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(Article begins on next page)

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3 Although plants are able to respond to the P shortage, climatic factors might modify the soil-plant-
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1 **EFFECT OF BEECH (*FAGUS SYLVATICA* L.) RHIZOSPHERE ON PHOSPHOROUS**
2 **AVAILABILITY IN SOILS AT DIFFERENT ALTITUDES (CENTRAL ITALY).**

3
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47 community is key for fuelling the rhizospheric processes and, in particular, P cycling.

48

49 **1. Introduction**

50 Phosphorus (P) is one of the most critical nutrients for the growth of plants and microorganisms,
51 and is present in soil both in inorganic and organic forms. The inorganic P includes primary
52 minerals (e.g., apatites, strengite) and secondary minerals such as calcium-, iron-, and aluminum-
53 phosphates (Shen et al., 2011), while the organic P is mainly made up of phospholipids,

54 orthophosphate monoesters, nucleic acids, teichoic acids and phosphonates (Rubæk et al., 1999;
55 Kruse et al., 2015). The content and distribution of these different P forms do not have a constant
56 trend along the soil profile (Makarov et al., 2004; Chiu et al., 2005; Backnäs et al., 2012). In
57 grassland and beech forest soils located on north-facing slope of southern Swiss Alps, Beck and
58 Elsenbeer (1999) found that the variation with depth of the organic P concentration mainly depends
59 on type and age of vegetation, and soil characteristics. Then, Chiu et al. (2005) studied grassland
60 and coniferous forest soils and found that the inorganic orthophosphate concentration decreased, but
61 orthophosphate monoesters increased with increasing soil depth. The generally low availability of P
62 in soil is due to the scarce solubility of P-bearing compounds, both for inorganic and organic forms
63 (Hinsinger, 2001). For example, in the soil solution P exists as orthophosphate anions and dissolved
64 forms of organic P, with concentrations that range from 0.01 to 3.0 mg l⁻¹ (Frossard et al., 2000).
65 However, plants are able to respond to P deficiency by root-exudation of organic acids that increase
66 P availability in the soil close to the roots (Ström et al., 2002; Oburger et al., 2009; Zhao et al.,
67 2010). Furthermore, the simple organic compounds comprising the plant exudates enhance the
68 activity of the microorganisms that, in turn, favours P availability by *i*) soil acidification due to the
69 CO₂ produced through respiration, and *ii*) releasing organic acids and phosphatase enzymes
70 (Marschner et al., 2011). A great part of the complex interactions among P-bearing compounds,
71 plant and microorganisms occurs in the small soil volume between fine roots and earthy material,
72 the rhizosphere, where most of the chemical, biochemical and biological reactions take place (e.g.,
73 Hinsinger et al., 2003; Richter et al., 2007; Lambers et al., 2009). Because of its high sensitivity to
74 the environmental conditions (Turpault et al., 2007), the biogeochemical processes occurring in the
75 rhizosphere can be strongly affected by climate. Indeed, climate (temperature, precipitation amount
76 and pattern) is one of the key soil forming factors that inherently controls the soil profile
77 development (Darwish and Zurayk, 1997; Fernández Sanjurjo et al., 2003; Riebe et al., 2004), soil
78 microbial activity (Qiu et al., 2005; Devi and Yadava, 2006), soil organic matter dynamics (Jobbagy
79 and Jackson, 2000; Brevik, 2013), and macro- and micro-nutrients cycles (Butler et al., 2012;

80 Vincent et al., 2014; Zhang et al., 2014). For example, in a phytotron experiment, Kumar et al.
81 (2011) found that higher temperatures increased the amount of available P, but decreased organic P
82 in the rhizosphere of wheat. Instead, as far as we are aware, *in vivo* studies on the P dynamics in the
83 rhizosphere of forest species at different temperature have never been achieved, although they could
84 help better understanding the resilience of forest ecosystems with respect to global (and more
85 regionally localized) warming. The objective of this study was to provide novel field and laboratory
86 information on this argument. To assess the influence of temperature on the rhizospheric P pool, we
87 selected one of the main diffused forest species in Europe, i.e. the European beech (*Fagus sylvatica*
88 L.). By using latitude and altitude as proxies for temperature change (Vincent et al., 2014), we
89 contrasted the associated changes in European beech rhizosphere and bulk soil collected from the
90 different horizons of forest soils at two altitudes (800 and 1000 m) on three mountains located
91 within 1° of latitudinal gradient in central Italy. Specifically, we tested the hypotheses that: 1) soil
92 organic C, total N, and organic and available P decrease with increasing latitude and altitude, and 2)
93 the rhizosphere effect on P availability becomes more pronounced when potential nutrient
94 limitations are more severe, as it happens with increasing latitude and altitude. The above two
95 hypotheses were tested on rhizosphere and bulk soil from the three study areas through measuring
96 of organic C, total N, organic and available P, and phosphatase activities; additionally, ³¹P-NMR
97 analyses were performed to assess the different forms of soil P.

