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This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1637884> since 2017-05-24T13:58:25Z

Published version:

DOI:10.1016/j.apsoil.2017.03.004

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2 **Wild *Camellia japonica* specimens in the Shimane prefecture (Japan) host previously undescribed AMF**
3 **diversity**

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17 **Abstract**

18 The native range of the broadleaf evergreen *Camellia japonica* L. includes natural non-model
19 ecosystems that have been largely overlooked in the investigation of the diversity of arbuscular mycorrhizal
20 fungi (AMF). Despite a recent overview of the AMF assemblages associated in the naturalized range of *C.*
21 *japonica*, no such survey has ever been carried out within the native range of this plant species. For this reason,
22 we examined through 454 sequencing the diversity and structure of AMF assemblages in camellia roots and
23 surrounding soil from four locations within the Shimane prefecture (Japan), a region that harbors native *C.*
24 *japonica* trees. The specific objectives were as follows: (i) to evaluate the differences between the root-
25 colonizing and the soil-dwelling AMF community through different measurements of diversity and (ii) to
26 evaluate if and how deeply the small-scale environmental changes affect the structure of AMF assemblages.

27 We found that a large number of AMF (~90%) could not be assigned to previously known phylotypes,
28 suggesting the occurrence of several undescribed taxa. Diversity was generally higher in roots than in soil
29 samples and the level of dominance was low. Almost 70% of soil-dwelling AMF were retrieved inside the
30 roots and also community structure was very similar between the two niches. Most AMF clades/genera were
31 infrequent and only *Rhizophagus/Sclerocystis* and *Glomus sensu lato* were very abundant in both root and soil
32 samples. Above all, soil Fe and Mg content, soil C/N ratio, and the distance from the nearest source of saline
33 water were consistently correlated with AMF community shifts at the local scale.

34

35 **Keywords:**

36 arbuscular mycorrhizal fungi, native range, 454 GS-FLX Titanium pyrosequencing, SSU rDNA, Virtual Taxa

37 **1. Introduction**

38 Obligate symbiotic fungi that form arbuscular mycorrhizae (AMF) are among the most important soil
39 microorganisms. AMF facilitate mineral nutrient uptake from the soil and promote water-stress tolerance and
40 resistance to certain diseases, in exchange for plant-assimilated carbon (Smith and Read, 2008), and are
41 therefore considered promising biofertilizers (Berruti et al., 2016a). Different AMF species and isolates differ
42 in life-history (Maherali and Klironomos, 2012; Powell et al., 2009) and functional traits (Fitter et al., 2005;
43 van der Heijden and Scheublin, 2007; Hoeksema et al., 2010). Recent studies have found evidence that AMF
44 communities can be influenced by both environmental (Davison et al., 2011; Helgason et al., 2007; Kohout et
45 al., 2015; Öpik et al., 2009; Torrecillas et al., 2013; Verbruggen et al., 2013) and stochastic factors (Dumbrell
46 et al., 2010; Lekberg et al., 2012), with the contribution of the two varying depending on the ecological context
47 (Caruso et al., 2012). Although several factors notably affect AMF communities, most taxa are ubiquitously
48 found (Dumbrell et al., 2010; Fitter et al., 2005; Öpik et al., 2010, 2009) and apparently reveal very low
49 endemism on the global scale (Davison et al., 2015). While less common AMF tend to associate with host
50 plant species that occupy specific ecological niches, the generalist taxa interact symbiotically with a wide range
51 of host plants, including both native and invasive species, in a broad spectrum of environments (Davison et
52 al., 2011; Moora et al., 2011; Öpik et al., 2013, 2009). In addition, AMF distribution may vary in belowground
53 compartments since spore production rate and amounts of AMF hyphae in roots and soil have been
54 demonstrated to vary substantially in a taxon-specific manner (Hempel et al., 2007; Johnson et al., 2004;
55 Parniske, 2008; Varela-Cervero et al., 2015).

56 The broadleaf evergreen *Camellia japonica* L. (Magnoliophyta, Theales, Theaceae Mirb.) is a
57 mycorrhizal plant species (Berruti et al., 2013) that is traded worldwide as ornamental potted plant. Although
58 naturalized in several European countries, its center of origin resides in Japan (Mondal, 2011). Our research
59 group has already described the AMF communities associated to naturalized specimens of *C. japonica* in parks
60 and gardens around the Lake Maggiore area in Italy (Borriello et al., 2015), and found a strong difference in
61 the community composition between the root-colonizing and the soil-dwelling communities and among the
62 three closely located sites analyzed. The data suggest that different combinations of edaphic properties have a
63 pivotal role in shaping the AMF communities. However, no such study has ever been carried out within *C.*
64 *japonica* native range, which includes natural non-model ecosystems. Wild plants and natural, undisturbed

65 systems have associated with a high diversity of so-called ‘uncultured’ AMF (Ohsowski et al., 2014) and could
66 hide a number of taxa that have been previously overlooked.

67 In the present study, we specifically ask the following: (i) Do the root-colonizing and the soil-dwelling
68 AMF assemblages also differ strongly within the native range of *C. japonica*? (ii) Are small-scale
69 environmental changes more important than stochasticity in driving the structure of AMF assemblages within
70 the native range of *C. japonica*? Are they the same ones found in the naturalized range? To answer these
71 questions we examined the diversity and structure of AMF assemblages, using 454 GS-FLX Titanium
72 pyrosequencing technology, from four different locations within the Shimane prefecture (Japan), a region that
73 harbors native *C. japonica* trees.

74

75

76 **2. Materials and Methods**

77 **2.1. Sampling sites**

78 The research focused on four sites in the Shimane prefecture (Japan), each representative of different
79 soil properties and microclimatic conditions (Table S1). The first sampling site was the Matsue Castle Park
80 (Tonomachi, Matsue; 35.476174, 133.048735; site code - MATSUE), an evergreen oak forest that hosts
81 centennial camellia trees, including specimens of about 400 years old. The second sampling was done in the
82 area neighboring the Shimane University experimental fields (Kami-honjyocho, Matsue; 35.511772,
83 133.109521; site code - SHIMANE), another evergreen oak forest that hosts young camellias (~20 yrs). The
84 third sampling site was located near the village of Sagiura (Taisha-cho, Izumo; 35.444486, 132.686531; site
85 code - SAGIURA), in an evergreen forest of black pines, oaks, and young camellias (~30 yrs), on a hill over
86 the sea. The last sampling site was an evergreen/coniferous forest (Koshibara, Matsue; 35.447749,
87 133.076278; site code - BAMBOO) that hosts young camellia specimens (~30 yrs) and is invaded by
88 *Phyllostachys edulis* (Carrière) J.Houz. (moso bamboo).

89

90 **2.2. Soil and root sampling**

91 Two specimens of *C. japonica* were randomly selected in each of the four sites for a total of eight
92 biological replicates. Samples were collected during the first week of May 2013, during camellia late flowering

93 period. Sampling operations consisted in digging to the first 5-20 cm and collecting fine feeder roots belonging
94 to *C. japonica* and, separately, a portion of bulk soil (ca 1.5 Kg) surrounding the sampled roots. During the
95 digging, the main root branches were carefully followed and young camellia roots were visually recognized
96 and collected. Three root and soil samples were collected from each plant, for a total of 48 samples (24 root
97 samples and 24 bulk soil samples). Bulk soil samples were sieved and roots were washed free of adhering soil,
98 sonicated, and chopped into small fragments (~1 cm). The processed samples were in part frozen in liquid
99 nitrogen and separately stored at -80°C for further molecular analyses. The remaining bulk soil sample were
100 pooled in order to create a composite sample for each of the eight biological replicates and submitted to
101 physicochemical analyses (eight composite samples in total, two biological replicates for each site).

102

103 **2.3. Physicochemical analyses**

104 Electrical conductivity and pH were measured with a pH-meter on 10 g of soil in aqueous extract
105 (soil:water 1:5) according to the standard protocols EN13037 and EN13038. Total carbon and total nitrogen
106 were measured on 0.03 g of soil after complete dry combustion (method ISO 10694) and analyzed with element
107 analyzer NA2100 (CE INSTRUMENTS). Available phosphorous was measured with Olsen method (Olsen et
108 al., 1954). Fe, Ca, Mg, and K were measured on 0.5 g of soil through atomic absorption spectrophotometry
109 (AAAnalyst 400; Perkin Elmer) after digestion with aqua regia (HCl:HNO₃ 3:1; EPA method 3051A).

110

111 **2.4. DNA extractions from soil and roots**

112 Two different extraction kits were used according to the different nature of the sample, soil or roots.
113 DNA extractions (0.5 g of soil each, without roots) from the 24 soil samples were performed using a FastDNA
114 Spin Kit for Soil (MP BIOMEDICALS), according to the manufacturer's recommendations. DNA extractions
115 from the 24 root samples were performed using a DNeasy Plant Mini Kit (QIAGEN, Crawley, UK) on 0.1 g
116 of fresh root material, according to the protocol for frozen samples.

