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1 **Fungal diversity and specificity in *Cephalanthera damasonium* and *C. longifolia***  
2 **(Orchidaceae) mycorrhizas**

3

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29 Running title: **Mycorrhizal associations in *Cephalanthera* species**

30

31 **Abstract**

32 Orchids depend on mycorrhizal fungi for their nutrition, at least in the early stages of their growth and  
33 development and in many cases throughout the life. In spite of the increasing number of studies  
34 describing fungal diversity in orchids, there is still more to be learnt about the identity of fungal  
35 partners and specificity in orchid mycorrhizal associations. We investigated the fungal communities  
36 associated with the roots of *Cephalanthera damasonium* and *C. longifolia* adult plants, using  
37 morphological methods and fungal ITS-DNA PCR amplification, cloning and sequencing. A range of  
38 fungi belonging to Basidiomycota and Ascomycota was uncovered in the roots of the two investigated  
39 orchid species, showing a low degree of mycorrhizal specificity. At least 11 fungal taxa, including  
40 *Cenococcum geophilum*, *Ceratobasidium* sp., *Exophiala salmonis*, Hymenogastraceae, and  
41 Sebacinaceae colonized *C. damasonium* roots, while about 9 fungal types, such as *Bjerkandera adusta*,  
42 *Phlebia acerina*, Sebacinaceae, *Tetracladium* sp., and *Tomentella* sp. associated with *C. longifolia*.  
43 Phylogenetic and statistical analyses indicated significant differences in the fungal communities  
44 associated with the two studied *Cephalanthera* species, as well as distinct mycorrhizal partners  
45 associated with each orchid plant. Our results strongly suggest that both *C. damasonium* and *C.*  
46 *longifolia* are generalist in their mycorrhizal associations.

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58 **Keywords** Ascomycetes; basidiomycetes; fungal symbionts; mycorrhizal specificity; Orchidaceae;  
59 orchid mycorrhiza.

60

## 61 **1 Introduction**

62 Orchid mycorrhiza is recognized as a distinct type of endomycorrhiza where individual fungal  
63 hyphae cross the orchid cell wall by simple penetration and form pelotons (intracellular coils) in the  
64 cortical tissues of protocorms, roots, tubers and rhizomes, in close connection with the invaginated  
65 plant plasmalemma (Rasmussen, 1995; Smith & Read, 2008).

66 As well as from the anatomical point of view, orchid-fungus associations are unique in their  
67 physiological and nutritional aspects. Indeed, the great majority of plants associate with soil fungi that  
68 usually exchange mineral nutrients for plant carbon (Smith & Read, 1997), whereas orchids are  
69 dependent upon mycorrhizal fungi for the provision of carbohydrates, at least in the early development.  
70 Thus, the polarity of carbon movement in orchid mycorrhiza, occurring from the fungal partner to the  
71 plant, is inverted as compared with the general condition existing in the other mycorrhizal types  
72 (Smith, 1967). Moreover, the relationship between orchids and symbiotic fungi is considered a one-  
73 way system in favour of the plant (Merckx et al., 2009; Rasmussen & Rasmussen, 2009), instead of a  
74 mutualistic association as in the arbuscular mycorrhizas and ectomycorrhizas, with a very few  
75 exceptions (Cameron et al., 2006).

76 This fungus-dependent life style, called mycoheterotrophy (Leake, 1994; Bidartondo & Read,  
77 2008), is a necessity for all orchid species, during the achlorophyllous protocorm stage. At the adult  
78 stage, most orchids develop a photoassimilating apparatus and become autotrophic, although they  
79 continue to rely on their fungal associates for water and mineral salts (Liebel et al., 2010; Girlanda et  
80 al., 2011; Jacquemyn et al., 2011a). On the contrary, some orchid species, growing in forest habitats,  
81 remain dependent on fungal sugars even at maturity. Based on their carbon nutrition, these forest  
82 species can be divided into two physiological types (Dearnaley & Bougoure, 2010). Fully  
83 mycoheterotrophic orchids are achlorophyllous and completely depend on mycorrhizal fungi for their  
84 carbon, throughout their life cycle (Bidartondo et al., 2004; Roy et al., 2009). Partially  
85 mycoheterotrophic orchids, are green and perform photosynthetic carbon fixation, but also obtain  
86 additional carbon from their mycobionts with varying extents, depending on light availability (Preiss et  
87 al., 2010). All studied achlorophyllous orchids associate specifically with narrow phylogenetic fungal  
88 groups (Taylor et al., 2002; Selosse & Roy, 2009), while partially mycoheterotrophic orchids, using  
89 this newly discovered, dual nutritional strategy, also called mixotrophy (Selosse et al., 2004), show a  
90 variable level of mycorrhizal specificity (Julou et al., 2005; Girlanda et al., 2006).