98

99 **2. Materials and methods**

100 *2.1. Study sites*

101 As study areas, three calcareous massifs were selected on the Apennines chain (central Italy):
102 Mount Terminillo (42°28' N, 12°59' E), Mount San Vicino (43°19' N, 13°03' E), and Mount Acuto
103 (43°28' N, 12°41' E) (Figure S1 of the Supplementary Materials). For each area, two European
104 beech (*Fagus sylvatica* L.) forests were chosen on the north-facing slopes at about 800 and 1000 m
105 above sea level (a.s.l.). A description of the environmental conditions of each site is reported in

Table 1. Here it suffices to summarize that the three areas have a similar mean annual air temperature (MAAT) that varies from about 10°C at 800 m, to about 9°C at 1000 m a.s.l.. Following the latitudinal transect, coldest and warmest months showed a contrasting trend as, going north, the mean of the coldest month (January) decreased of 1.6-2.0°C, while that of the warmest month (July) increased of 1.6-1.7°C. In all the areas, the mean temperature for both coldest and warmest months is lower in the soils at 1000 m than in those at 800 m a.s.l. of 0.6-1.0 and 1.0-1.1°C, respectively. The mean annual precipitation, similar at both altitudes, do not follow a latitudinal transect, and is the highest at Mount Acuto, the lowest at Mount San Vicino. All the forests were coppices in conversion, with the conversion that started from about 20 to about 40 years ago. As indicated by the diameter at breast height (Table 1), the most recent conversions occurred at Mount Terminillo and Mount San Vicino, at 800 and 1000 m a.s.l., respectively; the oldest conversions started at Mount Terminillo for the coppice at 1000 m a.s.l., and at Mount Acuto for the woods at both altitudes. At all sites beech was the dominant tree, with dominances ranging from 80 to 100%. While the soil cover due to litter was always complete, the coverage due to understory ranged from 5 to 50%, with scarce to null signs of erosion. All the soils had developed from limestone rocks with small flintstone layers.

122

123 2.2. Soil sampling

During the winter 2014, at each altitudinal site two profiles were dug within a plot of about 100 m², for a total of 12 profiles (3 latitudes x 2 altitudes x 2 profiles). The rational of the winter sampling was that, in this season, root respiration and exudation, and root-associated microorganism activity are at their lowest intensity (Epron et al., 2001; Buée et al., 2005; Meinen et al., 2009; Ruehr and Buchmann, 2010; Calvaruso et al., 2014); hence, more reliable and stable information on the rhizosphere status can be obtained in winter rather than in more dynamic seasons like spring or summer. Each profile was opened at 50-60 cm from the stem of the biggest beeches found in the selected site. Approximately, the age of the trees ranged from about 40 years at Mount Terminillo

(800 m a.s.l.) to about 60-65 years at Mount Acuto. However, the age of the tree is of secondary importance as, for the protocol adopted to obtaining the rhizosphere samples (see below), we considered only the fine roots, which activity is little dependent on the age of adult plants as they are renewed every few year (Trumbore and Gaudinski, 2003; Agnelli et al., 2014).