117

118 *Nested PCR and sequencing of the fungal ribosomal (rRNA) gene*

119 Two sets of primers were used to amplify a region of the small subunit (SSU) of the Glomeromycota
120 (the phylum that includes all AMF) ribosomal DNA. The Nested PCR approach used consisted in a first

121 amplification with Glomeromycota-specific primers AML1 and AML2 (Lee et al., 2008) and a following
122 amplification round with tagged-primers AMADF (5'-GGGAGGTAGTGACAATAAATAAC-3', 121
123 nucleotides downstream from AML1 primer; newly designed by Desirò, 2013) and AMDGR (Sato et al., 2005)
124 which specifically amplifies ~423 bp (size suitable for 454 GS-FLX System) of the V3-V4 variable domains
125 within the 18S rDNA gene of AMF. PCR was carried out in 20 µl of a PCR reaction mix containing 2 µl of
126 template DNA, 4 µl of 5X Phusion HF Buffer, 0.2 mM dNTPs, 0.5 µM of each primer, and 0.4 U of Phusion®
127 High-Fidelity DNA Polymerase (FINNZYMES, Finland). Amplifications were carried out in 0.2 ml PCR tubes
128 using a Biometra T Gradient thermocycler according to the following steps: 5 min initial denaturation at 94°C;
129 35 cycles of 1 min at 94°C, 1 min at 58°C and 57°C for the two Nested PCR rounds, respectively, 1 min at
130 72°C; and a final elongation of 10 min at 72°C. A negative control was included in the PCR to check for
131 contamination. All PCR products were checked using 1.5% agarose gel stained with ethidium bromide (Sigma-
132 Aldrich). The PCR products bearing the same tags and coming from the three root or soil samples taken from
133 the same plant were pooled in order to create sixteen composite samples (eight biological replicates for both
134 roots and soil) and purified using the Wizard® SV Gel and PCR Clean-Up System kit (Promega). These sixteen
135 purified PCR products were equimolarly pooled and sequenced through 454 GS-FLX Titanium
136 pyrosequencing technology (Beckman Coulter).

137

138 **2.5. Sequence analyses and classification**

139 Raw sequencing data were treated with the open-source mothur v1.33 for Mac (Schloss et al., 2009).
140 Denoising of the flowgrams was performed using the PyroNoise algorithm (Quince et al., 2009). Tags and
141 adaptors were trimmed off. Then, sequences with ambiguous nucleotides, shorter than 350 bp or with
142 homopolymers longer than 13 bp were removed. Sequences were aligned and clustered according to a genetic
143 distance matrix computed using the *dist.seqs()* command in mothur, setting the “countends” parameter to false.
144 OTU picking was performed using the default Average Neighbor clustering method, implemented by mothur,
145 setting a 3% dissimilarity cutoff. Although this distance cutoff is arbitrary and can be considered controversial,
146 it was chosen on the basis of previous studies on AMF biodiversity (Borriello et al., 2015; Lumini et al., 2010).
147 Moreover, a recent study has demonstrated how the choice of the OTU delineation method negligibly affects
148 the interpretation of AMF community patterns (Lekberg et al., 2014). The most abundant unique sequence of

149 each cluster was selected as OTU representative. Pruning of OTUs with low numbers of sequences (<10) was
150 carried out on a per-sample basis, as an OTU that is common in one sample may occur as a low-abundant
151 contaminant in other samples due to tag switching (Carlsen et al., 2012) or slight cross-contamination. A search
152 for similar sequences was conducted with Blast v2.2.29 (Zhang et al., 2000) on the latest release of the
153 MaarjAM AMF Virtual Taxa (classified as VTXnnnnn, where “n” is a numeric code, e.g. VTX00113) type
154 online database (Öpik et al., 2010) integrated with the SSU Silva database (Yilmaz et al., 2013) cleared of
155 Glomeromycota sequences. Recently, two major reorganizations of the Glomeromycota classification were
156 published (Oehl et al., 2011; Schüßler and Walker, 2010). In this study, for ease of data handling, the phylogeny
157 derived from the work of Schüßler and Walker (Redecker et al., 2013) was basically adopted to affiliate OTUs
158 to the corresponding taxonomy. Since the ~423bp ribosomal DNA fragment under study can make it difficult
159 to clearly separate phylogenetically some of the genera described in the work of Redecker et al. (2013),
160 sometimes clades were used (i.e. *Rhizophagus/Sclerocystis*, *Funneliformis/Septoglomus*, and *Glomus sensu*
161 *lato*) in order to group sequences with a conservative approach. Non-Glomeromycota OTUs were removed
162 from the dataset. Sequences were considered belonging to AMF when they had a minimum 90% homology
163 with a VT type, minimum 93% homology with a Glomeromycota GenBank sequence, and did not better match
164 any other accession from a different taxonomic group. Minimum sequence coverage required during the
165 alignment was 93%. Potential chimeric sequences were identified and removed using the uchime algorithm
166 (Edgar et al., 2011). A further chimera check was performed manually by individually blasting terminal chunks
167 of sequences that had overall <97% homology with database accessions. Prior to statistical analyses, as a
168 normalization step to reduce bias associated with different sequencing depths, all samples were subsampled
169 down to the size of the smallest one.

170

171 **2.6. Statistical data analyses**

172 All statistical analyses were done using R v3.2.0 (R Development Core Team, 2015) and Past
173 multivariate statistics software package v3.0 (Hammer et al., 2011). The R libraries *vegan* (Oksanen et al.,
174 2015), *packfor* by Stephane Dray, and *indicspecies* (De Cáceres et al., 2010) were adopted. The number of
175 OTUs, the exponential of the Shannon’s diversity index (a biodiversity index based on the proportions of
176 individuals), the number of OTUs per AMF clade/genus, the sample accumulation curves (a sampling effort

177 graphical assessment) and the individual sample rarefaction curves (a sequencing effort graphical assessment)
178 were calculated for each sample. A one-way ANOVA (model = ~ sample type + Error(site)) was performed
179 on OTU counts (after log transformation) and on the exponential Shannon's index, in order to determine the
180 effect of sample type (soil or roots) on the AM fungal diversity. In order to untangle the relationship between
181 diversity and physicochemical, climatic (mean annual temperature and precipitations), and spatial (latitude,
182 longitude, distance from sea and distance from source of saline water) variables, Spearman's correlation
183 coefficients were calculated between OTU counts of three AMF taxonomy levels (orders, families, and
184 clades/genera) and environmental variables. The Non-metric Multi-Dimensional Scaling (NMDS), based on
185 the Bray-Curtis distance (Wisconsin/square-root transformed OTU relative abundance dataset) was
186 constructed to graphically assess the differences in the community composition between the two sample types.
187 Soil physicochemical, climatic, and spatial variables (standardized as z-scores) were plotted as vectors in the
188 Bray-Curtis NMDS and their squared correlation coefficients were calculated as indicator of goodness of fit,
189 to assess their potential role in the community structuring and composition. In order to quantify the fractions
190 of AMF community variance explained by the measured environmental variables and by the sample type, the
191 partition of variation was performed. Only environmental variables that were measured at the plant level (i.e.,
192 soil variables) were submitted to forward-selection (function *forward.sel* in package *packfor*), using adjusted
193 R^2 and $\alpha=0.05$ as cutoffs according to Blanchet et al. (2008), in order to avoid collinearity among
194 explanatory variables in the model and to search for parsimony. Subsequently, the amount of AMF community
195 (Hellinger-transformed) variance potentially explained by forward-selected soil variables was computed. A
196 PERMANOVA (999 permutations) based on the Bray-Curtis distance matrix was carried out to determine the
197 effect of sample type (soil or roots), correcting for the random effect of the site factor (model = ~ sample type,
198 strata = site). The heterogeneity of the communities was tested with a Beta-dispersion analysis. Finally, soil
199 physicochemical variables were individually submitted to a k-means clustering which grouped soil
200 physicochemical measures into two classes, corresponding to higher and lower values (Table S2). Indicator
201 species for each resulting classes were detected using only OTUs with relative abundance >1% as input. To
202 explore the differential distribution of OTUs between root and soil samples, the Similarity Percentage analysis
203 (SIMPER) was carried out. For the same reason, multiple Kruskal-Wallis tests were performed.

204

205

206 **3. Results**

207 **3.1. Physicochemical properties of the soils**

208 The physicochemical properties of the soils are reported in Table 1. The most remarkable differences
209 were seen in available P, which was five-fold higher in MATSUE than in the other soil samples. Fe content
210 was more than double in SHIMANE soil than in the other samples. Noteworthy, soil total C was much higher
211 in BAMBOO, compared to the other locations, while total N was very low in SAGIURA.

