabs in each sample aliquot. Pollen grains were identified with light-optic microscope at ×1000 magnification and using reference pollen atlas (Reille, 1992) as well as the Muséum modern reference collection.

A minimum of 300 pollen grains (excluding the over-represented family of Cyperaceae) and a minimum diversity of 20 taxa were counted in each sample to ensure the statistical significance. The obtained pollen spectra were used to set up a synthetic pollen diagram, in which the relative variation of each taxon is plotted against depth (Fig. 3). The rarer taxa were grouped, following their ecological requirements, as indicated in Table 1.

Due to its relative abundance and lack of ecological significance, *Pinus* was excluded from the sum to calculate Arboreal Pollen (AP) and Non Arboreal Pollen (NAP) rates. Cyperaceae, spores and undetermined pollen grains were also excluded from the sum and their relative representation calculated on the basis of the total sum of counted palynomorphs.

Compositional data analysis (CoDa) of assemblages, based on Constrained Cluster Analysis (CCA) of log-centered data (Grimm, 1987; Di Donato et al., 2008; 2009) and Relative Variation Biplot (RVB; Aitchison and Greenacre, 2002), were applied to the results to establish an objective zonation of the pollen diagram (Fig. 3) and to clarify the significance of taxa or groups of taxa with similar ecological meaning. The most abundant taxa were included in the analysis at the genus rank. Other taxa were included at broader family level. Rarer taxa, characterized by scattered occurrences were not included in the analysis. The CCA, which is based on incremental sum of squares, was computed by adopting as a distance metric, the euclidean distance between log-centered observations, which is equal to the Aitchison distance (Aitchison, 1983; 1986). Zero values occurring in the data are an impediment in CoDa because log-centered transformation requires positive data matrices. In this

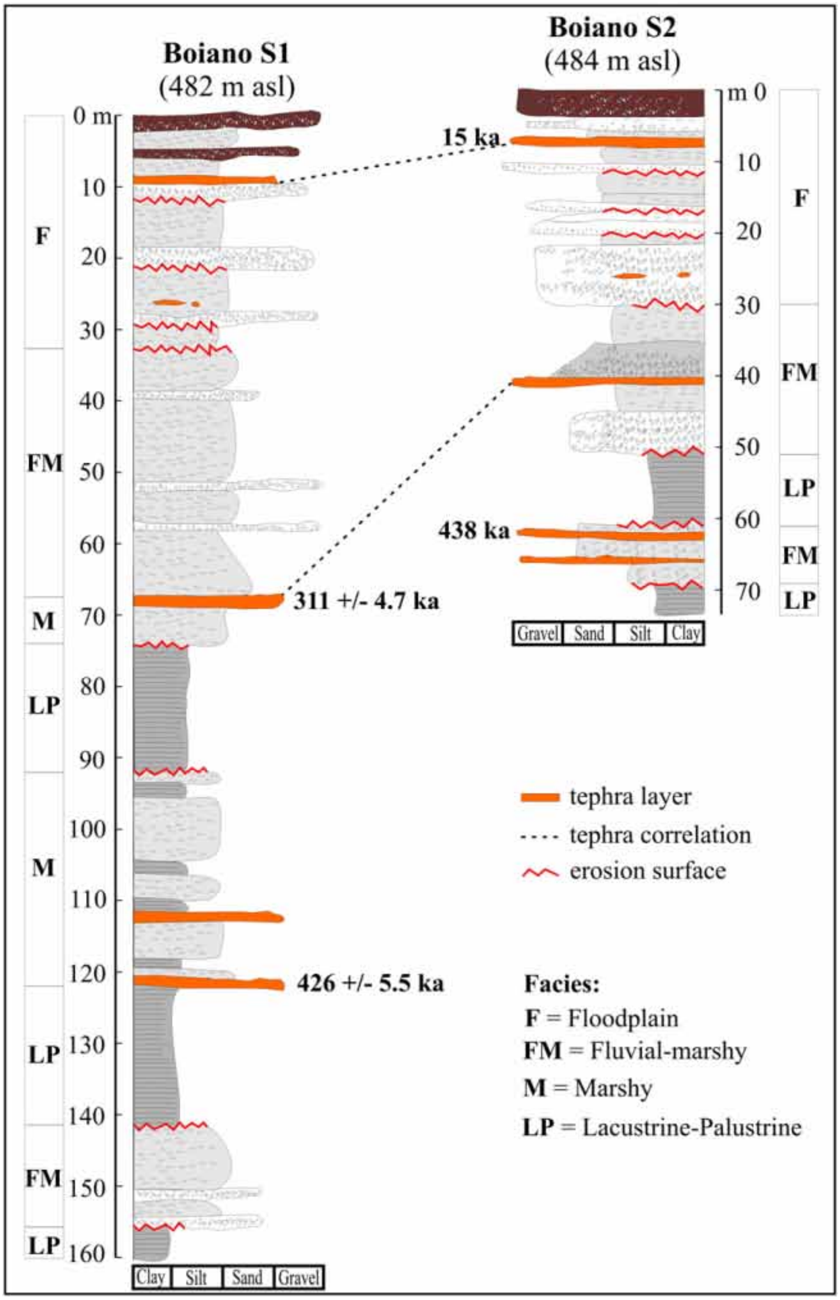

Fig. 2. Lithostratigraphy and facies analysis of cores S1 (this study) and S2 from the Boiano basin (modified after Amato et al., 2014).