91           The genus *Cephalanthera* Rich. mainly belongs to the latter trophic group. This orchid taxon  
92 comprises a total of 15 species with a mostly Eurasian distribution (Delforge, 2006). Only one species  
93 *C. austinae* (A. Gray) A. Heller, characterised by permanent loss of chlorophyll and strong leaf  
94 reduction, has been found in North America (Colemann, 1995). Seven species are the European  
95 representatives of the genus (Delforge, 2006). Among them, *C. damasonium* (Mill.) Druce and *C.*  
96 *longifolia* (L.) Fritsch have been found to obtain carbon both through photoassimilation and from their  
97 fungal root associates (Gebauer & Mayer, 2003; Julou et al., 2005; Abadie et al., 2006), thus indicating  
98 that these species constitute typical examples of mixotrophic orchids. These two phylogenetically close  
99 orchid species (Bateman et al., 2004) are rhizomatous plants with perennial roots, summer-green and  
100 overwinter underground, growing in broadleaved, coniferous, and mixed forests, often colonizing  
101 shadowy forest edge, between shrubs and trees (Rossi, 2002; Delforge, 2006). Previous studies have  
102 focused on the identification of their mycorrhizal fungi. Fungal diversity in *C. damasonium* has been  
103 assessed in three different works carried out in France, Germany, and Hungary showing that this orchid  
104 associates with a variety of both basidiomycetes and ascomycetes (Bidartondo et al., 2004; Julou et al.,  
105 2005; Illyes et al., 2010), while Abadie et al. (2006) and Liebel et al. (2010) have respectively  
106 demonstrated that *C. longifolia* associates with several fungal taxa, such as Thelephoraceae and  
107 Sebacinaceae, in Estonia, whereas *Hebeloma*, *Russula*, and *Tomentella* are the main mycorrhizal fungi  
108 in the same orchid species collected in Italy. All these studies have reported on mycorrhizal diversity in  
109 only one of the two *Cephalanthera* species, analysing a small number of samples (four *C. damasonium*  
110 individuals in Julou et al. (2005) and Bidartondo et al. (2004), only two *C. longifolia* adult plants in  
111 Liebel et al. (2010)), from a single sampling site. Very different environmental conditions have been  
112 described for the sampling sites investigated in the above mentioned works. These conditions, together  
113 with the geographical distance between studied areas, may influence the fungal community in each site  
114 (Gale et al., 2010; McCormick & Jacquemyn, 2014), and hence make difficult to understand whether  
115 the mycorrhizal diversity up to now reported in *C. damasonium* and *C. longifolia* reflects the ecological  
116 preference of the two orchid species or is mainly a consequence of local factors. Therefore, the degree  
117 of mycorrhizal specificity in *C. damasonium* and *C. longifolia* is still uncertain. The extent of  
118 specificity towards fungi shown by these two orchid species has been previously investigated just in a  
119 single work, carried out by Bidartondo & Read (2008). Specificity of orchid-fungus relationships has  
120 an important role in orchid biology and conservation (Jacquemyn et al., 2010; Phillips et al., 2011).

121 Orchid species that establish generalist associations with multiple fungal symbionts may be more  
122 adaptive under changing environmental condition or in fragmented habitats than orchids that associate  
123 with only a few fungal partners (Swarts & Dixon, 2009). On the other hand, specialist orchid taxa may  
124 increase their fitness in specific habitats or under a narrow range of environmental conditions by  
125 selecting a specific, highly ecologically competent fungal symbiont (Bonnardeaux et al., 2007), but this  
126 high degree of mycorrhizal specificity may be linked to orchid rarity when the fungal partner has a  
127 limited distribution (Swarts et al., 2010).

128 In this study, we analysed fungal diversity and specificity in *C. damasonium* and *C. longifolia*  
129 mycorrhizal associations, using morphological and molecular methods. Orchid roots were collected  
130 from different sites, both total root DNA and DNA from isolated fungi were extracted and fungal ITS  
131 regions were PCR amplified, cloned and sequenced.

132 First, we investigated for each species whether an association with different fungal partners  
133 might occur in different sites. Second, we assessed specificity between the two orchids and their  
134 mycobionts by analysing the phylogenetic distance of their fungal associates. Finally, we tested  
135 mycorrhizal specificity for the studied orchid species by determining whether they associate with the  
136 same fungi when they grow in sympatric populations or they maintain distinct mycorrhizal diversity.

137

## 138 **2 Materials and methods**

### 139 *2.1 Study sites and sampling*

140 *Cephalanthera damasonium* and *C. longifolia* plants were sampled from nine forest edge sites  
141 located in three geographically distinct protected areas in Tuscany (Central Italy), “Monte Cetona”,  
142 “Monte Penna” (specifically on “Monte Rotondo”), and “Cornate di Gerfalco” Natural Reserves,  
143 characterized by the presence of dry calcareous meadow habitats with *Bromus erectus* Hudson  
144 dominating among herbaceous plants, surrounded by forests with various broad-lived species such as  
145 *Fagus sylvatica* L., *Quercus cerris* L., *Ostrya carpinifolia* Scop., and *Acer* sp.pl. mixed with conifers  
146 such as *Pinus nigra* Arnold. The study sites lie on the top of mountains, at an altitude ranging from  
147 755 to 1026 m a.s.l.

148 The two analysed orchid species were growing together only in one (“Monte Rotondo”) out of  
149 the three investigated areas.

150           During the early summer in 2007 and 2008, at orchid flowering, root samples were collected  
151 from a total of eleven individuals for each studied *Cephalanthera* species (six *C. longifolia* individuals  
152 in “Cornate di Gerfalco”, six *C. damasonium* in “Monte Cetona”, and five plants for each species in  
153 “Monte Rotondo”). All roots were washed under running water, carefully brushed, and treated in an  
154 ultrasonic bath (three cycles of 30 s each) in order to remove soil debris and to minimize the detection  
155 of microorganisms adhering to the root surface. Fresh root samples were cut into 1 cm long pieces and  
156 their mycorrhizal morphology was observed under a light microscope, on thin cross sections. Root  
157 portions exhibiting high fungal colonization were partly processed for fungal isolation and partly  
158 frozen in liquid nitrogen and stored at -80°C for molecular analysis.

159

## 160 2.2 Fungal isolation

161           Fresh orchid root fragments were immediately processed after sampling. Five or six roots per  
162 plant were surface-sterilized with consecutive washes of 5% sodium hypochlorite (30 s) and three  
163 rinses of sterile water. Ten 3-5 mm long pieces from each root were cultured in malt extract agar  
164 (MEA) and potato dextrose agar (PDA) amended with gentamycin (40 mg/l) and/or chloramphenicol  
165 (50 µg/ml). Petri dishes were incubated at room temperature in the dark for up to two months to allow  
166 the development of slow-growing mycelia.