212

213 **3.2. Sequencing output**

214 The 454 GS-FLX Titanium pyrosequencing yielded 101514 raw sequences. A preliminary removal of
215 short and low quality sequences resulted in 95249 Glomeromycota sequences and 1398 aspecific amplicons
216 (1247 belonging to Dikarya and 151 belonging to plants, annelids and unclassified Eukaryota). After removing
217 chimeric, rare, or artifact OTUs, 75829 good quality sequences were left (Table S3). Sequencing depth ranged
218 from 1858 to 9565 sequences, therefore, subsampling was carried out at 1858 reads (minimum sequencing
219 depth). Total OTU count was 254, ranging from 16 to 52 per sample. Overall, the root samples counted 216
220 OTUs while soil samples only 125. The 254 OTU representative sequences were registered in GenBank under
221 the following accession number string: **KT325597-KT325850**. Each rarefaction curve was able to reach the
222 asymptote at a much smaller number of sequences than the corresponding sample size, suggesting an optimal
223 sequencing effort for all samples (Fig. S1). All four Glomeromycota orders were retrieved, indicating a good
224 coverage of the biodiversity by the primers used, and the sequences were distributed in nine families (Fig. S2)
225 and 13 clades/genera (Fig. 1). Only 25 OTUs (9.84%) had a homology equal to or higher than 97% to a Virtual
226 Taxon type sequence. Even when considering only OTUs that were found in at least two samples (107 in total),
227 this value remained very low (16 OTUs, 14.95%). Overall, the Glomeraceae family was the most abundant
228 and diverse (88.4%, 222 OTUs), followed by Gigasporaceae (5.0%, 8 OTUs), Paraglomeraceae (3.6%, 4
229 OTUs), and marginal occurrence of Diversisporaceae (5 OTUs), Claroideoglomeraceae (6 OTUs),
230 Acaulosporaceae (5 OTUs), Ambisporaceae (2 OTUs), Archaeosporaceae (1 OTU), and Geosiphonaceae (1
231 OTU), together accounting for 2.9% sequences. The most abundant and diverse clade/genus was
232 *Rhizophagus/Sclerocystis* (51.4%, 124 OTUs), followed by *Glomus sensu lato* (36.1%, 93 OTUs), *Paraglomus*

233 (3.6%, 4 OTUs), *Scutellospora* (3.0%, 5 OTUs), *Gigaspora* (2.1%, 3 OTUs), *Claroideoglossum* (1.0%, 6
234 OTUs), and marginal occurrence of *Funneliformis/Septoglossum* (5 OTUs), *Diversispora* (4 OTUs),
235 *Acaulospora* (5 OTUs), *Redeckera* (1 OTU), *Ambispora* (2 OTUs), *Archaeospora* (1 OTU), and *Geosiphon* (1
236 OTU), together accounting for 2.9% sequences. The root and the soil samples shared 87 OTUs, so 129 OTUs
237 were only found in root samples while 38 OTUs were only found in soil samples. The four locations shared
238 14 OTUs (OTU001, OTU003, OTU004, OTU005, OTU006, OTU007, OTU008, OTU016, CHI001, OTU021,
239 OTU024, OTU025, OTU035, and OTU045) that were phylogenetically related to ten Virtual Taxa
240 (VTX00154, VTX00123, VTX00079, VTX00345, VTX00093, VTX00112, VTX00260, VTX00412,
241 VTX00322, and VTX00111). Thirteen of these OTUs belonged to Glomeraceae (11 *Rhizophagus/Sclerocystis*
242 and 2 *Glomus sensu lato*) and 1 to Gigasporaceae (*Scutellospora*). Of these, only three OTU representative
243 sequences had homology higher than 97% with a Virtual Taxon type sequence (VTX00260, VTX00112, and
244 VTX00093). No OTU was shared by all samples.

245

246 **3.3. Effect of sample type on AMF community and diversity**

247 The number of observed OTUs (richness) was significantly lower in the soil (p-value = 0.0043, Table
248 2, Fig. S3). No significant difference in the exponential Shannon diversity index was found between the root
249 and the soil. The number of OTUs assigned to *Glomus sensu lato* was significantly lower in soil samples, while
250 the opposite was true for *Ambispora* (Fig. S4), although the number of OTUs recorded for this genus was
251 negligible. No OTU was significantly differentially distributed between root and soil samples, although some
252 trends were noted (Table S4).

253 The NMDS ordination shown in Fig. 2 was based on the Bray-Curtis (stress: 0.142, 2D) distance
254 matrix. A major overlap is visible between the 95% confidence ellipses of the two niches. The one-way
255 PERMANOVA (Table 3) showed that the AMF community composition was not significantly affected by
256 sample type. The test for homogeneity of multivariate dispersion proved that the results of PERMANOVA are
257 reliable, since no significant heterogeneity of dispersion was detected (Table 3).

258

259 **3.4. Explanatory variables of the AMF community structure and diversity**

260 Soil physicochemical, climatic, and spatial variables that significantly ($\alpha = 0.05$) fitted the NMDS
261 ordination (Table S5) were plotted as vectors in the biplot in Fig. 2. Latitude, longitude, distance from saline
262 or sea water, mean annual temperature and precipitation, Fe, Mg, and C/N ratio significantly correlated with
263 the Bray-Curtis ordination.

264 Soil physicochemical variables that best explained AMF community variation are listed in Fig. 3.
265 Overall, selected soil variables *per se* accounted for a highly significant portion (according to adjusted R^2
266 transformed into percentage, 50.21%) of the total community variance (Fig. 3). The fraction of variation
267 explained by the sample type was instead low (3.29%) and not significant (p -value <0.10). Less than half AMF
268 community variance (46.49%) remained unexplained.

269 Table 4 reports highly significant (p -value <0.01) Spearman's correlations between the environmental
270 variables and the OTU richness of AMF orders, families, and clades/genera. Increasing distance from the sea
271 and total C were shown to reduce the occurrence of Diversisporaceae diversity. Conversely, higher levels of
272 soil EC, K, and pH were correlated with a higher diversity of this AMF family. *Diversispora* diversity also
273 increased with pH. The ratio between total C and total N was negatively correlated with the diversity of
274 Archaeosporales and Paraglomerales, while was positively correlated with *Rhizophagus/Sclerocystis* OTU
275 count. Finally, the number of Paraglomerales OTUs increased with soil P content.

276 Indicator species analysis was carried out to test whether specific AMF OTUs could be predictive of
277 particular soil physicochemical features. Measured soil variable values were clustered in two groups using the
278 k-means algorithm. This made it possible to allocate each value to a rank/level called HIGH, for higher values,
279 or LOW, for lower values. Table 5 reports the AMF OTUs that yielded consistent results ($\text{IndVal} \geq 0.8$, $P < 0.05$)
280 as indicator species for one of the two levels grouping the measured values of each soil physicochemical
281 variable considered in this study. Three indicator OTUs were detected for lower pH, one for lower EC, one for
282 both lower and higher available P, two for higher Fe, one for higher Mg, one for higher total C, and two for
283 higher C/N ratio (Table 5).

284

285

286 **4. Discussion**

287 As previously demonstrated, the targeted amplification of sequences exclusively belonging to
288 Glomeromycota from environmental samples is challenging, often resulting in frequent aspecific amplification
289 and incomplete coverage of the AMF diversity (Alguacil et al., 2011; Kohout et al., 2014; Liu et al., 2011;
290 Lumini et al., 2010; Van Geel et al., 2014). The use of AMADF forward primer, specifically designed to detect
291 Glomeromycota by Nested PCR approach (Desirò, 2013), combined with the 454 GS-FLX Titanium
292 pyrosequencing, proved to be successful, resulting in very high quality output. In fact, only 23.9% raw
293 sequences were removed due to low quality (judged as candidate chimeras or potentially erroneous) and,
294 unexpectedly, merely 1.4% sequences were the result of aspecific amplification. The coverage of the
295 Glomeromycota phylum was wide, highlighting 254 OTUs, members of all four orders and nine out of the ten
296 previously described families (Krüger et al., 2012; Redecker et al., 2013). Similarly, in a recent study in which
297 the same protocol was adopted, only ~28% raw sequences were discarded due to low quality and the use of
298 AMADF primer made it possible to achieve a near-complete coverage of the Glomeromycota phylum (Berruti
299 et al., 2016b).

300 Overall, only less than 10% OTUs could be identified ($\geq 97\%$ homology) as known Virtual Taxa using
301 the MaarjAM database (Öpik et al., 2010) as a reference. This corroborates that our knowledge of the diversity
302 of the Glomeromycota phylum is still limited, with particular regards to natural systems, which have been
303 largely overlooked so far (Ohsowski et al., 2014; Öpik et al., 2013). However, although our bioinformatic
304 pipeline provided a very conservative approach for detecting and discarding most artifact OTUs, the complete
305 removal of erroneous sequences cannot be achieved and diversity can consequently be somehow inflated
306 (Lindahl et al., 2013), resulting in some spurious OTUs that cannot be affiliated to known reference sequences.

307 The per-sample OTU count (≥ 26) and the exponential Shannon index (> 9.2) were generally high in
308 both roots and soil, suggesting the presence of a very high level of AMF diversity. Accordingly, the per-sample
309 relative abundance of the dominant taxon was always lower than 42%, meaning that the level of dominance
310 was not high. Diversity indices were much higher than the ones found by Borriello et al. (2015) in *C. japonica*
311 naturalized range. However, these authors have investigated AMF diversity based on Sanger sequencing that
312 is often biased by its lower sequencing effort potential. If we add that 454 pyrosequencing can inflate diversity
313 by bringing up to light several spurious OTUs with low read number, then OTU counts become incomparable
314 between the two ranges. Conversely, the Shannon index and derived indices are more comparable, since they

315 are less affected by species count, being based on species proportions. In support, in our study the communities
316 were quite even, with the dominant OTU only being averagely 2 times more abundant than the second most
317 abundant OTU and 3.4 times more abundant than the third most abundant OTU, unlike in Borriello et al. (2015)
318 and Dumbrell et al. (2010) where these ratios were higher. In addition, the relative OTU counts seemed to be
319 higher in soil than in root samples in the work by Borriello et al. (2015) while we highlighted a diametrically
320 opposite situation, more similarly to other studies where plant species were growing in their native range soil
321 (Pivato et al., 2007; Saks et al., 2014).