study, since the vectors of proportions arise from counts, a zero substitution was made by means of a Bayesian-multiplicative replacement (Daunis-i-Estadella et al., 2008). Methods of RVB follow Aitchison and Greenacre (2002). RVB are commonly carried out by favoring the display of either individuals (form biplot) or variables (covariance biplot). In the biplot, distances between row points are approximations of distances between the log centered observations. In the form biplot, distances are measured in the Euclidean metric, while in the covariance biplot they are measured in the Mahalanobis metric. In the covariance biplot, distances between column points approximate the standard deviation of the corresponding log-ratio.

Within the covariance biplot realized for the analysis of the Boiano S1 record (Fig. 4), observations are symbolized according to the results of the CCA (Fig. 3). Data management and analyses were carried out with functions developed with MATLAB.

4. Results

Among the 212 pollen samples, only 121 provided spectra with statically significant results. They cover the depth interval from the core base (158 m) up to ca. 57 m. Samples collected above this depth, corresponding to the beginning of coarse fluvial sedimentation, were barren or very poor. Pollen concentrations range from ca. 1800 to ca. 283,000 grains per gram of sediment. Taxa diversity ranges from 21 to 38 pollen taxa per samples. The pollen flora was rather diversified with a total of 74 identified taxa. Based on both analytic description and CCA (Fig. 3), five Local Pollen Zones (LPZ) have been distinguished.

In the RVB (Fig. 4), computed on the main pollen taxa of the dataset, Axis 1 highlights a strong opposition, and thus a high variability, between herbs (at the negative side) and arboreal taxa (at the positive side). This opposition accounts for the main vegetation changes

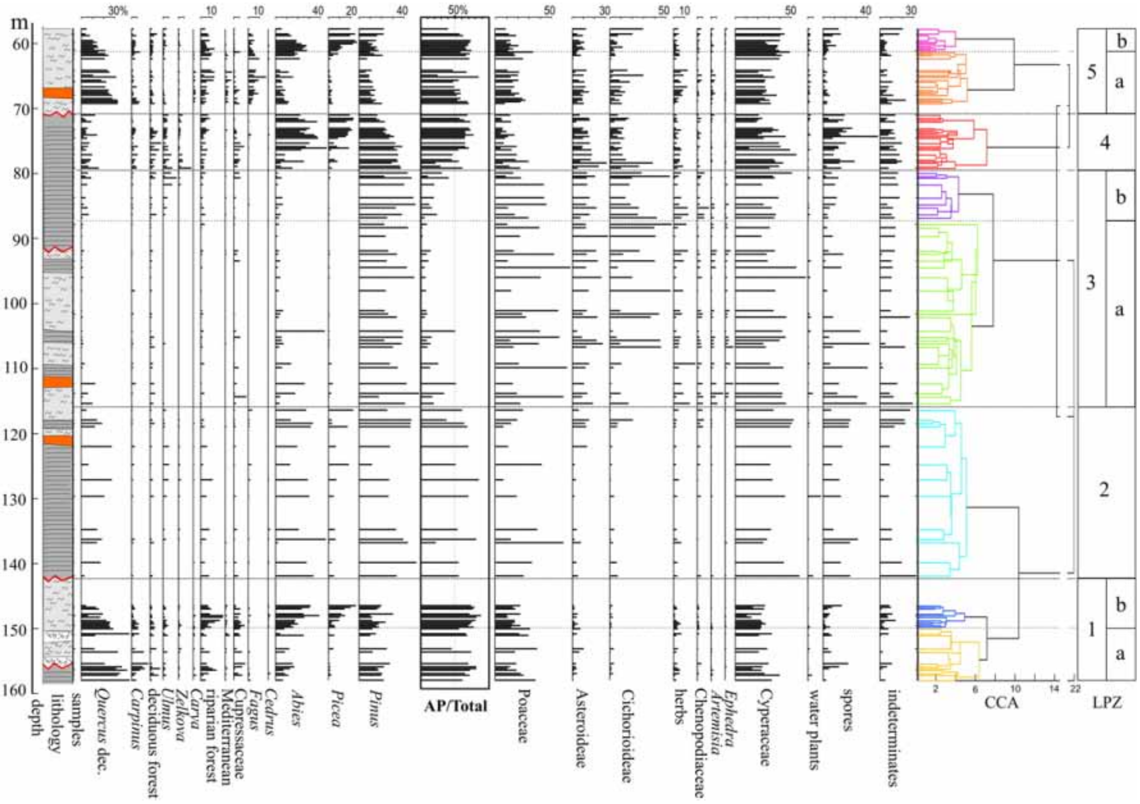

Fig. 3. Synthetic pollen diagram of the Boiano S1 sequence. CCA = Constrained Cluster Analysis; LPZ = Local Pollen Zones. The AP/Total curve is plotted with a percentage scale which is smaller with respect to all the other taxa.