The profiles were dug till the parent rock, and the soils were morphologically described according to Schoeneberger et al. (2012). As a whole, the soils at 800 m a.s.l. showed a *solum* made of the following sequence of horizons, with respective mean thicknesses (standard deviations in parentheses): O = 7.2 cm (2.4), A = 7.0 cm (3.2), AB = 7.0 cm (1.5), Bw1 = 13.2 cm (3.7), Bw2 = 12.8 cm (4.7), Bw3 = 26.5 cm (8.9), Bw4 = 18.3 cm (4.2). The soils at 1000 m a.s.l. showed the following *solum*: O = 10.2 cm (6.2), A = 10.3 cm (3.2), AB = 14.2 cm (7.7), Bw1 = 19.8 cm (9.4), Bw2 = 10.0 cm (4.7). The mean thickness (excluding the O horizons) of the *solum* was 68.8 cm (36.3) at 800 m, and 49.2 cm (19.9) at 1000 m. The underneath C horizons are not part of the *solum* and were excluded from sampling. The litter was made by O horizons that were typical of the *amphimus* type of humus (Baize and Girard, 2008), which are present in soils with well-developed O horizons rich of pedofauna, and resting on A horizons with well-developed crumb structure.

Roughly, in the soils at 800 m the fine earth content ranged from 85% in the A horizon to 50% in the Bw3 and Bw4 horizons, while in those at 1000 m it went from 80% in the A horizon to 35-40% in the Bw1 and Bw2 horizons. All the soils had a *mesic* soil temperature regime, and an *udic* soil moisture regime, and were classified as Mollisols or Inceptisols (Table 1) according to the Soil Survey Staff (2014).

For each profile, a large amount of sample (at least 3 kg) from each mineral horizon forming the *solum* was collected and stored in a portable refrigerator for the transport to the laboratory.

2.3. Sample preparation

Within one week from the sampling, the beech rhizosphere of each sample was isolated by picking up the roots together with the adhering soil (Cocco et al., 2013; Massaccesi et al., 2015). The roots

158 with a diameter larger than 2 mm were discarded. After a light shaking to detach the weakly
159 adhering soil particles, which were then added to the bulk soil (i.e., the soil not strictly adhering to
160 the roots), the remaining soil material firmly adhering to the fine roots was considered as
161 rhizosphere and was recovered by further shaking and gentle brushing. An aliquot of the field moist
162 rhizosphere and bulk of each horizon was stored at 4°C for measuring the phosphatase activities,
163 while the remaining material was air-dried and sieved through a 2 mm mesh to be used for the
164 chemical and spectroscopic analyses.

165

166 2.4. Chemical analysis

167 The soil pH was determined potentiometrically in water ($\text{pH}_{\text{H}_2\text{O}}$) and in 1 M KCl solution (pH_{KCl})
168 (solid:liquid ratio of 1:2.5) after 30 minutes of stirring by a combined glass-calomel electrode. Total
169 organic C content (TOC) was estimated by K-dichromate digestion, heating the suspension at 180
170 °C for 30 minutes (Nelson and Sommers, 1996), and total N content was determined by a Carlo
171 Erba EA1110 dry combustion analyzer (Carlo Erba Instruments, Italy). To measure the water
172 extractable organic C (WEOC), 1 g of sample was placed into a plastic container, submerged with
173 distilled water (solid:liquid ratio 1:10) and shaken overnight with an orbital shaker (140 rpm). The
174 mixture was left to rest for a while, centrifuged at 1400 g for 10 minutes, and then filtered through
175 Whatman 42 filter paper. The resulting solution was analyzed with a TOC-500A (Shimadzu, Japan)
176 analyzer after the addition of a few drops of concentrated H_3PO_4 to eliminate carbonates. The total P
177 was determined by the ignition method, and the organic P was calculated by difference between the
178 total and inorganic P content (Kuo, 1996). Available P was estimated according to Olsen et al.
179 (1954).

180 Acid and alkaline mono-phosphatase activities were determined according to Tabatabai (1994).
181 Briefly, in a 50-ml flask, 1 g of sample was added with 0.2 ml of toluene, 4 ml of modified
182 universal buffer (at pH 6.5 and pH 11 for the acid and alkaline phosphatases, respectively), and 1 ml
183 of 0.025 M *p*-nitrophenyl phosphate (*p*-NPP) solution. The mixture was incubated at 37 °C for 1 h

184 so to induce the transformation of *p*-NPP into *p*-nitrophenol (*p*-NP) via phosphatase. After
185 incubation, 1 mL of 0.5 M CaCl₂ and 4 mL of 0.5 M NaOH were added to the samples, mixed for
186 few seconds, and then filtered through a Whatman 42 filter paper. The color intensity of the filtrate
187 was measured against a blank at 420 nm by a Lambda EZ 150 UV/VIS Spectrometer (Perkin Elmer,
188 USA). The results are expressed as µg of *p*-NP produced by 1 g of soil per h of incubation (µg *p*-NP
189 g⁻¹ h⁻¹).