322 Nonetheless, the difference in OTU richness between roots and soil did not reflect in a major difference
323 in AMF community structure, since the majority of soil-dwelling AMF (69.6% OTUs) were retrieved inside
324 the root as well. It might be argued that soil, being the reservoir from which AMF are recruited by the host
325 plant during specific time lapses, should logically harbor the highest level of diversity. An explanation could
326 be that the most abundant family found, i.e. the Glomeraceae, had a higher OTU number in roots than in soil,
327 presumably due to the fact that some of its members are less prone to extend very far from the roots (Maherali
328 and Klironomos, 2007) and is therefore more likely to be overlooked in soil samples. Another possibility is
329 that AMF taxa in soil might have been underestimated since AMF biomass, and consequently AMF DNA, is
330 expected to be an order of magnitude less than in roots (Olsson et al., 2010). This hypothesis is partially
331 supported by our results that show a generally lower number of good quality AMF reads in soil samples. In
332 addition, since the distribution of AMF nuclei is uneven among fungal structures (Gamper et al., 2008), the
333 occurrence of AMF taxa characterized by different life styles (e.g. profuse sporulation vs. soil hyphal growth)
334 might have partially biased the correct assessment of soil AMF richness due to a dilution effect. A possible
335 reason why root and soil communities were highly similar is that *C. japonica* might be more prone to
336 indiscriminately welcome inside its root apparatus most of the AMF taxa that are available from its native soil
337 potential, that might have co-evolved and could therefore be more specific. Moreover, the soil mycelial
338 network could be more shared between plant species clusters of the same geographic origin than between plant
339 species introduced from distinct regions, such as the ones hosted in parks and gardens of the Lake Maggiore
340 area (Borriello et al., 2015), where soil AMF diversity poorly matched root AMF diversity.

341 Diversity at the clade/genus level was also high in *C. japonica* native range, although most genera
342 were underrepresented and only *Rhizophagus/Sclerocystis* and *Glomus sensu lato* were very abundant in both

343 root and soil samples. Similarly, Glomeraceae of the *Rhizophagus/Sclerocystis* (VTX00412, VTX00219,
344 VTX00223, VTX00074) and *Glomus sensu lato* (VTX00122) clades were dominant in the roots of *C. japonica*
345 in its naturalized range (Borriello et al., 2015). However, these authors found evidence that *Paraglomus* was
346 prevailing in the soil community. In addition, the globally distributed Diversisporales order (Öpik et al., 2010)
347 was lacking in the naturalized range, differently than in the native range where it was more common (overall
348 >5%).

349 Only two Virtual Taxa (the *Rhizophagus/Sclerocystis* VTX00093 and the *Paraglomus* VTX00239)
350 were present in both the native range under study and the naturalized range of *C. japonica* investigated by
351 Borriello et al. (2015). However, VTX00093 was common in the native range while very rare in the naturalized
352 range while VTX00239 was not common in the native range while abundant and ubiquitous in the naturalized
353 range. In another study on windmill palm, *Trachycarpus fortunei* (Hook.) H.Wendl., a higher number of shared
354 Virtual Taxa (10) was detected between the native, the experimentally introduced, and the invasive range
355 (Moora et al., 2011). However, unlike in the present study and in the work of Borriello et al. (2015), these
356 authors have investigated the AMF diversity associated to seedlings at a relatively young stage (1-3 leaves).

357 As in *C. japonica* naturalized range (Borriello et al., 2015), the native range also demonstrated a high
358 degree of heterogeneity in AMF community structure at the local scale. The variance partition analysis
359 suggested that these changes were by a considerable extent mediated by soil variables. Above all, soil Fe
360 content, C/N ratio, and Mg were consistently identified as the variables most likely involved in AMF
361 community structuring. Previous studies strongly support the role of soil Fe (Moebius-Clune et al., 2013) and
362 C/N (Dumbrell et al., 2009), as major determinants regulating the composition and structure of AMF
363 communities. The increase of C/N ratio, which was previously described as negatively correlated with soil
364 AMF biomass (Wang et al., 2012), caused a decline in the diversity of Archaeosporales and Paraglomerales,
365 which are, in line with our results, notorious soil explorers (Hempel et al., 2007) and rather occasional
366 (Alguacil et al., 2011) and patchy (Varela-Cervero et al., 2015) root colonizers. Conversely,
367 *Rhizophagus/Sclerocystis* diversity benefitted from this condition. Accordingly, two *Rhizophagus/Sclerocystis*
368 OTUs were highlighted as indicators of high C/N ratio. The concentration of Mg in the soil, and especially the
369 ratio between soil Ca and soil Mg, are also commonly recognized as AMF community drivers (Schechter and
370 Bruns, 2012, 2008). All soils examined in our study featured serpentine-like properties (Ca/Mg<1), with

371 SAGIURA showing the lowest ratio. One OTU of *Rhizophagus/Sclerocystis* was indicator of higher soil Mg.
372 In the study on *C. japonica* naturalized range by Borriello et al. (2015), instead, a member of the *Glomus sensu*
373 *lato* clade was found exclusively in high soil Mg condition, however Mg content was more than 10-fold higher
374 than what found in the native range of *C. japonica*.

375 Some other variables, although poorly or less affecting the AMF community as a whole, had a clear effect on
376 the diversity of specific taxonomic ranks or on the occurrence of single AMF taxa. The pH range examined in
377 our study was rather narrow (5.78-6.43), however, similarly to another study (Fitzsimons et al., 2008), it was
378 enough to be candidate as a potential driver of AMF community shifts. The viability and infectivity of different
379 AMF taxa are known to vary in different pH ranges (van Aarle et al., 2002). In our study, pH positively affected
380 the diversity of Diversisporaceae (in particular *Diversispora*). However, no *Diversispora* OTU was selected
381 as indicator of higher pH. Instead, three *Rhizophagus/Sclerocystis* were found as indicator for lower pH. Soil
382 N, P, and K showed a major involvement in AMF community structuring in *C. japonica* naturalized range
383 (Borriello et al., 2015). In our study, total soil N did not influence AMF community structure while soil
384 available P content, one of the major variables associated to the decline in AMF diversity in literature (Gosling
385 et al., 2013; Lin et al., 2012; Sheng et al., 2013), unexpectedly showed to increase along with the OTU count
386 of Paraglomerales. One *Paraglomus* OTU was indeed indicator of higher available P, along with a *Glomus*
387 *sensu lato* OTU. One *Rhizophagus/Sclerocystis* OTU was instead indicator of lower available P. This is in line
388 with Chen et al. (2014), who found that members of the Glomeraceae can be differentially distributed in
389 response to different regimes of fertilization. Soil salinity (EC and proximity to seawater) positively affected
390 Diversisporaceae diversity. Our results are in line with the work of Yamato et al. (2012), who, in the Tottori
391 prefecture (Japan), which is adjacent to the location under study (Shimane prefecture), detected *Diversispora*
392 members in association with high salinity, in the proximity of seawater. In previous studies, *Diversispora* was
393 abundantly retrieved in a salt marsh environment (Estrada et al., 2013) and, interestingly, the species
394 *Diversispora spurca* was demonstrated to have a role in salt stress alleviation in orange tree species (Zou and
395 Wu, 2011).

396 It can be concluded that root-colonizing and soil-dwelling AMF communities associated to *C. japonica*
397 in its native range are very similar and host a high number of previously undescribed AMF taxa. Multiple
398 predictors (above all soil Fe, soil C/N, Mg, and distance from the nearest source of saline water) could explain

399 a considerable portion of the community variance and/or triggered important diversity shifts at several
400 taxonomic levels of AMF at the local scale. We elucidated the edaphic preference of several AMF taxa that
401 were shown to exclusively occur under certain environmental conditions. These taxa might be of interest when
402 looking for AMF inoculants suitable for agriculture under different soil conditions.

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405 **Acknowledgements**

406 This study was financially supported by the Regione Piemonte. AB was funded by PROLACTE (Regione
407 Piemonte project). The mobility of AB and SD was funded by ForESTFlowers (FP7-PEOPLE-2010-IRSES-
408 269204).

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- 411 1. **Cited literature** Alguacil, M.M., Torres, M.P., Torrecillas, E., Díaz, G., Roldán, A., 2011. Plant type
412 differently promote the arbuscular mycorrhizal fungi biodiversity in the rhizosphere after revegetation of a
413 degraded, semiarid land. *Soil Biol Biochem* 43, 167–173. doi:10.1016/j.soilbio.2010.09.029.
- 414 2. Berruti, A., Borriello, R., Lumini, E., Scariot, V., Bianciotto, V., Balestrini, R., 2013. Application of
415 laser microdissection to identify the mycorrhizal fungi that establish arbuscules inside root cells. *Front. Plant.*
416 *Sci.* doi:10.3389/fpls.2013.00135.
- 417 3. Blanchet, F.G., Legendre, P., Borcard, D., 2008. Forward selection of explanatory variables. *Ecology*
418 89, 2623-2632.
- 419 4. Borriello, R., Berruti, A., Lumini, E., Della Beffa, M.T., Scariot, V., Bianciotto, V., 2015. Edaphic
420 factors trigger diverse AM fungal communities associated to exotic camellias in closely located Lake
421 Maggiore (Italy) sites. *Mycorrhiza* 25, 253–265. doi:10.1007/s00572-014-0605-4.
- 422 5. Berruti, A., Lumini, E., Balestrini, R., Bianciotto, V., 2016a. Arbuscular mycorrhizal fungi as natural
423 biofertilizers: Let's benefit from past successes. *Front. Microbiol.* 6, 1559. doi:10.3389/fmicb.2015.01559.
- 424 6. Berruti, A., Lumini, E., Bianciotto, V., 2016b. AMF components from a microbial inoculum fail to
425 colonize roots and lack soil persistence in an arable maize field. *Symbiosis.* doi:10.1007/s13199-016-0442-7.