occurring between glacial and interglacial phases, attesting to the good representation of the dataset structure given by the RVB. Among the tree taxa, two groups seem to frame in the biplot. A first group made up of *Quercus* dec., *Carpinus*, *Fagus*, riparian and Mediterranean forests is projected toward the positive side of Axis 2. The second group of tree taxa, which includes *Ulmus*, *Zelkova*, *Abies* and *Picea*, is located at the negative side of Axis 2, along with the long vector representing the Spores, sub-parallel to Axis 2. If the opposition between Spores and Mediterranean forest is taken into account, it can be hypothesized that the variability oriented along this direction, almost parallel to Axis 2, could represent the humidity factor, with more humid conditions for samples located at the negative side of Axis 2 and less humid conditions at its positive side. The scarce representation of *Carya* and *Cedrus* (Fig. 3) led to their exclusion from the RVB (Fig. 4). These taxa, only recorded by a few grains and frequently absent from the assemblages, do not constitute a consistent dataset and therefore would have invalidated the test. Also the Cichorioideae were excluded from the RVB due to their misleading pollen signal. Actually, differential preservation could be the cause of the over-representation of this taxon in the pollen spectra although its representation in the environment remains scarce (Bottema, 1975; Lebreton et al., 2010). Therefore, the Cichorioideae vector would not directly be linked to their ecological significance while its weight in pollen assembles may drive the CCA for the distinction of LPZ. In the whole pollen sequence, the continuous occurrence of hygrophilous plants, mainly Cyperaceae, is evidence for local edaphic humidity.

LPZ 1 (157.75–142.00 m) is characterized by a forested environment. This zone is divided in two sub-zones: LPZ 1a (157.75–150.00 m) and LPZ 1b (150.00–142.00 m). LPZ 1a is dominated by a rich and diversified mixed deciduous forest with *Quercus* (ca. 15–35%) and *Carpinus* (ca. 5–10%). *Abies*, which increases up to 25%, may have been favored by the presence of high mountains in the vicinity of the Boiano basin. *Carya*

Table 1
Taxa list used in the synthetic pollen diagram of Fig. 3. Some taxa include several elements grouped on the basis of their similar ecological requirements.

Quercus deciduous	
Carpinus	*Carpinus betulus* type
Deciduous forest	*Acer*, *Betula*, *Corylus*, *Euonymus*, *Juglans*, *Hedera*, *Pterocarya*, *Tilia*
Ulmus	
Zelkova	
Carya	
Riparian forest	*Alnus*, *Fraxinus excelsior* type, *Salix*
Mediterranean	*Buxus*, *Carpinus orientalis*/*Ostrya carpinifolia* type, *Cistus*, *Fraxinus ornus* type, *Myrtus*, *Olea*, *Phyllirea*, *Pistacia*, *Quercus ilex* type
Cupressaceae	
Fagus	
Cedrus	
Abies	
Picea	
Pinus	
Poaceae	
Asteroideae	
Cichorioideae	
Herbs	Amaryllidaceae, Apiaceae, Boraginaceae, Brassicaceae, Campanulaceae, Caryophyllaceae, *Herniaria* type, Centaurea, Convolvulaceae, Centaurea, Convolvulaceae, Crassulaceae, Dipsacaceae, *Dipsacus* type, Ericaceae, Euphorbiaceae, Fabaceae, Gentianaceae, Geraniaceae, Helianthenum, Lamiaceae, Liliaceae, *Plantago*, Polygonaceae, Primulaceae, Rosaceae, Rubiaceae, Saxifragaceae, Scrophulariaceae, Solanaceae, Urticaceae
Chenopodiaceae	
Artemisia	
Ephedra	*Ephedra distachya* type, *Ephedra fragilis* type
Cyperaceae	
Water plants	*Myriophyllum*, *Potamogeton*, Ranunculaceae, *Typha*
Spores	Monolete spores, *Polypodium*, trilete spores
Indeterminates	

and *Zelkova* are never abundant and the Mediterranean taxa are rare. In LPZ 1b, the mixed deciduous forest decreases (*Quercus* passes from ca. 25% down to ca. 5%) while the montane conifers increase at first with *Abies* (up to ca. 40%) and then with *Picea* (up to ca. 20%). The Mediterranean taxa slightly increase at that time of mesotherm to microtherm plant replacement.

LPZ 2 (142.00–117.00 m) is an heterogeneous zone where numerous samples proved barren or with very poor pollen material. The limit between LPZ 1 and LPZ 2 matches with a major change in the sedimentary record marked by an erosion surface (at 142 m depth, Fig. 2). AP are dominated by conifers with *Abies* (up to ca. 40%) and *Picea* (up to ca. 20%), while the deciduous trees are mainly represented by *Quercus* (ranging from ca. 5 to 25%) and the Mediterranean taxa are almost absent.