167

## 168 2.3 Molecular identification of orchid root fungi

169           Both total DNA from orchid root samples and DNA from isolated fungi were extracted using  
170 the cetyltrimethyl ammonium bromide (CTAB) procedure modified from Doyle & Doyle (1990).

171           Fungal ITS regions were PCR amplified using the primer pair ITS1F/ITS4 (Gardes & Bruns,  
172 1993) in 50 µL reaction volume, containing 38 µL steril distilled water, 5 µL 10 × buffer (100 mM Tris-  
173 HCl pH 8.3, 500 mM KCl, 11 mM MgCl<sub>2</sub>, 0.1% gelatine), 1 µL 10 mM dNTP, 1 µL of each primer  
174 (ITS1F and ITS4), 1.5 U of RED *Taq*<sup>TM</sup> DNA polymerase (Sigma) and 2.5 µL of extracted genomic  
175 DNA at the appropriate dilution. Amplifications were performed in a PerkinElmer/Cetus DNA thermal  
176 cycler, under the following thermal conditions: 1 cycle of 95°C for 5 min, 30 cycles of 94°C for 40 s,  
177 55°C for 45 s, 72°C for 40 s, 1 cycle of 72°C for 7 min. The resulting PCR products were  
178 electrophoresed in 1% agarose gel with ethidium bromide and purified with the QIAEX II Gel  
179 Extraction Kit (QIAGEN) following the manufacturer’s instructions.

180 The purified ITS fragments were cloned into pGEM-T (Promega) vectors that were used to  
181 transform XL-2 Blue ultracompetent cells (Stratagene). After transformation, twenty white colonies per  
182 plant were randomly taken and transferred to a fresh LB (Luria Broth) plate and the bacterial cells  
183 lysed at 95°C for 10 min. Plasmid inserts were amplified using the ITS1F and ITS4 primers under the  
184 following conditions: 94°C for 5 min (1 cycle); 94°C for 30 s, 55°C for 45 s, 72°C for 1 min (25  
185 cycles); 72°C for 7 min (1 cycle).

186 Cloned ITS inserts were purified with Plasmid Purification Kit (QIAGEN) and sequenced  
187 with the same primer pair used for amplification. Dye sequencing was carried out on ABI 310 DNA  
188 Sequencer (Applied Biosystems, Carlsbad, California, USA).

189 Sequences were edited to remove vector sequence and to ensure correct orientation and  
190 assembled using the program Sequencher 4.1 for MacOSX from Genes Codes (Ann Arbor, Michigan).  
191 Sequence analysis was conducted with BLAST searches against the National Center for Biotechnology  
192 Information (NCBI) sequence database (GenBank, <http://www.ncbi.nlm.nih.gov/BLAST/index.html>)  
193 to determine closest sequence matches allowing taxonomic identification. DNA sequences were  
194 deposited in GenBank (Accession Numbers KT1222767–KT1222789).

195 Phylogenetic analysis was conducted using the software Mega v. 5.0 (Tamura et al., 2011).  
196 Sequences were aligned with Clustal X v. 2.0 (Larkin et al., 2007). Both a neighbour-joining tree and a  
197 maximum likelihood tree against selected database sequences were constructed using Kimura 2-  
198 parameter distances, with bootstrapping of 1000 replicates (Felsenstein, 1985). A *Geastrum* species (*G.*  
199 *schmidelii* Vittad.) was used as outgroup to root the tree, following Weiss et al. (2004).

200

#### 201 2.4 Statistical analysis

202 In order to test the hypothesis that the two orchid species differ in terms of fungal  
203 communities, we calculated a community dissimilarity matrix using the Jaccard index on the individual  
204 plant-fungal taxon binary matrix and applied a PERMANOVA test to this matrix (McArdle &  
205 Anderson, 2001; Anderson, 2001; Legendre & Legendre, 1998; Oksanen et al., 2011). PERMANOVA  
206 is a non-parametric equivalent of MANOVA and solves all the issues that may affect the application of  
207 MANOVA to ecological matrices, especially binary ones. The main focus of the analysis was the factor  
208 “Orchid species”: to avoid spurious effects due to sampling sites and spatial positions of samples, we  
209 tested for the main factor after statistically removing the effects of all other confounding factors. In any



210 case, factors such as “sampling site” did not have statistically significant effects on the fungal  
211 assemblage.

212 We compared fungal taxa richness between different orchid species and sites using rarefaction  
213 curves to “standardize” comparisons. We used various richness estimators (only Chao estimator is  
214 reported) to generate sample-based rarefaction curves of species richness and associated 95% CI.

215 All analyses were conducted with R version 3.0.2 (R Development Core Team, 2011) and the  
216 vegan package (Oksanen et al., 2011).

217

## 218 **3 Results**

### 219 *3.1 Microscopical features of Cephalanthera mycorrhizal roots and fungal isolation*

220 All *Cephalanthera* individuals collected in the three studied areas were dissected and  
221 examined. Microscopical observation clearly showed that both *C. damasonium* and *C. longifolia* roots  
222 were extensively colonized by fungi forming pelotons, dense intracellular hyphal coils, predominantly  
223 confined to the cortical cells and just marginally approaching the central stele (Fig. 1a, b, c). Fungal  
224 hyphae emanating from pelotons mostly appeared to be dark, septate and clamped, measuring 10-12  
225  $\mu\text{m}$  in diameter (Fig. 1d). Given the paucity of distinctive morphological characters, taxonomic  
226 delimitation of the orchid root associated fungi, based on microscopy, was extremely limited. These  
227 mycobionts were subsequently identified using molecular taxonomy.