190 For the ³¹P-NMR measurements, which were run only on the A horizons, the extracts were obtained
191 by shaking 5 g of sample with 100 ml of a solution containing 0.25 M NaOH and 0.05 M EDTA for
192 16 h at room temperature, in the dark. The mixture was centrifuged at 10,000 g for 30 min and the
193 liquid phase, once separated from the precipitated, was freeze-dried. The freeze-dried NaOH-EDTA
194 extracts were re-dissolved in 0.1 ml of 10 M NaOH solution and 0.5 ml of D₂O, and transferred to a
195 5-mm NMR tube for the analysis. The ³¹P-NMR spectra were obtained using an Arance 600 MHz
196 NMR spectrometer (Bruker, USA) operating at 243 MHz, with an acquisition time of 0.673 s, and a
197 delay time of 0.5 s. For each sample 24,576 scans were run. Peak assignments were according to
198 Turner et al (2003), and the intensities of signals were determined by integration.

199 The accuracy of the run soil analyses follows: pH in water, 0.14; pH in KCl, 0.11; TOC, 2.05 g kg⁻¹;
200 total N, 0.19 g kg⁻¹; WEOC, 0.024 g kg⁻¹; total P, 35 mg kg⁻¹; organic P, 24 mg kg⁻¹; available P, 2.5
201 mg kg⁻¹; acid and alkaline mono-phosphatase activity, 5 µg *p*-NP g⁻¹ h⁻¹.

202

203 2.5. Statistical analyses

204 To test the effect of each variable (latitude, altitude, soil horizons, and soil fractions) on the soil
205 properties we performed canonical redundancy analyses (RDA). The RDA model was tested for
206 significance using 999 random permutations. The variations of soil properties as a function of
207 latitude, altitude, soil horizons, and soil fractions were assessed by a Principal Component Analysis
208 (PCA). For each property, all the data were standardized prior the RDA and PCA by subtracting the
209 mean and dividing by the standard deviation.

210 The RDA indicated a lack of significant effect for latitude (ANOVA, $F= 2.39$, $P=0.057$), whereas
211 the effects of altitude (ANOVA, $F= 15.84$, $P=0.001$), soil horizons (ANOVA, $F=4.13$, $P=0.001$) and
212 soil fractions (ANOVA, $F=62.86$, $P=0.001$) on the soil properties were significant. Because of this,
213 only these three latter significant variables were considered in further detail in our study, and the
214 three latitudinal areas were therefore considered as replicates. Consequently, the analytical results
215 obtained from the two samples collected for each horizon at each latitude and altitude were
216 averaged, and these averages used as replicates so to have $n=3$. The data were checked for the
217 normality of the distribution and the homogeneity of the variances by Shapiro-Wilk and Levene
218 tests, respectively, and, if necessary, transformed by the Box and Cox (1964) procedure. To assess
219 significant differences among altitudes, horizons and soil fractions (rhizosphere and bulk soil),
220 three-way ANOVA was performed, and the comparison of means was assessed by Fisher's LSD
221 post-hoc test ($P<0.05$). Box plot diagrams were used to show the obtained data. The line inside each
222 box represents the median. The bottom and top of the box are the first and third quartiles, while the
223 upper and lower whiskers indicate the minimum and maximum values, respectively; the + sign
224 within each box plot indicates the average.

225 The statistical analyses were performed using R software (R Core Team, 2014).

226

227 **3. Results**

228 *3.1. PCA*

229 The PCA scoring plot (Figure 1) showed variations of the soil properties between rhizosphere and
230 bulk and between the soils at 800 and 1000 m a.s.l., and identified the axes 1 and 2 that explained
231 about 53 % and 24 % of the variation, respectively. All the soil parameters showed positive
232 correlation with PC1 (Figure S2a of the Supplementary Materials), with TOC, alkaline and acid
233 phosphatase activities, total N, and available and organic P contributing for more than 83 % to the
234 variability (Table 2). While the pH_{H_2O} and pH_{KCl} only slightly affected PC1, they explained 57 % of
235 the variability along PC2 axis. The scoring plot (Figure 1) showed that the soil properties were

236 affected mainly by altitude and soil fractions and to a lesser extent by soil horizons. Moreover, the
237 PCA indicated that the differences between the rhizosphere and bulk were somewhat greater at
238 1000 m than at 800 m a.s.l..