LPZ 3 (117.00–81.25 m) is divided in two sub-zones: LPZ 3a (117.00–89.00 m) and LPZ 3b (89.00–81.25 m). An open environment is recorded within LPZ 3a. NAP are here dominant, reaching more than 90% in some samples. The steppic association *Artemisia*, *Ephedra* and Chenopodiaceae is always recorded among the herbs, each taxon ranging between ca. 5 and 10%. High rates of Cichorioideae (up to 50%) highlight the occurrence of important taphonomic processes, potentially reinforced during a poorly vegetated period. The tree cover is scarce but diversified. During LPZ 3b, the steppic plants slightly decrease while *Quercus* and *Ulmus* increases up to 10%. However, both CCA (Fig. 3) and RVB (Fig. 4) show that samples from LPZ 3b are close to those from LPZ 3a. Finally, the overall LPZ 3 depicts an open environment.

LPZ 4 (81.25–73.00 m) is a homogeneous zone recording an important AP increase. A mixed forested environment is dominated by conifers with *Abies* (up to 40%) and *Picea* (up to 20%) whereas mesophilous trees are diversified but with percentages always under 10% per taxon.

LPZ 5 (73.00–59.50 m) divided in two sub-zones: LPZ 5a (73.00–63.00 m) and LPZ 5b (63.00–59.50 m). The limit between LPZ 4b and LPZ 5 is coincident with an erosion surface (at 73 m depth, Fig. 2). A rich and diversified deciduous forest is recorded from the base of LPZ 5a. *Quercus* reaches ca. 30%, *Fagus* occurs with the highest amount recorded in the whole sequence (ca. 8%, with a peak at ca. 15%), as well as *Carya* (ca. 5%). Various Mediterranean taxa are present while *Abies* and *Picea* strongly decrease (ca. 15% and <5% respectively). Conifers increase again within LPZ 5b with *Abies* (ca. 30%) and *Picea* (ca. 20%) dominant. *Fagus* is persistent but with lower amounts (<5%) compared to LPZ 5a. Deciduous *Quercus* decreases from ca. 20% to less than 5%, as other deciduous trees, and the mixed mesophilous forest gradually impoverishes. *Carya* is no more recorded in LPZ 5b and *Zelkova* disappears at the top of the sequence. The Mediterranean taxa are scarce or absent.

5. Discussion

5.1. Vegetation patterns and climatostratigraphy

The multidisciplinary study conducted on the infilling deposits of the Boiano basin provided a suitable chronological framework for a high resolution pollen study (Amato et al., 2014). The five local pollen zones (LPZ) identified in the diagram (Fig. 3), by means of the application of CCA, show the succession of different vegetation states which characterized the landscape around the Boiano site during the deposition of the fluvio-lacustrine sediments.

The vegetation response to the 100 ka glacial–interglacial cyclicity is observable through fluctuations between open environments and mixed mesophilous forests, locally with *Juglans*, *Pterocarya* and *Carya*, in agreement with what observed in other Middle Pleistocene sites of central and southern Italy (Russo Ermolli, 1994; Munno et al., 2001; Bertini, 2010; Russo Ermolli et al., 2010a; 2010b; Petrosino et al., 2014a). In the Boiano sequence, despite the presence of sedimentary hiatuses and erosional surfaces, owing to the nature of the continental infilling (Fig. 2), palynology accurately details the local and regional vegetation changes linked to climate cycle alternation from glacial to interglacial episodes, and provides a refined climatostratigraphy. The proposed correlation between LPZs and MIS stratigraphy (Fig. 5), based on ^{40}Ar/^{39}Ar dating and vegetation patterns, strongly reinforces the preliminary assumptions on the Boiano basin evolution (Aucelli et al., 2011; Orain et al., 2012; Amato et al., 2014).

The basal zone LPZ 1 shows an interglacial vegetation cycle, though the pioneer phase is not recorded, with the development of the deciduous forest, associated with *Carya* and the Mediterranean elements, then followed by the progressive expansion of the altitude forest probably under a drop in temperatures (Fig. 3). Across the RVB, LPZ 1a raw points are strictly distributed in the area driven by mesophilous forest vectors (Fig. 4). This constricted repartition reflects the relatively limited impact of the humidity factor during the climate optimum of an interglacial of Mediterranean type. On the other hand, the distribution of LPZ 1b raw points is slightly more scattered along the negative part of Axis 2 (Fig. 4), highlighting the importance of the humidity factor under temperature decrease, which characterize the end of an interglacial phase.

The limit between LPZ 1 and LPZ 2 corresponds to the first erosional surface recognized in the core S1 (Fig. 2). In the RVB (Fig. 4), the LPZ 1a and LPZ 1b raw points are constricted at the positive side of Axis 1, whereas LPZ 2 samples are scattered toward its negative side. This shift aligned along Axis 1, from LPZ 1a and LPZ 1b to LPZ 2, documents the vegetation dynamics during the final phases of an interglacial period. Additionally, the last LPZ 2 pollen spectra record the first open assemblages, which illustrate this transition from humid to dry environments (Fig. 3). LPZ 2 can thus be interpreted as a long interglacial–glacial transition. The last sample of the LPZ 2 corresponds to the tephra layer dated to 426 ± 5.5 ka. This age corresponds to late MIS 12 according to the δ^{18}O stack record (Lisiecki and Raymo, 2005). On these bases, LPZ 2 can be correlated to the transition MIS 13–MIS 12 and to early MIS 12 (Fig. 5) while LPZ 1 can be ascribed to the interglacial signal of MIS 13, as previously assumed (Aucelli et al., 2011; Orain et al., 2012; Amato et al., 2014). An attribution to an older interglacial period (MIS 15?) cannot be completely excluded due to the occurrence of erosional processes between LPZ 1 and 2 which could have canceled part of the sedimentary record.