228 Fungal *in vitro* isolation was in most cases unsuccessful or just yielded endophytic  
229 ascomycetous fungi, such as *Fusarium* strains, playing an ambiguous role in orchid-fungus interactions  
230 (Tondello et al., 2012; Pecoraro et al., 2015). However, mycelia that could be morphologically  
231 assigned to basidiomycetes by the presence of clamp connections were isolated from two *C. longifolia*  
232 plants, MR8 and CG1, respectively collected in “Monte Rotondo” and “Cornate di Gerfalco”.  
233 Ribosomal gene sequence analysis of these isolated fungi was further performed in order to assess their  
234 identity.

235

### 236 *3.2 Molecular assessment of fungal diversity in C. damasonium and C. longifolia*

237 Molecular approach revealed several fungal taxa colonizing *C. damasonium* and *C. longifolia*  
238 roots. Total DNA was extracted both from root tissues and from fungal cultures. PCR products with the  
239 ITS1F/ITS4 primer combination were obtained from 8 out of 11 analysed plants for each orchid

240 species. Fungal ITS sequencing following direct amplification of total orchid root DNA indicated that  
241 the two analysed orchid species were mostly associated with different fungal types (Table 1), even  
242 when sampled in sympatric populations, with only one exception represented by *Sebacina* species  
243 found both in *C. damasonium* (samples MC1 and MC4) and *C. longifolia* (sample CG4) from different  
244 areas. *Sebacina* sequences from the investigated orchids could be aligned with sequences from a  
245 variety of orchid and non-orchid plant species, as well as from fungal strains and fruitbodies. Both the  
246 neighbour-joining and the maximum likelihood trees showed that the *Sebacina*-like fungi identified in  
247 this work are phylogenetically close to other Sebacinaceae including *Sebacina incrustans* (Pers.) Tul.  
248 & C. Tul. and an uncultured ectomycorrhizal fungus associated with *Tuber magnatum* Picco in a  
249 natural truffle-ground from Italy (AJ879657), that formed a clade with the sequence from *C. longifolia*  
250 sample CG4, while Sebacinaceae sequences amplified from *C. damasonium* sample MC4 (clones a and  
251 b) and MC1 (clone e) respectively clustered with a sebacinoid fungus previously found in  
252 ectomycorrhizal root tip from *Tilia* sp. in Austria (AF509964) and with a mycobiont (AF440653) from  
253 roots of *Neottia nidus-avis* (L.) L.C. Rich. collected in France (100% bootstrap support, Figs. 2, 3).

254 As regards other fungal taxa collected from the roots of the studied orchids, results showed  
255 that *C. damasonium* associated with fungi belonging to Hymenogastraceae family, both in “Monte  
256 Cetona” and “Monte Rotondo” sampling areas (Table 1). Sequence from *C. damasonium* sample MC3  
257 matched instead a sequence from *Ceratobasidium* sp. found in *Fragaria ananassa* Duch. The closest  
258 match for sample MC1 clone a was with *Cenococcum geophilum* Fr. from *F. sylvatica* in France,  
259 whereas clone d from sample MC4 shared 96% (over 881 bp) of similarity with an ascomycete  
260 detected on ectomycorrhizal root tips from an oak-dominated tropical montane cloud forest in Mexico.  
261 In “Monte Rotondo” Natural Reserve, the main fungal root associate of *C. damasonium* sample MR2  
262 was a fungus with identity to Pezizomycetes found in *C. damasonium* roots in France.

263 By contrast, *C. longifolia* was found to be associated with *Tomentella* species in “Monte  
264 Rotondo” (Table 1). ITS sequencing of DNA extracted from basidiomycetous isolates obtained from *C.*  
265 *longifolia* showed that the studied orchid was associated with fungi belonging to Meruliaceae,  
266 *Bjerkandera adusta* (Willd.) P. Karst. from sample MR8 and *Phlebia acerina* Peck from sample CG1,  
267 in the two investigated areas.

268 Ascomycetes such as *Davidiella macrospora* (Kleb.) Crous & U. Braun, *Exophiala salmonis*  
269 J.W. Carmich., *Neonectria radicola* (Gerlach & L. Nilsson) Mantiri & Samuels, *Tetracladium* sp. and  
270 *Fusarium* sp. were sporadically found in the two analysed orchid species.

271

#### 272 *Statistical results*

273 There was not statistical difference between the fungal communities associated with the two  
274 orchid species. This negative result is due to the fact that each and every individual plant possess one or  
275 two fungal associates but the identity of the fungi changes from plant to plant, and so between the two  
276 orchid species: there is not a set of fungi uniquely associated with an orchid species. Overall, this result  
277 implies a thorough fungal compositional turnover from plant to plant and high number of fungal taxa  
278 retrieved on a collection of plants belonging to the same orchid species, with no difference in richness  
279 between orchid species. For example, the estimated mean ( $\pm 95\%$  CI) number of fungal taxa was  $26 \pm$   
280  $14$  for *C. damasonium* and  $30 \pm 22$  for *C. longifolia*.

281

#### 282 **4 Discussion**

283 The accurate analysis of fungal diversity associated with *C. damasonium* and *C. longifolia*  
284 performed in the present work, using fungal isolation, microscopy, and DNA sequencing, uncovered a  
285 range of fungi in the roots of the investigated orchids.

286 The first evidence of the establishment of orchid-fungus associations in the studied orchid  
287 species was provided by microscopic observations, showing abundant pelotons in the sampled root  
288 cells, which represent the main morphological aspect of orchid mycorrhiza (Rasmussen, 1995;  
289 Kristiansen et al., 2001).