239

240 *3.2. Soil pH, organic C and total N*

241 In the soils at both altitudes, $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} remained relatively constant throughout the profile,
242 and no significant difference was observed between rhizosphere and bulk soil (Figure 2a, b).
243 However, both $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} from A to Bw2 horizons were higher at 1000 m than at 800 m
244 altitude.

245 As expected, TOC content tended to decrease with depth throughout all the soils (Figure 3a). On a
246 horizon by horizon comparison between the two altitudes, TOC content was greater at 1000 m than
247 at 800 m. Then, TOC concentration was always higher in the rhizosphere than in the bulk soil of the
248 same horizon. In contrast to TOC, WEOC concentration was similar at 800 and 1000 m a.s.l.
249 (Figure 3b); however, whereas for the soils at 800 m no difference in WEOC content occurred
250 between rhizosphere and bulk soil, at 1000 m the rhizosphere had consistently a greater WEOC
251 content than the bulk soil.

252 The total N content decreased with depth in all the soils and, as for the TOC, on a horizon by
253 horizon comparison it was higher at 1000 than at 800 m (Figure 3c). Rhizosphere and bulk showed
254 similar total N contents at both altitudes, with the exceptions of the Bw1 horizon of the soils at 800
255 m, where the rhizosphere displayed a greater total N content than the bulk soil.

256

257 *3.3. Total, organic and available phosphorus contents, and phosphatase activities*

258 The total and organic P content was much higher in the soils at 1000 m than in those at 800 m
259 (Figure 4a, b). At both altitudes, rhizosphere and bulk soil generally did not show significant
260 differences, with the exceptions of the Bw1 horizon for total and organic P, and Bw3 horizon for
261 total P, always for the soils at 800 m. The available P content (Figure 4c) was also generally higher

262 in the soils at 1000 m than in those at 800 m; further, in the higher altitude soils the rhizosphere had
263 a greater concentration of available P than the bulk soil in all the horizons, while in the soils at 800
264 m this occurred in four over six horizons (A, AB, Bw2, and Bw3). The TOC:organic P ratio (Table
265 S1 of the Supplementary Materials) showed a decreasing trend for both rhizosphere and bulk soil at
266 800 m, but it was not significantly different between the two altitudes and between the fractions,
267 with the exception of the Bw4 horizon at 800 m where the rhizosphere showed a greater value than
268 that of the bulk soil.

269 In the soils at 800 m, alkaline and acid phosphatase activities (Figure 5a, b) decreased with
270 increasing depth from the A to the Bw1 horizons (Bw2 for acid phosphatase), to remain rather
271 constant more in depth. At 1000 m, both enzymatic activities decreased from the surface to the AB
272 horizon, to remain rather constant in the horizon underneath. By contrasting horizon by horizon, the
273 alkaline phosphatase activity (Figure 5a) was greater in the soils at 1000 m, where small differences
274 between rhizosphere and bulk were observed only in the Bw1 horizon. The acid phosphatase
275 activity (Figure 5b) was similar in the A and AB horizons at the two altitudes, and greater at 1000 m
276 than at 800 m in the Bw1 and Bw2 horizons. The rhizosphere showed higher acid phosphatase
277 activities than the bulk soil in the Bw1, Bw2 and Bw4 horizons at 800 m, and in the A and Bw1
278 horizons at 1000 m.

279

280 3.4. ³¹P-NMR spectroscopy

281 The ³¹P-NMR spectra (Figure S3 of the Supplementary Materials) indicated that the orthophosphate
282 monoesters (from 3 to 6 ppm of the chemical shift) were the dominating P forms of the spectral
283 area, followed by inorganic orthophosphates (from 5.9 to 6.5 ppm), orthophosphate diesters (from -
284 2 to 0 ppm) and pyrophosphates (from -3.5 to -5.5 ppm). The spectra showed similar patterns for
285 rhizosphere and bulk soil. Between the two altitudes, the orthophosphate diesters were more
286 abundant at 1000 m than at 800 m for both rhizosphere and bulk soil (Figure 6).