LPZ 3 is the only pollen zone in the Boiano sequence that records the dominance of herbs and steppe elements, including high rates of Cichorioideae which attest to important taphonomic processes (Fig. 3). In this zone, deciduous *Quercus* strongly decreases while other mesophilous trees remain as scarce as in LPZ 2 (Fig. 3). Middle Pleistocene glacial phases in central and southern Italy are characterized by open environments in which a certain amount of deciduous trees

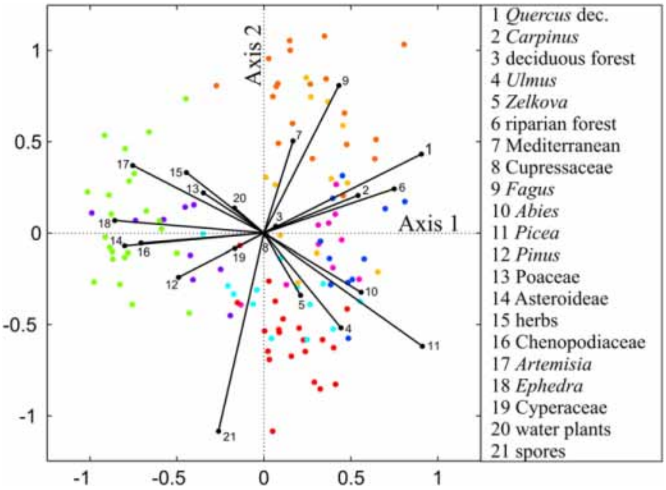

Fig. 4. Relative Variation Biplot (RVB) of pollen data from Boiano S1 core. Colors indicate samples and their position into the cluster of Fig. 3. Vectors indicate taxa, as listed at the right side of the biplot. Cichorioideae, *Carya* and *Cedrus* are excluded from the dataset.

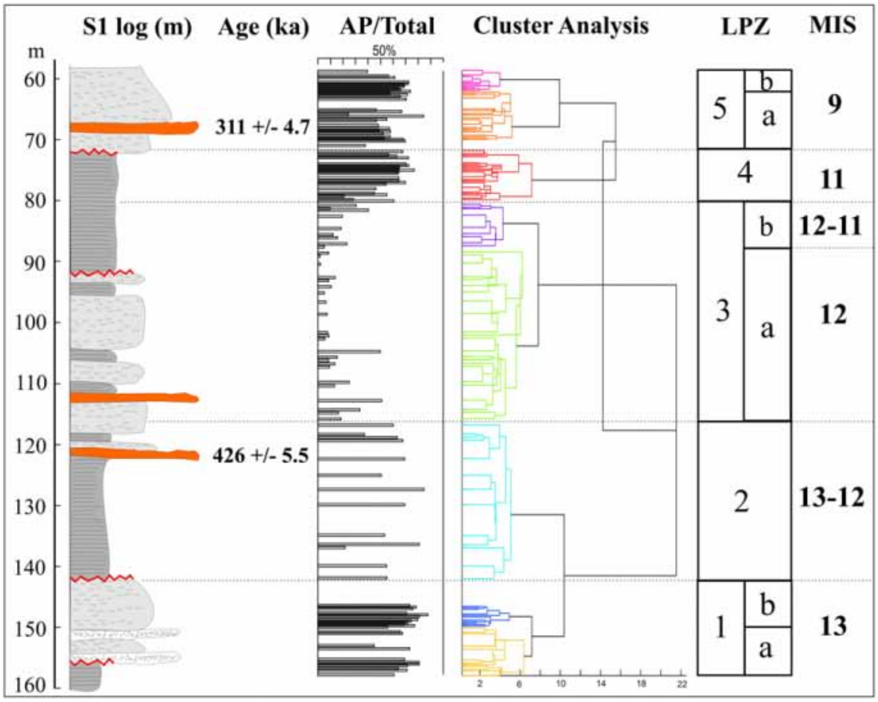

Fig. 5. Synthesis of lithology, local pollen zones and chronostratigraphy of the Boiano S1 sequence.