290 In spite of the poor success in the isolation of fungal associates from the analysed  
291 *Cephalanthera* plant roots, culture-dependent methods complemented PCR-based approach, as the  
292 basidiomycetes isolated from *C. longifolia* yielded ITS sequences that were not amplified using direct  
293 total orchid root DNA amplification. These fungal isolates from samples MR8 and CG1 respectively  
294 showed close identity to *B. adusta* and *P. acerina*, two species of wood-decaying fungi, in the  
295 Meruliaceae family, that colonize both hardwood and conifer wood, and are capable of degrading a  
296 variety of substrates by secreting specific enzymes (Nakasone & Sytsma, 1993; Romero et al., 2007).  
297 Wood-inhabiting fungal species have been previously identified in orchid mycorrhizal associations.

298 *Erythromyces crocicreas* (Berk. & Broome) Hjortstam & Ryvarden has been found to support seed  
299 germination and to be effective for further development of the orchid *Galeola altissima* (Bl.) Reichb. f.  
300 (Umata, 1995), while *Armillaria mellea* (Vahl) P. Kumm. has been shown to associate with *Gastrodia*  
301 *elata* Blume (Kusano, 1911; Kikuchi et al., 2008). *Resinicium* sp., that is a member of Meruliaceae, has  
302 been identified by Martos et al., (2009) in *Gastrodia similis* Bosser mycorrhizal roots, using molecular  
303 methods. Our findings of Meruliaceae fungi in the roots of *C. longifolia* could support the hypothesis  
304 of a trophic relationship between the studied orchid and wood-inhabiting fungal taxa, although further  
305 analyses are needed to verify this hypothesis.

306 A range of fungi was identified through fungal ITS sequencing from amplified total orchid  
307 root DNA. Neither *C. damasonium* nor *C. longifolia* were associated with a dominant fungal taxon,  
308 thus showing a low level of mycorrhizal specificity that is consistent with their mixotrophic life style  
309 (Selosse et al., 2004; Dearnaley et al., 2012). To date, specificity in associations between  
310 *Cephalanthera* species and fungal symbionts has been controversial. Previous studies have been mostly  
311 based on a very limited number of *Cephalanthera* plant samples collected in a single site. As a  
312 consequence, results obtained from these studies could not provide a clear picture of fungal diversity  
313 associated with *C. damasonium* and *C. longifolia*, and therefore, exhaustive information on their  
314 mycorrhizal specificity has been hardly available. Bidartondo et al. (2004) and Liebel et al. (2010) have  
315 found low degree of mycorrhizal specificity in *C. damasonium* and *C. longifolia* respectively, the  
316 fungal associates being *Cortinarius*, *Hymenogaster*, *Inocybe*, *Thelephora*, and *Tomentella* in *C.*  
317 *damasonium*, while *C. longifolia* has been found to associate with *Hebeloma*, *Russula*, and *Tomentella*.  
318 On the contrary, Abadie et al. (2006) have shown a very specific association between *C. longifolia* and  
319 Thelephoraceae considering that all ITS, in a typing of fungal ITS on 60 orchid root pieces (from 7  
320 plants) harbouring pelotons, were from thelephoroid fungi, with the exception of two root pieces  
321 exhibiting ITS from a Sebacinaceae and an ascomycete belonging to *Wilcoxina*. Interesting information  
322 about mycorrhizal associations in *C. damasonium* has been provided by Julou et al. (2005). These  
323 authors have amplified a number of asco- and basidiomycetes sequences from 4 *C. damasonium*  
324 samples collected from a single population in France, using ITS sequencing. Among these sequenced  
325 fungi, Thelephoraceae, Cortinariaceae (including *Hymenogaster*), and Pezizomycetes (including  
326 Helotiales, Pezizales, *Tuber*, *Phialophora*, and *Leptodontidium*) were over-represented. One *Sebacina*  
327 and one *Ceratobasidium* sequences were also amplified from the same orchid plants. Julou and co-

328 authors, in the analysis of data collected during their investigation, have proposed a quite specific  
329 mycorrhizal association between *C. damasonium*, Thelephoraceae and Cortinariaceae, but at the same  
330 time, they have not excluded a symbiotic role for the other fungal taxa identified from the studied  
331 orchid roots. The only one previous work, in which *C. damasonium* and *C. longifolia* have been  
332 investigated together, for their mycorrhizal associations, has reported on a high degree of specificity in  
333 the relationship between the two investigated orchids and Thelephoraceae fungi during the seedling  
334 stage, while mycorrhizal specificity was lower in different plant life stages (Bidartondo & Read, 2008).  
335 Indeed, these authors have found seedlings of both *Cephalanthera* species to associate with only a  
336 subset of the thelephoroid fungi capable of stimulating seed germination, and to lack completely  
337 Cortinariaceae and Sebacinaceae that have been collected from germinating seeds and mature plants.  
338 The present study, based on the analysis of 22 orchid samples from three geographically distinct  
339 protected areas to allow statistical validation, revealed at least 11 fungal taxa colonizing *C.*  
340 *damasonium* roots, while about 9 endophytic fungal types were found to associate with *C. longifolia*  
341 (Table 1). Such a large diversity of fungal associates strongly suggests that both *C. damasonium* and *C.*  
342 *longifolia* are generalist in their mycorrhizal associations. Statistical analyses clearly show distinct  
343 fungal communities associated with each and every orchid plant individual, irrespective of the orchid  
344 species and the site of origin.