287

288 4. Discussion

289 4.1 Altitude and rhizosphere effect on pH, C and N

290 The PCA performed on all the measured soil properties showed a marked difference between
291 rhizosphere and bulk of the studied soils, indicating that the beech roots induce a rhizosphere effect.
292 Similar results were reported by several other authors. For example, Wang et al. (2001) studied the
293 soil solution chemistry of beech and Norway spruce and found lower pH and nutrient
294 concentrations in the rhizosphere than in the bulk soil solutions. Esperschütz et al. (2009), studying
295 carbon fluxes from beech trees into the rhizosphere found that during the growing season the
296 rhizosphere had a higher amount of dissolved organic matter than the bulk soil. Calvaruso et al.
297 (2011) found that the rhizosphere of several tree species including beech was enriched in organic C,
298 N, Ca, Mg and K with respect to the bulk soil, and the extent of the rhizosphere effect depended on
299 the tree species. Finally, Cesarz et al. (2013) accomplished a rhizotron experiment and found that
300 beech induced a strong rhizosphere effect mostly because of roots exudates and associated
301 microbial community. Further, the PCA scoring plot (Figure 1) highlighted a clear distinction
302 between the soils at 800 m and those at 1000 m, confirming the effect of altitude on soil properties,
303 as commonly was reported by many authors (e.g., Tsui et al., 2004; Seibert et al., 2007; Cioci et al.,
304 2008).

305 Even though the pH was the parameter that most strongly differentiated rhizosphere and bulk on the
306 basis of PCA2, contrasting the two fractions for each horizon, no difference occurred for both
307 $\text{pH}_{\text{H}_2\text{O}}$ and pH_{KCl} . The weak rhizosphere effect on soil pH was ascribed, at least partly, to the
308 sampling period as the reduced winter root activity probably lessened the release of H^+ at the soil-
309 root interface in response to the lowered uptake of cations (Hinsinger et al., 2003). However,
310 Calvaruso et al. (2014), in a study conducted on soil solutions of an acidic beech forest soil,
311 measured lower pH values in the rhizosphere than in the bulk soil during winter, the reverse in
312 spring, and similar pH values in the two fractions in fall. In our case, the scarcity of pH differences
313 between rhizosphere and bulk could be also ascribed to the nature of the parent material, whose

314 carbonate content makes the rhizosphere little susceptible to acidification as *i)* the carbonate
315 dissolution neutralizes the activity of the released protons (Agnelli et al., 2016), and *ii)* the rate of
316 chemical weathering and decarbonation in mountain soils is minor than at lower altitudes (Riebe et
317 al., 2004). However, these observations support the higher pH values that we found for both
318 rhizosphere and bulk of the soils at the higher elevation.

319 The TOC and total N content followed a similar decreasing trend with depth for both rhizosphere
320 and bulk soil at the two altitudes. This result was expected for soils with well-developed A horizons
321 characterized by a strong crumb structure whose cement is mostly made of organics. According to
322 several authors (e.g., Lemenih and Itanna, 2004; Dai and Huang, 2006; Follett et al., 2012), the
323 higher content of TOC and total N at 1000 than at 800 m was related to climatic conditions and,
324 among those, mostly to the temperature, which drops with increasing altitude; in contrast, the
325 precipitation generally do not follow such a clear altitudinal trend (Körner, 2007; Griffiths et al.,
326 2009). The accumulation of higher amounts of organic matter at 1000 m may have been fostered by
327 the combination of the different effects caused by the lower temperature on the plant biomass
328 production and on the activity of the soil microbial community. Although the plant biomass
329 production decreases with increasing altitude (Zianis and Mencuccini, 2005), the higher amounts of
330 TOC happens because of a lower microbial activity, which is due to colder soil temperatures
331 occurring at higher elevations (Blume et al., 2002; Xu et al., 2014). In our study areas, a larger TOC
332 content was found in the rhizosphere than in the bulk in the soils at both altitudes, as it has generally
333 been observed in many different environments (e.g., Turpault et al., 2007; Zhao et al., 2010). As at
334 1000 m the rhizosphere had a larger WEOC content than the respective bulk soil in all the horizons,
335 whereas this did not occur at 800 m, it suggested that beech was able to induce a stronger
336 rhizosphere effect at the higher altitude. The enrichment of WEOC in the rhizosphere is mainly
337 attributed to rhizodeposition processes (Chiang et al., 2006; Tuason and Arocena, 2009), which
338 supply most of the energetic substrates for the rhizosphere microbial community (Koranda et al.,
339 2011; Cesarz et al., 2013). According to Kuzyakov (2002, 2010), the availability of easily