- 426 7. Carlsen, T., Aas, A.B., Lindner, D., Vrålstad, T., Schumacher, T., Kausrud, H., 2012. Don't make a
427 mista(g)ke: is tag switching an overlooked source of error in amplicon pyrosequencing studies? *Fungal Ecol.*
428 5:747–749. doi:10.1016/j.funeco.2012.06.003.
- 429 8. Caruso, T., Hempel, S., Powell, J.R., Barto, E.K., Rillig, M.C., 2012. Compositional divergence and
430 convergence in arbuscular mycorrhizal fungal communities. *Ecology* 93, 1115–1124. doi:10.1890/11-1030.1.
- 431 9. Chen, Y.L., Zhang, X., Ye, J.S., Han, H.Y., Wan, S.Q., Chen, B.D., 2014. Six-year fertilization
432 modifies the biodiversity of arbuscular mycorrhizal fungi in a temperate steppe in Inner Mongolia. *Soil Biol.*
433 *Biochem.* 69, 371–381. doi:10.1016/j.soilbio.2013.11.020.
- 434 10. Davison, J., Öpik, M., Daniell, T.J., Moora, M., Zobel, M., 2011. Arbuscular mycorrhizal fungal
435 communities in plant roots are not random assemblages. *FEMS Microbiol. Ecol.* 78, 103–115.
436 doi:10.1111/j.1574-6941.2011.01103.x.
- 437 11. Davison, J., Moora, M., Öpik, M., Adholeya, A., Ainsaar, L., Bâ, A., Burla, S., Diedhiou, A.G.,
438 Hiiesalu, I., Jairus, T., Johnson, N.C., Kane, A., Koorem, K., Kochar, M., Ndiaye, C., Pärtel, M., Reier, Ü.,
439 Saks, Ü., Singh, R., Vasar, M., Zobel, M., 2015. Global assessment of arbuscular mycorrhizal fungus
440 diversity reveals very low endemism. *Science.* 349, 970–973. doi:10.1126/science.aab1161.
- 441 12. De Cáceres, M., Legendre, P., Moretti, M., 2010. Improving indicator species analysis by combining
442 groups of sites. *Oikos.* 119, 1674–1684. doi:10.1111/j.1600-0706.2010.18334.x.
- 443 13. Desirò, A., 2013. Basal plants, arbuscular mycorrhizal fungi and their endobacteria: A
444 morphological, molecular and phylogenetic study of a tripartite interaction. Dissertation, University of
445 Torino.
- 446 14. Dumbrell, A.J., Nelson, M., Helgason, T., Dytham, C., Fitter, A.H., 2010. Idiosyncrasy and
447 overdominance in the structure of natural communities of arbuscular mycorrhizal fungi: is there a role for
448 stochastic processes? *J. Ecol.* 98, 419–428.
- 449 15. Dumbrell, A.J., Nelson, M., Helgason, T., Dytham, C., Fitter, A.H., 2009. Relative roles of niche and
450 neutral processes in structuring a soil microbial community. *ISME J.* 4, 337–345.
451 doi:10.1038/ismej.2009.122.
- 452 16. Edgar, R.C., Haas, B.J., Clemente, J.C., Quince, C., Knight, R., 2011. UCHIME improves sensitivity
453 and speed of chimera detection. *Bioinformatics.* 27, 2194–2200. doi:10.1093/bioinformatics/btr381.

- 454 17. Estrada, B., Beltrán-Hermoso, M., Palenzuela, J., Iwase, K., Ruiz-Lozano, J.M., Barea, J.-M., Oehl,
455 F., 2013. Diversity of arbuscular mycorrhizal fungi in the rhizosphere of *Asteriscus maritimus* (L.) Less., a
456 representative plant species in arid and saline Mediterranean ecosystems. *J. Arid Environ.* 97, 170–175.
457 doi:10.1016/j.jaridenv.2013.05.019.
- 458 18. Fitter, A.H., Gilligan, C.A., Hollingworth, K., Kleczkowski, A., Twyman, R.M., Pitchford, J.W.,
459 2005. Biodiversity and ecosystem function in soil. *Funct. Ecol.* 19, 369–377. doi:10.1111/j.0269-
460 8463.2005.00969.x.
- 461 19. Fitzsimons, M.S., Miller, R.M., Jastrow, J.D., 2008. Scale-dependent niche axes of arbuscular
462 mycorrhizal fungi. *Oecologia.* 158, 117–127. doi:10.1007/s00442-008-1117-8.
- 463 20. Gamper, H.A., Young, J.P.W., Jones, D.L., Hodge, A., 2008. Real-time PCR and microscopy: Are
464 the two methods measuring the same unit of arbuscular mycorrhizal fungal abundance? *Fungal Genet. Biol.*
465 45, 581–596. doi:10.1016/j.fgb.2007.09.007.
- 466 21. Gosling, P., Proctor, M., Jones, J., Bending, G.D., 2013. Distribution and diversity of *Paraglomus*
467 spp. in tilled agricultural soils. *Mycorrhiza.* doi:10.1007/s00572-013-0505-z.
- 468 22. Hammer, Ø., Harper, D.A.T., Ryan, P.D., 2011. PAST: Paleontological statistics software package
469 for education and data analysis. *Palaeontol. Electron.* 4, 1–9.
- 470 23. Helgason, T., Merryweather, J.W., Young, J.P.W., Fitter, A.H., 2007. Specificity and resilience in
471 the arbuscular mycorrhizal fungi of a natural woodland community. *J. Ecol.* 95, 623–630.
472 doi:10.1111/j.1365-2745.2007.01239.x.
- 473 24. Hempel, S., Renker, C., Buscot, F., 2007. Differences in the species composition of arbuscular
474 mycorrhizal fungi in spore, root and soil communities in a grassland ecosystem. *Environ. Microbiol.* 9,
475 1930–1938. doi:10.1111/j.1462-2920.2007.01309.x.
- 476 25. Hoeksema, J.D., Chaudhary, V.B., Gehring, C.A., Johnson, N.C., Karst, J., Koide, R.T., Pringle, A.,
477 Zabinski, C., Bever, J.D., Moore, J.C., Wilson, G.W.T., Klironomos, J.N., Umbanhowar, J., 2010. A meta-
478 analysis of context-dependency in plant response to inoculation with mycorrhizal fungi. *Ecol. Lett.* 13, 394–
479 407. doi:10.1111/j.1461-0248.2009.01430.x.

- 480 26. Johnson, D., Vandenkoornhuise, P.J., Leake, J.R., Gilbert, L., Booth, R.E., Grime, J.P., Young,
481 J.P.W., Read, D.J., 2004. Plant communities affect arbuscular mycorrhizal fungal diversity and community
482 composition in grassland microcosms. *New Phytol.* 161, 503–515. doi:10.1046/j.1469-8137.2003.00938.x.
- 483 27. Kohout, P., Doubková, P., Bahram, M., Suda, J., Tedersoo, L., Voříšková, J., Sudová, R., 2015.
484 Niche partitioning in arbuscular mycorrhizal communities in temperate grasslands: a lesson from adjacent
485 serpentine and nonserpentine habitats. *Mol. Ecol.* 24, 1831–1843. doi:10.1111/mec.13147.
- 486 28. Kohout, P., Sudová, R., Janoušková, M., Čtvrtlíková, M., Hejda, M., Pánková, H., Slavíková, R.,
487 Štajerová, K., Vosátka, M., Sýkorová, Z., 2014. Comparison of commonly used primer sets for evaluating
488 arbuscular mycorrhizal fungal communities: Is there a universal solution? *Soil Biol. Biochem.* 68, 482–493.
489 doi:10.1016/j.soilbio.2013.08.027.
- 490 29. Krüger, M., Krüger, C., Walker, C., Stockinger, H., Schübler, A., 2012. Phylogenetic reference data
491 for systematics and phylotaxonomy of arbuscular mycorrhizal fungi from phylum to species level. *New*
492 *Phytol.* 193, 970–984. doi:10.1111/j.1469-8137.2011.03962.x.
- 493 30. Lee, J., Lee, S., Young, J.P.W., 2008. Improved PCR primers for the detection and identification of
494 arbuscular mycorrhizal fungi. *FEMS Microbiol. Ecol.* 65, 339–349. doi:10.1111/j.1574-6941.2008.00531.x.
- 495 31. Lekberg, Y., Gibbons, S.M., Rosendahl, S., 2014. Will different OTU delineation methods change
496 interpretation of arbuscular mycorrhizal fungal community patterns? *New Phytol.* 202, 1101–1104.
497 doi:10.1111/nph.12758.
- 498 32. Lekberg, Y., Schnoor, T., Kjølner, R., Gibbons, S.M., Hansen, L.H., Al-Soud, W.A., Sørensen, S.J.,
499 Rosendahl, S., 2012. 454-sequencing reveals stochastic local reassembly and high disturbance tolerance
500 within arbuscular mycorrhizal fungal communities. *J. Ecol.* 100, 151–160. doi:10.1111/j.1365-
501 2745.2011.01894.x.
- 502 33. Lindahl, B.D., Nilsson, R.H., Tedersoo, L., Abarenkov, K., Carlsen, T., Kjølner, R., Kõljalg, U.,
503 Pennanen, T., Rosendahl, S., Stenlid, J., Kausrud, H., 2013. Fungal community analysis by high-throughput
504 sequencing of amplified markers – a user’s guide. *New Phytol.* 199, 288–299. doi:10.1111/nph.12243.
- 505 34. Lin, X., Feng, Y., Zhang, H., Chen, R., Wang, J., Zhang, J., Chu, H., 2012. Long-term balanced
506 fertilization decreases arbuscular mycorrhizal fungal diversity in an arable soil in North China revealed by
507 454 pyrosequencing. *Environ. Sci. Technol.* 46, 5764–5771. doi:10.1021/es3001695.