usually persist with percentages up to ca. 20% (Russo Ermolli, 1994; Munno et al., 2001; Bertini, 2010; Russo Ermolli et al., 2010a; Manzi et al., 2011). The weak presence of mesophilous trees recorded at Boiano during this glacial phase could be related to the physiography of the basin and high altitude of surrounding reliefs (Orain et al., 2012). *Ulmus* and the riparian forest taxa appear less impacted, probably benefiting from local edaphic humidity, as highlighted by lithology (Fig. 2) and continuous high rates of hygrophilous taxa (Fig. 3; Orain et al., 2012; 2013). This environmental character may also explain the lower rates of *Artemisia* (ca. 5%), found all along the glacial zone LPZ 3, with respect to those recorded in other Southern Apennines basins (up to 20% in Vallo di Diano and Acerno; Russo Ermolli, 1994; Munno et al., 2001). The development of *Ulmus* and *Zelkova* recorded at the end of LPZ 3 (sub-zone 3b) was also evidenced in the Boiano S2 sequence, where it was potentially attributed to a short temperate and/or humid episode within the glacial period (Orain et al., 2012). In fact, during the Middle Pleistocene glacial phases in the Italian peninsula, *Zelkova* was still well represented during temperate episodes, benefiting of both temperate climate and humid biotopes (Follieri et al., 1986; Bertini, 2010; Manzi et al., 2011). The position of LPZ 3 in the RVB is consistent with an attribution to a glacial phase (Fig. 4). In fact, LPZ 3a and 3b raw points are located at the negative side of Axis 1, close to the herb vectors. This glacial period is then correlated to MIS 12, on the basis of chronology (Fig. 5; Amato et al., 2014). It is worth noticing that the LPZ 3b raw points are distributed on less extreme negative values of Axis 1 with respect to LPZ 3a (Fig. 4), distinguishing LPZ 3b samples from a fully glacial signal. Sub-zone 3b can thus be interpreted as a transition to the subsequent interglacial period recorder in LPZ 4 (Fig. 5).

LPZ 4 is, in fact, a tree dominated zone illustrating peculiar arboreal vegetation dynamics. The assemblages are characterized by the meaningful occurrence of deciduous *Quercus*, *Ulmus*, *Zelkova* and the riparian forest elements while montane conifers strongly develop (Fig. 3). The LPZ 4 raw points in the RVB are mainly distributed at the positive side of Axis 1, matching the LPZ 1b raw points position (Fig. 4), thus enabling the attribution of the LPZ 4 signal to an interglacial phase. Indeed, the whole LPZ 4 describes the vegetation succession of a humid interglacial. In fact, such rather humid edaphism and/or conditions would have been more propitious to *Ulmus*, *Zelkova* and the riparian forest elements than to deciduous *Quercus*, explaining its relatively limited re-expansion after a glacial phase. The absence of Mediterranean elements (Fig. 3) would support this hypothesis. This assumption is also strengthened by the LPZ 4 raw points distribution at the negative side of Axis 2 (Fig. 4). In conclusion, the vegetation trends from open environments to deciduous then montane forests, recorded through LPZ 3 and LPZ 4, draw a glacial–interglacial dynamic (Figs. 3 and 5). Considering the chronological framework of the sequence (Amato et al., 2014) this singular interglacial phase can only be assigned to MIS 11 (Fig. 5). The Boiano sequence then evidences the first central Mediterranean continental record of this interglacial phase. MIS 11 has been assumed to be a peculiar episode of the Middle Pleistocene (Yin and Berger, 2010). In fact, during MIS 12–11, the precession influence dropped to its lowest intensity over the last million years (Berger and Loutre, 1991), probably playing a major role in the climate pattern of the Mediterranean region. This specific orbital configuration has led to important seasonal temperature variability of surface water in the Atlantic Ocean, to higher precipitations in Northern Africa and to higher atmospheric humidity in the Mediterranean region (Rohling and Hilgen, 1991; Bar-Matthews et al., 2003). The influence of such conditions in the Mediterranean is also testified by the formation of thick sapropel layers dated to MIS 11 (Rohling and Hilgen, 1991; Langereis et al., 1997). In the central Mediterranean, the increasing humidity could have favored the expansion of exigent taxa such as *Zelkova* and the montane trees which constitute the dominant taxa during LPZ 4 (Fig. 3). Actually, similar ecological conditions have been recorded in previous interglacial periods of the late Early/early Middle Pleistocene characterized, as well, by low precession values (Capraro et al., 2005; Joannin et al., 2007). The different vegetation composition recorded at Boiano during MIS 11 with respect to MIS 13 and 9, when precession influence was moderate (Berger and Loutre, 1991), can thus be, at least partly, related to the role of precession in climate dynamics.

The boundary between LPZ 4 and LPZ 5a is marked by a sedimentary hiatus and a complete change in the sedimentary filling (Fig. 2). The erosion surface between LPZ 4 and LPZ 5a, therefore, certainly corresponds to glacial erosion processes between MIS 11 and MIS 9, as the sedimentary study suggested (Amato et al., 2014). On the basis of this evidence, it can be assumed than MIS 10 is not recorded in the cored sediments of the Boiano infilling. The overall LPZ 5 is relatively similar to LPZ 1 (Fig. 3), starting with a rich and well developed deciduous forest associated to Mediterranean elements (LPZ 5a), followed by a diminution in deciduous taxa while the montane elements *Abies* and then *Picea* expand (LPZ 5b). Within the LPZ 5a assemblages, *Carya* records a further development, which documents its latest record in western Europe (Orain et al., 2012; 2013) and then it disappears in LPZ 5b. Similarly to LPZ 1a, the LPZ 5a raw points are mainly located at the positive side of Axis 2 in the RVB (Fig. 4), while LPZ 5b raw points are scattered toward the negative side of Axis 2 indicating a temperate interglacial of Mediterranean type. The lack of pioneer plants at the beginning of LPZ 5a supports the assumption that the first part of this interglacial is not recorded in the Boiano sequence, probably due to erosional processes (Figs. 2 and 3). The whole LPZ 5 thus records a well-developed interglacial vegetation cycle that could be attributed to MIS 9 thanks to the tephra layer dated to 311 ± 4.7 ka (Figs. 2 and 5).