degradable compounds (and their consumption by the microflora) triggers a further mineralization of stable organic matter through the so-called “priming effect”. As a consequence, the rhizosphere priming effect induced by root exudation boosts the organic matter cycling and the microbially-mediated release of nutrients (Kaiser et al., 2011). This process may play a key role in the rhizosphere of the soils at higher altitude, where a scarcer soil development and a generally lowered microbial activity due to climatic constraints limited nutrients availability. The allocation of plant resources in the rhizosphere through rhizodeposition can therefore be seen as a strategy of the plants to overcome ecosystem (nutrient availability) restrictions (Boddy et al., 2008; Massaccesi et al., 2015). The fact that at 800 m the WEOC/TOC ratios for both rhizosphere and bulk were higher than those at 1000 m (data not shown), indicated a more active organic matter cycling occurring at the lower altitude, where the microbial activity has less limitations because of a milder temperature (Pietikäinen et al., 2005; Creamer et al., 2015).

352

4.2. *Altitude and rhizosphere effect on P availability and related enzymatic activities*

In agreement with many previous observations on forest soils, the total P content was mostly made up of organic P, which showed mean contents that are commonly reported for mountain soils (e.g., Makarov et al., 2004; Talkner et al., 2009). According to Turner et al. (2002) and Stutter et al. (2015), the greater concentration of organic P in the soils at 1000 m was attributed to the higher abundance of organic matter in these soils. The dependence of the organic P concentration on soil organic matter content was also confirmed by the TOC:organic P ratio, which showed no difference between the two altitudes and between rhizosphere and bulk soil, although this ratio could be also affected by the amount of available P (Makarov et al., 2004) and P plant uptake (Saikh et al., 1998). As the organic P is the main source of available P in soil (Turner et al., 2014), the larger concentration of available P for both rhizosphere and bulk in the soils at 1000 m was ascribed to a greater alkaline phosphatase activity all throughout these soils, which was probably induced by the larger WEOC and TOC contents (Lemanowicz and Krzyzaniak, 2015; Stutter et al., 2015), and the

366 higher pH of these soils, all factors able to promote the alkaline phosphatase activities (Nannipieri
367 et al., 2011). For the Bw1 and Bw2 horizons, also the acid phosphatase activity was higher in the
368 soils at 1000 m, but in this case the fostering factors were probably only the high contents of
369 WEOC and TOC. The question on whom, between plants roots and rhizosphere microbial
370 community, was the main responsible for the different production of phosphatase in the soils at 800
371 and 1000 m remains open. Previous studies found that the acid and alkaline phosphatase activities
372 are higher in the rhizosphere than in the bulk soil (Marschner et al., 2005; Zhao et al., 2007; Shi et
373 al., 2011) because of rhizodepositions, which fuels the microbial activity and enhances the
374 production of extracellular enzymes in the rhizosphere (Brzostek et al., 2013). However, also the
375 plant roots produce enzymes (Nannipieri et al., 2011; Rejsek et al., 2012). To this regard, in a
376 mesocosm experiment with young *Fagus sylvatica* L., Hofmann et al. (2016) found that plant
377 phosphatases contributed lesser than microbial ones to the total phosphatase activity in P-rich soil.
378 In our case, we hypothesized that the greater alkaline phosphatase activities found in the
379 rhizosphere of the soils at 1000 m was due to the release from both beech roots and a specifically
380 adapted microbial biomass. In the soils at 1000 m, the larger phosphatase activities and the higher
381 availability of easily degradable organics (WEOC) probably counterbalanced the minor microbial
382 activity caused by the lower temperature.