- 508 35. Liu, Y., He, J., Shi, G., An, L., Öpik, M., Feng, H., 2011. Diverse communities of arbuscular
509 mycorrhizal fungi inhabit sites with very high altitude in Tibet Plateau. *FEMS Microbiol. Ecol.* 78, 355–365.
510 doi:10.1111/j.1574-6941.2011.01163.x.
- 511 36. Lumini, E., Orgiazzi, A., Borriello, R., Bonfante, P., Bianciotto, V., 2010. Disclosing arbuscular
512 mycorrhizal fungal biodiversity in soil through a land-use gradient using a pyrosequencing approach.
513 *Environ. Microbiol.* 12, 2165–2179. doi:10.1111/j.1462-2920.2009.02099.x.
- 514 37. Maherali, H., Klironomos, J.N., 2007. Influence of phylogeny on fungal community assembly and
515 ecosystem functioning. *Science.* 316, 1746-1748. doi:10.1126/science.1143082.
- 516 38. Maherali, H., Klironomos, J.N., 2012. Phylogenetic and trait-based assembly of arbuscular
517 mycorrhizal fungal communities. *PLoS ONE.* 7, e36695. doi:10.1371/journal.pone.0036695.
- 518 39. Moebius-Clune, D.J., Moebius-Clune, B.N., van Es, H.M., Pawlowska, T.E., 2013. Arbuscular
519 mycorrhizal fungi associated with a single agronomic plant host across the landscape: Community
520 differentiation along a soil textural gradient. *Soil Biol. Biochem.* 64, 191–199.
521 doi:10.1016/j.soilbio.2012.12.014.
- 522 40. Mondal, T.K., 2011. *Camellia*, in: Kole, C. (ed), *Wild crop relatives: Genomic and breeding*
523 *resources.* Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 15–39.
- 524 41. Moora, M., Berger, S., Davison, J., Öpik, M., Bommarco, R., Bruehlheide, H., Kühn, I., Kunin, W.E.,
525 Metsis, M., Rortais, A., Vanatoa, A., Vanatoa, E., Stout, J.C., Truusa, M., Westphal, C., Zobel, M., Walther,
526 G.-R., 2011. Alien plants associate with widespread generalist arbuscular mycorrhizal fungal taxa: evidence
527 from a continental-scale study using massively parallel 454 sequencing. *J. Biogeogr.* 38, 1305–1317.
528 doi:10.1111/j.1365-2699.2011.02478.x.
- 529 42. Oehl, F., Sieverding, E., Palenzuela, J., Ineichen, K., da Silva, G.A., 2011. Advances in
530 Glomeromycota taxonomy and classification. *IMA FUNGUS* 2, 191–199.
531 doi:10.5598/ima fungus.2011.02.02.10.
- 532 43. Ohsowski, B.M., Zaitsoff, P.D., Öpik, M., Hart, M.M., 2014. Where the wild things are: looking for
533 uncultured Glomeromycota. *New Phytol.* 204, 171–179. doi:10.1111/nph.12894.

- 534 44. Oksanen, J., Blanchet, F.G., Kindt, R., Legendre, P., Minchin, P.R., O'Hara, R.B., Simpson, G.L.,
535 Solymos, P., Henry, M., Stevens, H., Wagner, H., 2015. Package "vegan". [https://cran.r-](https://cran.r-project.org/web/packages/vegan/vegan.pdf)
536 [project.org/web/packages/vegan/vegan.pdf](https://cran.r-project.org/web/packages/vegan/vegan.pdf).
- 537 45. Olsen, S.R., Cole, C.V., Watanabe, F.S., Dean, L.A., 1954. Estimation of available phosphorus in
538 soils by extraction with sodium bicarbonate. Gov. Print. Office, USDA, Washington D.C.
- 539 46. Olsson, P.A., Rahm, J., Aliasgharzag, N., 2010. Carbon dynamics in mycorrhizal symbioses is linked
540 to carbon costs and phosphorus benefits. *FEMS Microbiol. Ecol.* 72, 125–131. doi:10.1111/j.1574-
541 6941.2009.00833.x.
- 542 47. Öpik, M., Metsis, M., Daniell, T.J., Zobel, M., Moora, M., 2009. Large-scale parallel 454 sequencing
543 reveals host ecological group specificity of arbuscular mycorrhizal fungi in a boreonemoral forest. *New*
544 *Phytol.* 184, 424–437. doi:10.1111/j.1469-8137.2009.02920.x.
- 545 48. Öpik, M., Vanatoa, A., Vanatoa, E., Moora, M., Davison, J., Kalwij, J.M., Reier, Ü., Zobel, M.,
546 2010. The online database MaarjAM reveals global and ecosystemic distribution patterns in arbuscular
547 mycorrhizal fungi (Glomeromycota). *New Phytol.* 188, 223–241. doi:10.1111/j.1469-8137.2010.03334.x.
- 548 49. Öpik, M., Zobel, M., Cantero, J.J., Davison, J., Facelli, J.M., Hiiesalu, I., Jairus, T., Kalwij, J.M.,
549 Koorem, K., Leal, M.E., Liira, J., Metsis, M., Neshataeva, V., Paal, J., Phosri, C., Pöhlme, S., Reier, Ü., Saks,
550 Ü., Schimann, H., Thiéry, O., Vasar, M., Moora, M., 2013. Global sampling of plant roots expands the
551 described molecular diversity of arbuscular mycorrhizal fungi. *Mycorrhiza.* 23, 411–430.
552 doi:10.1007/s00572-013-0482-2.
- 553 50. Parniske, M., 2008. Arbuscular mycorrhiza: the mother of plant root endosymbioses. *Nat. Rev.*
554 *Microbiol.* 6, 763–775. doi:10.1038/nrmicro1987.
- 555 51. Pivato, B., Mazurier, S., Lemanceau, P., Siblot, S., Berta, G., Mougél, C., van Tuinen, D., 2007.
556 *Medicago* species affect the community composition of arbuscular mycorrhizal fungi associated with roots.
557 *New Phytol.* 176, 197–210. doi:10.1111/j.1469-8137.2007.02151.x.
- 558 52. Powell, J.R., Parrent, J.L., Hart, M.M., Klironomos, J.N., Rillig, M.C., Maherali, H., 2009.
559 Phylogenetic trait conservatism and the evolution of functional trade-offs in arbuscular mycorrhizal fungi.
560 *Proc. Biol. Sci.* 276, 4237–4245. doi:10.1098/rspb.2009.1015.