345 We mainly found different fungal associates in the two investigated orchids (Table 1).  
346 *Sebacina* represents the only putative mycorrhizal fungus that was associated with both *C. damasonium*  
347 (two plants on “Monte Cetona”) and *C. longifolia* (one plant on “Cornate di Gerfalco”). Phylogenetic  
348 analysis suggests that the sequences of sebacinoid fungi amplified from the studied orchids are  
349 sufficiently different to include at least three related species (Figs. 2, 3). *C. longifolia* mycobiont has  
350 close affinity with *S. incrustans* previously found in symbiotic relationship with the achlorophyllous  
351 orchid *N. nidus-avis* (Selosse et al., 2002) and with Sebacinaceae playing a symbiotic role in  
352 unidentified morphotypes of ectomycorrhizal tips collected in a truffle-ground by Murat et al. (2005).  
353 *C. damasonium* sebacinoid associates are instead phylogenetically close to Sebacinaceae that have been  
354 previously found to establish mycorrhizal associations with orchid (Selosse et al., 2002) and non-orchid  
355 plants (Urban et al., 2003). Sebacinoid basidiomycetes show a remarkable diversity of mycorrhizal  
356 types (Weiss et al., 2004). Moreover, Sebacinoid mycobionts can support the myco-heterotrophic  
357 growth of achlorophyllous orchids (McKendrick et al., 2002; Selosse et al., 2002; Taylor et al., 2003)

358 as well as they can play a functional role in association with chlorophyllous orchid species  
359 (Bonnardeaux et al., 2007; Wright et al., 2010). Considering the puzzling variety of symbiotic plant-  
360 fungus associations in which Sebacinaceae are involved, including orchid mycorrhizas, we speculate  
361 that sebacinoid fungi found in the present study from the roots of *C. damasonium* and *C. longifolia*,  
362 may play a trophic role in their relationship with the analysed orchids. Much further work is required to  
363 provide an integrated view of *Sebacina-Cephalanthera* interactions based on morphological,  
364 molecular, and physiological data.

365 Together with *Sebacina*, another fungal taxon belonging to the anamorphic form genus  
366 *Rhizoctonia* was associated with only one of the two analysed orchids, the best match for the sequence  
367 amplified from *C. damasonium* sample MC3 being with *Ceratobasidium* sp. collected by Sharon et al.  
368 (2007) from *F. ananassa* in Israel. Ceratobasidioid fungi have been found in symbiotic associations  
369 with terrestrial orchids from both forests and meadows, as well as epiphytic orchids (Shefferson et al.,  
370 2005; Otero et al., 2005; Otero et al., 2007, 2011; Irwin et al., 2007; Yagame et al., 2008, 2012;  
371 Girlanda et al., 2011; Jacquemyn et al., 2011a, b; Pecoraro et al., 2012a; Tondello et al., 2012).  
372 Moreover, the trophic relationship between a *Ceratobasidium* species *C. cornigerum* (Bourdot) D.P.  
373 Rogers and the green forest orchid *Goodyera repens* (L.) R. Br. represents the first known example of  
374 mutualistic mycorrhiza in orchids (Cameron et al., 2006). The second best match for the  
375 *Ceratobasidium* sequence that was amplified from *C. damasonium* in the present work is with *C.*  
376 *cornigerum* (isolate XSD-44, Jiang et al., unpublished, GenBank record EU273525). We propose the  
377 role of symbiont for this *Ceratobasidium* taxon associated with the roots of *C. damasonium*, although  
378 the confirmation of its exact physiological role would require detailed analyses.

379 Ectomycorrhizal (ECM) fungi were also found to colonize the roots of the two investigated  
380 *Cephalanthera* species. Hymenogastraceae were collected from 37,5 % of *C. damasonium* analysed  
381 plants, being the only fungal partners associated with the studied orchid in both of the two geographical  
382 distinct sampling areas (“Monte Cetona” and “Monte Rotondo”, see Table 1). All the  
383 Hymenogastraceae sequences amplified in the present work had the same BLAST search closest match  
384 with a *C. damasonium* mycorrhizal symbiont (GenBank accession code AY634136) collected by  
385 Bidartondo et al. (2004) from orchid root samples, in a German forest site. Identification of *C.*  
386 *damasonium* mycobiont as a member of Hymenogastraceae family is supported by the high similarity  
387 that the sequences collected in the present study also showed, as their second best match, with

388 sequences amplified from *Hymenogaster bulliardii* Vittad. (Peintner et al., 2001) and *H. citrinus*  
389 Vittad. (Brock et al., 2009) specimens deposited in herbaria. ECM thelephoroid basidiomycetes  
390 belonging to *Tomentella* were instead associated with *C. longifolia* in “Monte Rotondo” Natural  
391 Reserve. Tomentelloid fungi found in the roots of the studied orchid shared similarity with *Tomentella*  
392 species involved in ectomycorrhizal associations with several tree species growing in boreal forests  
393 (Tedersoo et al., 2003; Kjølner, 2006; Bidartondo & Read, 2008). In particular, *Tomentella* taxa  
394 detected in tree ectomycorrhizas in England by Bidartondo & Read (2008) have been shown to support  
395 both *C. damasonium* and *C. longifolia* seed germination, seedling development and adult plant growth.  
396 Symbiotic associations with thelephoroid fungi have previously been reported in several  
397 *Cephalanthera* species including *C. austinae* (Taylor & Bruns, 1997), *C. damasonium* (Bidartondo et  
398 al., 2004; Julou et al., 2005; Bidartondo & Read, 2008), *C. erecta* Blume (Matsuda et al., 2009), *C.*  
399 *falcata* Blume (Yamato & Iwase, 2008; Matsuda et al., 2009), *C. longifolia* (Abadie et al., 2006;  
400 Bidartondo & Read, 2008; Liebel et al., 2010), and *C. rubra* Rich. (Bidartondo et al., 2004). Yagame &  
401 Yamato (2012) demonstrated the establishment of tripartite symbioses between the mycoheterotrophic  
402 orchid *C. falcata*, Thelephoraceae fungi, and *Quercus serrata* Murray (Fagaceae), in culture condition.