5.2. Main features of the pollen flora

With a total of 74 identified pollen taxa, the Boiano flora was rather diversified. Most of the taxa still take part in the modern vegetation of central and southern Italy (Ozenda, 1994). The pollen flora and vegetation identified at Boiano are similar to those evidenced in other regional Middle Pleistocene records (Follieri et al., 1988; Russo Ermolli, 1994; Karner et al., 1999; Munno et al., 2001; Lebreton, 2004; Bertini, 2010; Russo Ermolli et al., 2010a,b; Manzi et al., 2011), however, several singularities can be noticed, such as the continuous occurrence of hygrophilous plants (Cyperaceae), which highlights the importance of soil moisture.

The striking presence of relatively high amounts of *Picea*, locally up to 20% (Fig. 3), constitutes a further singularity of the Boiano basin which was already evidenced by the analysis of the S2 core (Orain et al., 2012). Spruce pollen grains are known for their limited dispersion capacity (Hicks, 2001), therefore the meaningful pollen amount found at Boiano could support the assumption of a locally preserved population. Furthermore, in the pollen sequence from the close Sessano basin (Fig. 1), *Picea* locally overcomes 5% whereas it never reaches 2% in any other Middle Pleistocene sequence recovered in similar intramontane basins of southern Italy (Russo Ermolli, 1994; Munno et al., 2001; Ravazzi, 2002; Bertini, 2010; Russo Ermolli et al., 2010a; Petrosino et al., 2014b). The pollen records available for the Middle Pleistocene in central Italy are too scanty to demonstrate that *Picea* was not locally present. However during the Late Pleistocene, *Picea* is found in central Italy with values > 5% at Lagaccione (Magri, 1999), Lago di Vico (Magri and Sadori, 1999) and Stracciacappa (Giardini, 2007). The occurrence of *Picea* at Boiano could pinpoint a regional persistence, favored by the presence of high surrounding reliefs, such as the Matese massif. It can be assumed, in fact, that during the Middle Pleistocene most of the Southern Apennines relief had already been acquired and that the elevation of the mountains surrounding the basin was not much lower than the modern ones (Santangelo et al., 2012). *Cedrus* is, whenever represented, always under 1% in the Boiano pollen sequence (Fig. 3). Although the taxon is broadly considered as extinct from central and southern Italy during the Middle Pleistocene (Bertini, 2010; Manzi et al., 2011), its record at Boiano with low rates cannot constitute a sufficient clue to figure a local input. The record of a few *Cedrus* pollen grains in the Boiano sediments may be linked to long distance transport, potentially from the Atlas region, rather than to the local occurrence of the taxon (Magri, 2012).

Along the sequence, *Fagus* is punctually represented and only reaches significant amounts in LPZ 5 (up to 15%; Fig. 3). Also the position and length of the *Fagus* vector in the RVB could be linked to its main occurrence in the LPZ 5 (MIS 9; Figs. 3, 4), inducing an important statistical sensitivity. Its position in the ecosystems of central and southern Italy since the Middle Pleistocene has been widely discussed (Magri et al., 2006). The development of *Fagus* could be limited by the competition with montane conifers and altitudinal resilience of mixed mesophilous forest (Magri et al., 2006; Russo Ermolli et al., 2010b; Orain et al., 2012; 2013). Its expansion in central and southern Italy has certainly been recorded since MIS 13 (Russo Ermolli, 1994; Karner et al., 1999; Bertini, 2010; Russo Ermolli et al., 2010a; Manzi et al., 2011; Orain et al., 2012; 2013). Indeed, in the close basin of Sessano, *Fagus* is well represented in MIS 13 (up to 20%; Russo Ermolli et al., 2010a), while at the same time, it is almost absent from the Vallo di Diano record (Russo Ermolli, 1994; Karner et al., 1999). It then amplified during the later interglacial phases, until it became an important element of the montane vegetation during the Late Pleistocene (Follieri et al., 1988; Munno et al., 2001; Bertini, 2010; Manzi et al., 2011). The progression of *Fagus* could be linked to the weakening of *Picea* and *Abies* during the late Middle and Late Pleistocene which has been related to decreasing moisture since the second half of the Middle Pleistocene in southern Europe (Tzedakis, 2005; Magri et al., 2006). *Fagus*, slightly less exigent than *Abies* and *Picea*, could have benefited of the withdrawal of these montane competitors to expand in their ecological niches along the Central and Southern Apennines.