- 561 53. Quince, C., Lanzén, A., Curtis, T.P., Davenport, R.J., Hall, N., Head, I.M., Read, L.F., Sloan, W.T.,
562 2009. Accurate determination of microbial diversity from 454 pyrosequencing data. *Nat. Methods.* 6, 639–
563 641. doi:10.1038/nmeth.1361.
- 564 54. R Development Core Team, 2015. R: A language and environment for statistical computing. R
565 Foundation for Statistical Computing, Vienna, Austria.
- 566 55. Redecker, D., Schüßler, A., Stockinger, H., Stürmer, S.L., Morton, J.B., Walker, C., 2013. An
567 evidence-based consensus for the classification of arbuscular mycorrhizal fungi (Glomeromycota).
568 *Mycorrhiza.* 7, 501-531. doi:10.1007/s00572-013-0486-y.
- 569 56. Saks, Ü., Davison, J., Öpik, M., Vasar, M., Moora, M., Zobel, M., 2014. Root-colonizing and soil-
570 borne communities of arbuscular mycorrhizal fungi in a temperate forest understory. *Botany.* 92, 277-285.
571 doi:10.1139/cjb-2013-0058.
- 572 57. Sato, K., Suyama, Y., Saito, M., Sugawara, K., 2005. A new primer for discrimination of arbuscular
573 mycorrhizal fungi with polymerase chain reaction-denature gradient gel electrophoresis. *Grassl. Sci.* 51,
574 179–181. doi:10.1111/j.1744-697X.2005.00023.x.
- 575 58. Schechter, S.P., Bruns, T.D., 2008. Serpentine and non-serpentine ecotypes of *Collinsia sparsiflora*
576 associate with distinct arbuscular mycorrhizal fungal assemblages. *Mol. Ecol.* 17, 3198–3210.
577 doi:10.1111/j.1365-294X.2008.03828.x.
- 578 59. Schechter, S.P., Bruns, T.D., 2012. Edaphic sorting drives arbuscular mycorrhizal fungal community
579 assembly in a serpentine/non-serpentine mosaic landscape. *Ecosphere.* 3, art42. doi:10.1890/ES12-00059.1.
- 580 60. Schloss, P.D., Westcott, S.L., Ryabin, T., Hall, J.R., Hartmann, M., Hollister, E.B., Lesniewski,
581 R.A., Oakley, B.B., Parks, D.H., Robinson, C.J., Sahl, J.W., Stres, B., Thallinger, G.G., Horn, D.J.V.,
582 Weber, C.F., 2009. Introducing mothur: Open-source, platform-independent, community-supported software
583 for describing and comparing microbial communities. *Appl. Environ. Microbiol.* 75, 7537–7541.
584 doi:10.1128/AEM.01541-09.
- 585 61. Schüßler, A., Walker, C., 2010. The Glomeromycota. A species list with new families and new
586 genera. Edinburgh & Kew, UK: The Royal Botanic Garden; Munich, Germany: Botanische Staatssammlung
587 Munich; Oregon, USA: Oregon State University.

- 588 62. Sheng, M., Lalonde, R., Hamel, C., Ziadi, N., 2013. Effect of long-term tillage and mineral
589 phosphorus fertilization on arbuscular mycorrhizal fungi in a humid continental zone of Eastern Canada.
590 *Plant Soil*. 369, 599–613. doi:10.1007/s11104-013-1585-4.
- 591 63. Smith, S.E., Read, D.J., 2008. *Mycorrhizal Symbiosis*, 3rd editon Academic, London.
- 592 64. Torrecillas, E., Torres, P., Alguacil, M.M., Querejeta, J.I., Roldán, A., 2013. Influence of habitat and
593 climate variables on arbuscular mycorrhizal fungus community distribution, as revealed by a case study of
594 facultative plant epiphytism under semiarid conditions. *Appl. Environ. Microbiol.* 79, 7203–7209.
595 doi:10.1128/AEM.02466-13.
- 596 65. van Aarle, I.M., Olsson, P.A., Söderström, B., 2002. Arbuscular mycorrhizal fungi respond to the
597 substrate pH of their extraradical mycelium by altered growth and root colonization. *New Phytol.* 155, 173–
598 182.
- 599 66. van der Heijden, M.G.A., Scheublin, T.R., 2007. Functional traits in mycorrhizal ecology: their use
600 for predicting the impact of arbuscular mycorrhizal fungal communities on plant growth and ecosystem
601 functioning. *New Phytol.* 174, 244–250. doi:10.1111/j.1469-8137.2007.02041.x.
- 602 67. Van Geel, M., Busschaert, P., Honnay, O., Lievens, B., 2014. Evaluation of six primer pairs
603 targeting the nuclear rRNA operon for characterization of arbuscular mycorrhizal fungal (AMF)
604 communities using 454 pyrosequencing. *J. Microbiol. Methods.* 106, 93–100.
605 doi:10.1016/j.mimet.2014.08.006.
- 606 68. Varela-Cervero, S., Vasar, M., Davison, J., Barea, J.M., Öpik, M., Azcón-Aguilar, C., 2015. The
607 composition of arbuscular mycorrhizal fungal communities differs among the roots, spores and extraradical
608 mycelia associated with five Mediterranean plant species. *Environ. Microbiol.* 17, 2882–2895.
609 doi:10.1111/1462-2920.12810.
- 610 69. Verbruggen, E., van der Heijden, M.G.A., Rillig, M.C., Kiers, E.T., 2013. Mycorrhizal fungal
611 establishment in agricultural soils: Factors determining inoculation success. *New Phytol.* 197, 1104–1109.
612 doi:10.1111/j.1469-8137.2012.04348.x.
- 613 70. Wang, J.J., Li, X.Y., Zhu, A.N., Zhang, X.K., Zhang, H.W., Liang, W.J., 2012. Effects of tillage and
614 residue management on soil microbial communities in North China. *Plant Soil Environ.* 58, 28–33.

- 615 71. Yamato, M., Yagame, T., Yoshimura, Y., Iwase, K., 2012. Effect of environmental gradient in
616 coastal vegetation on communities of arbuscular mycorrhizal fungi associated with *Ixeris repens*
617 (Asteraceae). *Mycorrhiza*. 22, 623–630. doi:10.1007/s00572-012-0439-x.
- 618 72. Yilmaz, P., Parfrey, L.W., Yarza, P., Gerken, J., Pruesse, E., Quast, C., Schweer, T., Peplies, J.,
619 Ludwig, W., Glöckner, F.O., 2013. The SILVA and “All-species Living Tree Project (LTP)” taxonomic
620 frameworks. *Nucleic Acids Res.* doi:10.1093/nar/gkt1209.
- 621 73. Zhang, Z., Schwartz, S., Wagner, L., Miller, W., 2000. A greedy algorithm for aligning DNA
622 sequences. *J. Comput. Mol. Cell Biol.* 7, 203–214. doi:10.1089/10665270050081478.
- 623 74. Zou, Y.N., Wu, Q.S., 2011. Efficiencies of five arbuscular mycorrhizal fungi in alleviating salt stress
624 of trifoliolate orange. *Int. J. Agric. Biol.* 13, 991–995.

625 **Table captions**

626 Table 1. Physicochemical properties of the soils sampled in the four different sites (Matsue, Shimane, Sagiura,
627 and Bamboo). SD of means is provided.

628

629 Table 2. Species richness indicators calculated for the four sites (MATSUE, SHIMANE, SAGIURA, AND
630 BAMBOO) and the two sample types (roots and soil). ANOVA p-values are reported for sample type (model
631 = ~ sample type + Error(site)). SD of means is provided.

632

633 Table 3. Permutational multivariate analysis of variance (PERMANOVA) between sample types (model = ~
634 sample type, strata = site) using OTU-based Bray-Curtis distance matrix calculated on square-root/wisconsin
635 standardized read counts. The tests for homogeneity of multivariate dispersion (Beta-dispersion) are also
636 reported. Permutation number was set at 999.

637

638 Table 4. Highly significant ($p < 0.01$) Spearman's correlations between the OTU richness of several taxonomic
639 levels and environmental variables.

640

641 Table 5. Indicator species analysis for the k-means clusters (lower values and higher values) defined for each
642 soil physicochemical variable. Specificity, sensitivity, and IndVal values, p-value, and OTU affiliation
643 (taxonomy clade and closest virtual taxon type sequence) and units after subsampling are reported.

644

645 Table S1

646 Sampling site characteristics. Site code, location name, country, spatial variables (latitude, longitude, distance
647 from the sea, distance from brackish or salt water), climatic variables (mean annual temperature, mean annual
648 precipitations), biome, ecosystem type, plant approximate age, dominant canopy, and soil type are reported.

649

650 Table S2. K-means clusters (HIGH for higher values and LOW for lower values) used for indicator species
651 detection for the measured soil physicochemical variables.

652

653 Table S3. OTU table with OTU taxonomic affiliation (order, family, clade/genus). Closest Virtual Taxa, first
654 hit sequence code, homology, alignment length, sample codes with site and sample type information, and per
655 sample OTU units after subsampling are reported. At the bottom of the table, total OTU counts, sequencing
656 depth prior to subsampling, and order, family, and clade/genus level OTU counts are also reported.

657

658 Table S4. SIMPER analysis and Kruskal-Wallis tests to assess differential distribution of OTUs between root
659 and soil samples. Average dissimilarity index, average abundance in roots and soil (including bar charts),
660 cumulative contribution in variation (proportion of variation), SIMPER p-value, Kruskal-Wallis p-value and
661 false discovery rate are reported.

662

663 Table S5. Squared correlation coefficients of the environmental variable fitting with the NMDS distribution
664 (ns = non-significant p-value, * = $0.010 < p\text{-value} < 0.050$, ** = $0.001 < p\text{-value} < 0.010$, *** = $p\text{-value} < 0.001$).

665 **Figure captions**

666 Figure 1. Overall relative abundances of AMF clades/genera in root and soil samples. SE of the subsampled
667 read counts are reported.

668

669 Figure 2. Non-metric Multi-Dimensional Scaling (NMDS) biplot based on Bray-Curtis distance matrix of the
670 AMF communities found in each sample (filled circles = roots, open circles = soil). The vectors (arrows)
671 graphically represent the significant correlations (at $\alpha = 0.05$) of the NMDS axes with the measured
672 environmental variables. Standard deviation of point scores was used to plot 95% confidence ellipses. Stress
673 was 0.142.