403         The simultaneous association with rhizoctonia-forming fungi and ECM fungal groups is a  
404 noteworthy aspect of mycorrhizal diversity in the analysed *Cephalanthera* species. This feature  
405 suggests that *C. damasonium* and *C. longifolia* represent an intermediate step in the evolution from  
406 fully photosynthetic orchids, mostly associated with *Rhizoctonia*-like fungi, to fully mycoheterotrophic  
407 orchids, often found in symbiosis with ECM fungal associates (Bidartondo et al., 2004; Motomura et  
408 al., 2010; Dearnaley et al., 2012). It has been previously suggested by Taylor and Bruns (1997) that the  
409 achlorophyllous mycoheterotrophic *Cephalanthera* species *C. austinae* evolved from autotrophic  
410 ancestors by switching from *Rhizoctonia* to thelephoroid fungal partners, as a probable adaptation for  
411 colonizing dark, understory habitats.

412         Other fungal ITS sequences sporadically collected from the roots of the studied orchid species  
413 deserve to be discussed. Several mycorrhizal fungi previously found in a variety of environmental  
414 sources, such as *C. geophilum* from *F. sylvatica* ECM root tips (Buée et al., 2005), an ectomycorrhizal  
415 ascomycete from root tips in a tropical cloud Mexican forest (Morris et al., 2008), and pezizomycetes  
416 from orchid roots (Julou et al., 2005) were the best matches for sequences detected in *C. damasonium*.  
417 We cannot exclude that these fungal associates may be involved in a trophic relationship with the

418 analysed orchid. They could represent occasional symbionts for mycorrhizal associations that the  
419 investigated orchid explores, looking for the best partners available from the fungal community that  
420 characterizes a particular habitat.

421 A fungal taxon with 99% identity to *Tetracladium* sp. found in orchid roots (Abadie et al.,  
422 2006) and mycorrhizal roots of conifer seedlings (Menkis et al., 2005) was identified in *C. longifolia*.  
423 The genus *Tetracladium* is a member of the so-called Ingoldian fungi, asexual microfungi commonly  
424 occurring on dead plant material, in running freshwater (Bärlocher, 1992). These aquatic hyphomycetes  
425 have been recently found as endophytes in several plant tissues, including orchid roots (Abadie et al.,  
426 2006; Vendramin et al., 2010). Selosse et al. (2008) proposed that some Ingoldian fungi spend part of  
427 their life in plants and use water for dispersion. These authors suggested to investigate the impact of  
428 Ingoldian fungi on plant species, during their endophytic life stage, in order to test their protective  
429 effects on hosts. Other putative endophytic fungi, with a diverse and mostly unknown ecology, were  
430 detected in the studied orchids. Among them, *E. salmonis* was found in the roots of *C. damasonium*  
431 sample MR2, showing similarity with a fungal strain collected from *Salmo clarkii* (Untereiner &  
432 Naveau, 1999). *Exophiala salmonis* has been reported from the roots of several orchid species, such as  
433 *Orchis pauciflora* Tenore (Pecoraro et al., 2012b) and *Himantoglossum adriaticum* H. Baumann  
434 (Pecoraro et al., 2013) and has been also detected in the roots of *C. damasonium* adult plants by Julou  
435 et al. (2005). Such findings of orchid fungal associates that show a large ecological plasticity and are  
436 capable to play different roles in their interactions with several host organisms deserve further  
437 attention. More studies on their endophytic phase in orchid hosts are necessary to clarify their real  
438 function in colonized plants. These intriguing fungi could represent “unexpected” orchid symbionts  
439 with some important nutritional roles. A better understanding of the real diversity of orchid  
440 mycorrhizal fungi is a fundamental starting point to support any consideration on orchid-fungus  
441 specificity.

442

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680 **Table 1.** Fungal diversity molecularly detected in the analysed orchids. BLAST search closest matches  
681 of fungal ITS-DNA sequences amplified from *C. damasonium* and *C. longifolia* roots collected in  
682 “Monte Cetona” (samples MC1-MC4), “Monte Rotondo” (samples MR1-MR8), and “Cornate di  
683 Gerfalco” (samples CG1-CG4). Sample GenBank accession codes, accession codes for the closest  
684 GenBank matches, sequence identity, and overlap of each match are reported.