383 The mineralization of organic P compounds by hydrolysis of mononucleotides, sugar phosphates,
384 phosphoproteins and inositol-phosphates via phosphatases is the process responsible for the release
385 of inorganic orthophosphates, which are part of the available P and can be taken up by living
386 organisms (Turner and Haygarth, 2005; Nannipieri et al., 2011). However, no substantial difference
387 in phosphatase activities was found between rhizosphere and bulk soil at both altitudes. Because of
388 this, the larger available P content in the rhizosphere of all the horizons of the soils at 1000 m was
389 attributed to an intense P cycling that, in the soil close to the roots, was triggered by the exudation
390 of labile organic compounds (Ström et al., 2002; Palomo et al., 2006); these would have promoted
391 the microbial activity and the consequent release of P and other nutrients through the organic matter

392 mineralization (Kuziyakov, 2010). Further, the higher content of available P in the rhizosphere
393 compared to the bulk soil may be also favoured by the P uptake, which induces desorption of P
394 from mineral surfaces (Gerke, 2015). However, a P solubilisation due to root release of protons
395 following nutrient uptake and of organic acids cannot be excluded. This latter explanation would be
396 valid even if no pH difference was detected between rhizosphere and bulk soil because of the
397 buffering action of the calcareous parent material, and the complex spatial and temporal pattern of
398 micro-niches occurring in the rhizosphere (Richter et al., 2007; Faget et al., 2013).

399 The hypothesis of a more intense P cycling occurring in the soil close to the roots was not supported
400 by the results of the ^{31}P NMR analysis, as no significantly different proportions of P forms between
401 rhizosphere and bulk soil were detected. This absence of differences between the fractions may be
402 partly attributed to the soil variability (above and belowground) occurring even at the same altitude.

403 The most represented form of the P pools was that made of orthophosphate monoesters, either at
404 800 and 1000 m. This fact was rather expected as inositol-phosphates (which are the main
405 component of the P monoesters) are strongly stabilized in soil by abiotic reactions with minerals,
406 which thereby hinder their biological degradation and favour their accumulation in soil (Turner et
407 al., 2002; Giaveno et al., 2010). The only difference between the sites showed by the NMR spectra
408 was the larger proportion of orthophosphate diesters in the soils at 1000 m. As orthophosphate
409 diesters are considered indicators of microbial P cycling (Stutter et al., 2015), their greater amount
410 at 1000 m than at 800 m supports the occurrence of a general stronger P turnover in the soils at the
411 higher altitude. This is consistent with the concept that high-altitude ecosystems, due to more
412 pronounced nutrient limitations when compared to lower altitude ones, are more dependent on
413 mineralization of soil organic matter by microbial community (Parfitt et al., 2005). Indeed, when
414 the amount of available P in the soil is limited, P is largely immobilized in organic forms
415 (Bünemann et al., 2012).

416

417 **5. Conclusions**

418 In this work we evaluated the rhizosphere effect of beech in forest soils of central Italy, at two
419 altitudes (800 and 1000 m) and along 1° of latitudinal gradient. While the small latitudinal gradient
420 did not affect the rhizosphere and bulk soil properties, significant changes occurred between the
421 soils at the two altitudes, and a marked rhizosphere effect was detected in those at 1000 m. These
422 differences were observed in spite of the spatial and morphological heterogeneity of the forest soils,
423 which possibly affected the extent of the rhizosphere effect at the different altitudes. However, the
424 fact that we tested our hypotheses in natural soils, where above and belowground heterogeneities
425 are independent variables, may be considered as an added value to our research, and indicates that
426 sampling designs able to control the main climatic and physiographic variables may allow obtaining
427 significant results studying *in vivo* rhizosphere.

428 The clear rhizosphere effect that was found at the higher altitude and it was expressed by a greater
429 TOC, WEOC and available P concentrations, was attributed to rhizodepositions, which represent
430 the main source of energetic substrates for the rhizospheric microbial community- The greater
431 availability of easily degradable compounds (WEOC) in the rhizosphere should boost the
432 mineralization of organic matter, which in turn may favour the mineralization of the organic P
433 forms and increase the amount of available P (Figure 7). Therefore, we speculated that at high
434 altitude the energy supplied by the plants through rhizodeposition to the rhizosphere heterotrophic
435 microbial community is key for fuelling the rhizospheric processes and, in particular, P cycling.

436 Our results suggested that an increase of the air temperature of about 1°C, which is expected
437 globally for the year 2050 (IPCC, 2013), and that is equivalent to the temperature shift between our
438 study sites at 800 and 1000 m a.s.l., might cause a shortage of available P in the high altitude beech
439 forest soils.

440

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444

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