The record of the persistence and then disappearance of *Carya* during MIS 9 provides insight on its latest occurrence in Italy (Orain et al., 2012; 2013). *Carya* is assumed to be an element of the mesophilous humid forest during the early Middle Pleistocene interglacials, under rather temperate conditions (Delcourt et al., 1983; Delcourt and Delcourt, 1985; Barbour and Billings, 1988; Ravazzi and Strick, 1995; Bertini, 2010; Russo Ermolli et al., 2010b; Orain et al., 2013). Its occurrence in the Boiano basin is synchronous with the deciduous and Mediterranean taxa development in both LPZ 1 and 5 (Fig. 3). Likewise, *Carya* is a significantly mesophilous or rather humid-mesophilous tree that requires rainfall between 1000 and 1500 mm/year (or more), mean annual temperature around 16–18 °C and limited periods of temperatures below 0 °C (Barbour and Billings, 1988). The local persistence of *Carya* in the Boiano basin cannot only be associated to regional propitious atmospheric condition, as the taxon is absent at the same times in the nearby Sessano basin (Russo Ermolli et al., 2010a) as well as in the Acerno basin (Fig. 1; Petrosino et al., 2014a). Its persistence in the Boiano basin may therefore be linked to specific local characters, within overall propitious climate conditions, that favored the establishment of a vegetation refuge (Orain et al., 2012; 2013). The absence of *Carya* from LPZ 4 (Fig. 3), as that of the Mediterranean taxa, could then be linked to its ecological competition versus *Ulmus* and *Zelkova* under similar moist but slightly cooler conditions than those recorded in LPZ 1 and LPZ 5.

Ulmus and *Zelkova* are trees both requiring high edaphic and climate humidity. Thus, their development in the Boiano basin can be considered as an evidence of humid conditions within an interglacial optimum episode. These Ulmaceae trees could have benefited of the Middle Pleistocene optimum conditions to widely develop while the populations of relict mesophilous trees, such as Juglandaceae, underwent a progressive collapse under the pressure of the 100 ka climate cycles (Follieri et al., 1986; 1988; Ravazzi and Strick, 1995; Bertini, 2010; Russo Ermolli et al., 2010b; Manzi et al., 2011; Orain et al., 2012; 2013). Therefore, the spread of *Ulmus* and *Zelkova*, in concurrence with the Mediterranean taxa decrease, could reflect the occurrence of high moisture during each interglacial optimum. Especially the LPZ 5a, characterized by both the highest Mediterranean taxa amounts and the lowest *Ulmus* and *Zelkova* values (Fig. 3), could rather reflect a slightly less humid interglacial optimum. The later development of *Ulmus* and *Zelkova* in LPZ 5b would then correspond to their progression while more temperate exigent taxa retreated under progressive cooling. On the other hand, the LPZ4, where high rates of *Ulmus* and *Zelkova* are recorded and *Carya* and Mediterranean taxa are almost absent (Fig. 3), could display a less temperate and rather wet interglacial.

6. Conclusion

The pollen sequence from the Boiano basin documents the local and regional responses of vegetation to climate changes during the Middle

Pleistocene between MIS 13 and MIS 9. Despite the presence of discontinuities, the Boiano pollen record describes a fully developed interglacial–glacial–interglacial (MIS 13–12–11) succession followed by a further interglacial period (MIS 9) occurring after an erosional phase, certainly triggered by the cold and arid climate conditions related to MIS 10. Clear vegetation dynamics have been identified by the successions of (i) mixed-deciduous forest, sometimes with Mediterranean elements, (ii) montane conifer forest and (iii) open/steppe vegetation, consistent with the Middle Pleistocene interglacial–glacial cyclicity in the central Mediterranean. Within the interglacial periods, the climatic optimum phases are characterized by an important development of the deciduous forest, including humid mesophilous taxa such as *Ulmus*, *Zelkova* and sometimes *Carya*, whereas the only glacial phase recorded in the sequence is characterized by the spread of open associations with steppe elements, related to increasing aridity. The whole sequence also records the persistence of edaphic humidity in the basin, which provided suitable conditions for the maintenance of humidity-requiring taxa, such as *Carya* or *Zelkova*. The position of the Boiano basin within the Apennines and its physiography also favored a late maintenance of *Picea* and *Abies*, and then the progressive reoccupation of their niches by *Fagus* while the montane conifers disappeared. It may be assumed that edaphism, combined with physiography, could have constituted propitious factors for the maintenance of a refuge area along the late Middle Pleistocene in the Boiano basin.

Within the pollen record, peculiar vegetation trends have been highlighted and identified as a partial record of MIS 11. This interglacial phase has shown to be characterized by important climatic and edaphic humidity which favored the continuous record of *Ulmus* and *Zelkova* with relatively high pollen rates, and by limited amounts of deciduous *Quercus*.

The new pollen data from the Boiano sequence strongly enriches the environmental framework of the late Middle Pleistocene vegetation and climate trends in central and southern Italy. These data show that local ecological factors strongly influenced vegetation composition and distribution. Indeed, important differences have been highlighted between Boiano and other Middle Pleistocene records of the Southern Apennines, such as Sessano, Acerno and Vallo di Diano. The Boiano sequence improves the knowledge on the last occurrence of *Carya* in the region and provides key issues on the last substantial development of *Picea* in Italy. The Boiano record therefore contributes to fill the gap remaining within the Quaternary vegetation history of the Italian Peninsula.

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