| Orchid species                             | Sample                       | Clone    | Site     | GenBank code                                | Best BLAST match(es)                                       | Accession code               | Overlap length | % match |
|--|------------------------------|----------|----------|---|--|------------------------------|----------------|---------|
| <i>C. damasonium</i>                       | MC1                          | a        | B        | KT122776                                    | <i>Cenococcum geophilum</i> (from ectom.)                  | AY299214                     | 610            | 93%     |
|  |                              | c        | B        | KT122777                                    | <i>Cryptococcus carnescens</i>                             | AB105438                     | 854            | 98%     |
|  |                              | e        | B        | KT122778                                    | <i>Sebacina</i> (from <i>N. nidus-avis</i> )               | AF440653                     | 1002           | 96%     |
|  | MC2                          | c        | B        | KT122779                                    | <i>Sebacina aff. epigaea</i>                               | AF490393                     | 841            | 91%     |
|  |                              |          |          |   | <i>Hymenogastraceae</i> (from <i>C. damasonium</i> )       | AY634136                     | 1146           | 98%     |
|  | MC3                          | c        | A        | KT122780                                    | <i>Hymenogaster bulliardii</i>                             | AF325641                     | 1009           | 95%     |
|  |                              |          |          |   | <i>Ceratobasidium</i> sp. (from <i>F. ananassa</i> )       | DQ102416                     | 765            | 87%     |
|  | MC4                          | a        | A        | KT122781                                    | <i>Ceratobasidium cornigerum</i>                           | EU273525                     | 763            | 87%     |
|  |                              |          |          |   | <i>Sebacinaceae</i> (from <i>E. helleborine</i> )          | AY452676                     | 1003           | 96%     |
|  | MR1                          | c        | D        | KT122784                                    | <i>Sebacina</i> (from <i>N. nidus-avis</i> )               | AF440657                     | 806            | 90%     |
|  |                              |          |          |   | <i>Sebacina</i> (from <i>N. nidus-avis</i> )               | AF440647                     | 737            | 90%     |
|  |                              |          |          |   | Ascomycota (from ectomycorrhizal root)                     | EU624334                     | 881            | 96%     |
|  | MR2                          | c        | D        | KT122785                                    | <i>Agaricomycetes</i> (from forest soil)                   | FJ553950                     | 292            | 97%     |
|  |                              |          |          |   | <i>Pezizomycetes</i> (from <i>C. damasonium</i> )          | AY833035                     | 905            | 93%     |
|  | MR3                          | c        | D        | KT122787                                    | <i>Cadophora luteo-olivacea</i>                            | DQ404349                     | 898            | 96%     |
|  |                              |          |          |   | <i>Exophiala salmonis</i>                                  | AF050274                     | 715            | 92%     |
|  |                              |          |          |   | <i>Hymenogastraceae</i> (from <i>C. damasonium</i> )       | AY634136                     | 1013           | 94%     |
|  | MR4                          | b        | D        | KT122789                                    | <i>Hymenogaster citrinus</i>                               | EU784360                     | 928            | 94%     |
|  |                              |          |          |   | <i>Tetracladium furcatum</i>                               | EU883432                     | 739            | 90%     |
|  | <i>C. longifolia</i>         | MR5      | a        | D   | KT122767   | <i>Hymenogaster citrinus</i> | EU784360       | 942     |
| <i>Tomentella</i> (from mycorrhizal roots) |                              |          |          |   |  | EU668200                     | 1170           | 99%     |
| MR6  |                              | e        | D        | KT122769                                    | <i>Tomentella lilacinogrisea</i> (from <i>T. cordata</i> ) | AJ534912                     | 989            | 94%     |
|  |                              |          |          |   | <i>Neonectria radicolica</i> (from mushroom)               | FJ481036                     | 937            | 98%     |
| MR7  |                              | a        | C        | KT122770                                    | <i>Tetracladium</i> sp. (from <i>C. longifolia</i> )       | DQ182426                     | 985            | 99%     |
|  |                              |          |          |   | <i>Tetracladium maxilliforme</i> ( <i>P. sylvestris</i> )  | DQ068996                     | 985            | 99%     |
| MR8  |                              | Isolated | C        | KT122771                                    | <i>Tomentella bryophila</i> (from beech root)              | AM161534                     | 1147           | 98%     |
|  |                              |          |          |   | <i>Tomentella bryophila</i> (from sporocarp)               | AJ889981                     | 1147           | 98%     |
| CG1-4                                      |                              | Isolated | A        | KT122772                                    | Uncultured basidiomycete (from dust)                       | AM901992                     | 1092           | 98%     |
|  |                              |          |          |   | <i>Bjerkandera adusta</i>                                  | AJ006672                     | 1081           | 98%     |
|  | <i>Phlebia acerina</i>       |          |          |   | AB210083   | 1086                         | 98%            |         |
|  | <i>Davidiella macrospora</i> |          |          |   | EU167591   | 886                          | 98%            |         |
| CG3  | a                            | B        | KT122774 | <i>Fusarium</i> sp.                         | EU750682   | 957                          | 99%            |         |
|  |                              |          |          | <i>Sebacinaceae</i> (from mycorrhizal root) | AJ879657   | 1040                         | 98%            |         |
| CG4  | a                            | B        | KT122775 | <i>Sebacina</i> sp.                         | DQ520095   | 1037                         | 98%            |         |
|  |                              |          |          | <i>Sebacina incrustans</i>                  | DQ520095   | 1037                         | 98%            |         |

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690 **Fig. 1.** Microscopical features of *C. longifolia* mycorrhizal roots: **(a)** cross-section showing  
691 intracellular hyphal coils (pelotons). **(b-c)** Details of fungal pelotons in orchid root cells. **(d)** Details of  
692 dark, septate and clamped hyphae emanating from pelotons. Scale bars: 500  $\mu\text{m}$  (a), 200  $\mu\text{m}$  (b), 30  $\mu\text{m}$   
693 (c), 20  $\mu\text{m}$  (d).

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720 **Fig. 2.** Neighbour-joining phylogenetic tree showing the relationship between the Sebacinaceae  
721 sequences obtained from the two analysed *Cephalanthera* species (\*) and selected database relatives.  
722 Kimura 2-parameter distances were used. Bootstrap values are based on percentages of 1000 replicates.  
723 The tree was rooted with *Geastrum schmidelii* as outgroup

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750 **Fig. 3.** Maximum likelihood phylogenetic tree showing the relationship between the Sebacinaceae  
751 sequences obtained from the two analysed *Cephalanthera* species (\*) and selected database relatives.  
752 Kimura 2-parameter distances were used. Bootstrap values are based on percentages of 1000 replicates.  
753 The tree was rooted with *Geastrum schmidelii* as outgroup  
754