674

675 Figure 3. Variance partitioning between the forward-selected environmental variables and the sample types
676 (roots and soil). The fractions of variance explained by the forward-selected measured environmental variables,
677 the sample type factor, and the residual variance are reported as adjusted R^2 (transformed into percentages).
678 The level of significance of the explained fractions according to the modified F-test for multivariate datasets
679 implemented in the function *forward.sel* of the package *packfor* in R v3.2.0 are also reported. The forward-
680 selected environmental variables are listed and their individual statistical significance levels reported (* =
681 $0.010 < p\text{-value} < 0.050$, ** = $0.001 < p\text{-value} < 0.010$, *** = $p\text{-value} < 0.001$).

682

683 Figure S1. Rarefaction curves. The figure shows the OTU accumulation plotted as a function of the number of
684 sequences (prior to subsampling) at the sample level. The sample name (e.g. MAT_1R) identifies the
685 abbreviated site of origin (MAT=MATSUE, SHI=SHIMANE, SAG=SAGIURA, and BAM=BAMBOO), the
686 sample number (1-8) and the sample type of origin (R for roots and S for soil).

687

688 Figure S2. Overall relative abundances of AMF families in root and soil samples. SE of the subsampled read
689 counts are reported.

690

691 Figure S3. Sample accumulation curves. The figure shows the OTU accumulation plotted as a function of the
692 number of root or soil samples.

693

694 Figure S4. Variation in the number of OTUs between root and soil samples according to a Kruskal-Wallis test.

695

696

697 Table 1.

Site	pH (units)	EC (mS/m)	Available P (mg/Kg)	Fe (mg/Kg)	K (mg/Kg)	Mg (mg/Kg)	Ca (mg/Kg)	Total C (%)	Total N (%)	C/N (ratio)
MATSUE	5.78±0.45	26.90±0.33	82.93±2.92	17673±3356	3463±683	2371±1147	1970±1102	4.96±1.00	0.33±0.07	15.21±0.02
SHIMANE	6.05±0.26	30.15±3.89	15.02±5.16	52695±6290	6352±382	1333±24	867±6	5.22±1.58	0.34±0.04	15.14±2.84
SAGIURA	6.43±0.09	38.68±0.54	4.59±0.10	23276±4468	5959±1108	3075±457	1371±49	2.89±0.05	0.16±0.03	18.95±3.53
BAMBOO	5.95±0.07	28.77±0.19	10.57±0.15	23784±2115	4363±490	1936±267	1511±489	10.11±7.05	0.46±0.28	21.35±2.27

698

699 Table 2.

Site	Sample type	OTU richness	exp(Shannon index)
MATSUE	ROOTS	37.0±7.1	11.3±2.9
MATSUE	SOIL	29.0±0.0	15.2±1.1
SHIMANE	ROOTS	46.5±4.9	17.7±0.8
SHIMANE	SOIL	30.5±0.7	13.0±2.5
SAGIURA	ROOTS	49.0±4.2	11.5±2.4
SAGIURA	SOIL	26.0±4.2	9.2±2.3
BAMBOO	ROOTS	46.0±4.2	15.0±0.3
BAMBOO	SOIL	30.5±20.5	12.9±11.6
<i>p-values</i>	Sample type	0.0043	0.5600

700

701 Table 3.

PERMANOVA	pseudo-F	R²	p-value
OTU-based Bray-Curtis distance matrix			
sample type	0.981	0.065	0.211
Test for homogeneity of multivariate dispersion		F-value	p-value
among sample types		0.131	0.723

702

703 Table 4.

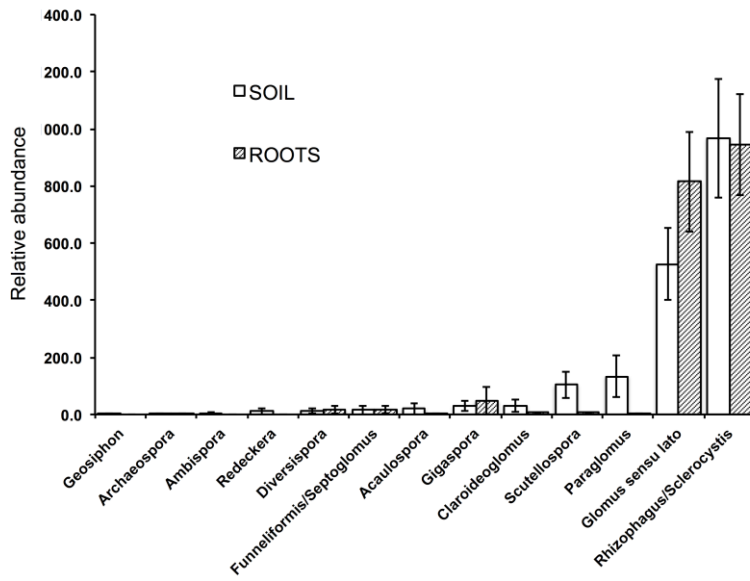
Taxonomic rank	Soil physicochemical variable	R	p-value
Diversisporaceae	vs. Distance from sea	-0.70	0.0025
	vs. pH	0.83	0.0000
	vs. EC	0.67	0.0045
	vs. K	0.64	0.0071
	vs. Total C	-0.71	0.0021
Archaeosporales	vs. C/N ratio	-0.67	0.0047
Paraglomerales, Paraglomeraceae, <i>Paraglomerus</i>[#]	vs. P	0.75	0.0008
	vs. C/N ratio	-0.66	0.0053
<i>Diversispora</i>	vs. pH	0.72	0.0015
<i>Rhizophagus/Sclerocystis</i>	vs. C/N ratio	0.67	0.0046

704 [#]Paraglomerales is a monophyletic order that includes one monophyletic family (Paraglomeraceae) that includes only

705 one genus (*Paraglomerus*).

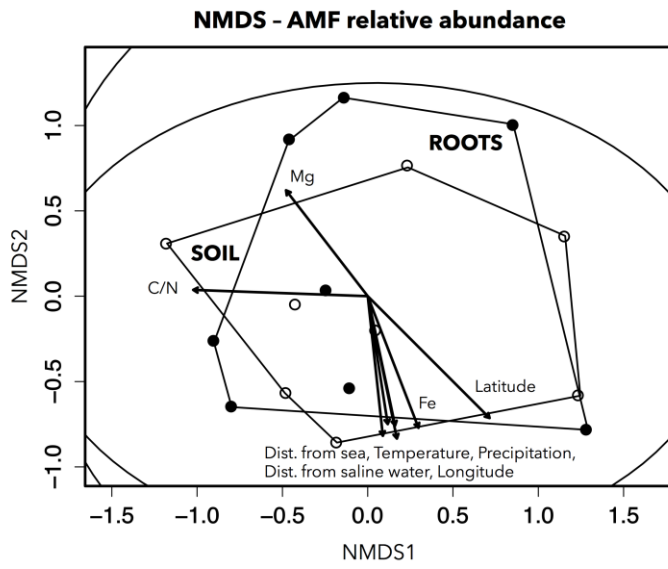
706 Table 5.

	Specificity	Sensitivity	IndVal	p-value	Clade	VT type (>97% ID)	units
Lower pH							
OTU012	1.000	1.000	1.000	0.0003	<i>Rhizophagus/Sclerocystis</i>	-	630
OTU005	0.823	1.000	0.907	0.0230	<i>Rhizophagus/Sclerocystis</i>	-	1730
CHI001	0.838	0.875	0.856	0.0089	<i>Rhizophagus/Sclerocystis</i>	-	656
Lower EC							
OTU012	1.000	0.800	0.894	0.0090	<i>Rhizophagus/Sclerocystis</i>	-	630
Lower Available P							
OTU002	1.000	0.833	0.913	0.0392	<i>Rhizophagus/Sclerocystis</i>	-	2755
Higher Available P							
OTU017	0.856	1.000	0.925	0.0019	<i>Paraglomus</i>	VTX00239	785
Higher Fe							
OTU011	0.993	1.000	0.996	0.0005	<i>Glomus sensu lato</i>	-	580
OTU010	0.970	1.000	0.985	0.0005	<i>Glomus sensu lato</i>	-	1033
Higher Mg							
OTU008	0.832	1.000	0.912	0.0087	<i>Rhizophagus/Sclerocystis</i>	VTX00112	944
Higher Total C							
OTU009	0.970	1.000	0.985	0.0092	<i>Rhizophagus/Sclerocystis</i>	-	764
Higher C/N ratio							
OTU002	0.939	1.000	0.969	0.0005	<i>Rhizophagus/Sclerocystis</i>	-	2755
OTU009	1.000	0.667	0.816	0.0072	<i>Rhizophagus/Sclerocystis</i>	-	764



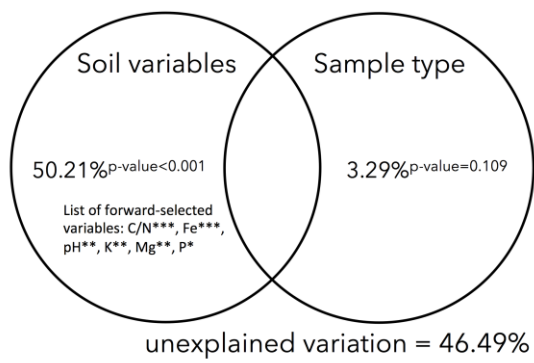
707

Figure 1.



708

Figure 2.



709

Figure 3.