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Recovery of arbuscular mycorrhizal fungi root colonization after severe anthropogenic disturbance: four species assessed in old-growth Mediterranean grassland

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1 Title Page

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4 **Mediterranean grassland.**

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7 Short title: Arbuscular mycorrhizal root colonization recovery after disturbance

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58 *Abstract*

59 Arbuscular mycorrhizal fungi (AMF) interact continuously with vegetation and soil and thus shape the dynamics
60 of plant communities. Yet the recovery of AMF after severe anthropogenic disturbance such as cultivation has
61 rarely been assessed. Here, to determine whether AMF root colonization recovers after such disturbance, we
62 compared AMF root colonization in abandoned fields last cultivated 2, 35, and 150 years ago in the La Crau area
63 (south-eastern France) with that of a grassland several thousands of years old (considered as the reference
64 ecosystem). We measured AMF root colonization of four species (*Carthamus lanatus* L., *Carduus pycnocephalus*
65 L., *Brachypodium distachyon* (L.) P. Beauv., and *Bromus madritensis*), and performed surveys of plant communities
66 and soil chemical properties. AMF root colonization was still significantly lower 35 years after disturbance for
67 one species (*B. distachyon*) and 2 years after disturbance for two species (*B. distachyon* and *B. madritensis*). The
68 main soil chemical properties (soil pH, phosphorus and potassium content) were similar to the reference ecosystem
69 35 years after disturbance. Average vegetation height and cover recovered after 35 years, whereas species richness
70 recovered only on the field abandoned for 150 years. Vegetation composition and structure did not recover in any
71 of the abandoned fields. Our results suggest that recovery of AMF root colonization is very low after a severe
72 anthropogenic disturbance, despite the recovery of soil chemical properties.

73 Key Words: Cultivation; Diversity; Plant Community; Steppe; Arbuscular Mycorrhizal Fungi

74

75 Introduction

76 The importance of taking into account arbuscular mycorrhizal fungus (AMF) interactions when exploring plant
77 community dynamics is increasingly acknowledged (Grime et al. 1987; O'Connor et al. 2002; van der Heijden and
78 Horton 2009; Bever et al. 2010; Koziol and Bever 2015). However, there are far fewer studies of AMF than of
79 plants because access to AMF data is more difficult (Bever et al. 2001). Mycorrhizas can be found in most plant
80 communities (van der Heijden and Sanders 2002), principally arbuscular mycorrhizal fungi (AMF), and interact
81 with 80% of plant species (Wang and Qiu 2006). AMF increase plant water and phosphorus uptake mainly through
82 the increased soil volume available for foraging (Allen 1982; Bolan 1991; Koide 1991; Augé 2001) and may thus
83 impact growth of plant individuals and of their descendants (Koide and Lu 1992; Heppell et al. 2002).
84 Consequently, AMF modify competition between plants, thereby affecting their coexistence (Grime et al. 1987;
85 Smith et al. 1999; Mariotte et al. 2012) as well as the structure (Wilson and Hartnett 1997; O'Connor et al. 2002),
86 species richness and composition of plant communities (Gange et al. 1993; Francis and Read 1994; Zobel and
87 Moora 1995). This makes AMF dynamics a key to improving our comprehension of ecosystem functioning, and
88 a topic that clearly warrants further investigation. Ecosystems in stressful environments are known to favor biotic
89 interactions such as facilitation within plant species (Callaway et al. 2002; He et al. 2013) or with AMF (van der
90 Heijden et al. 2003), especially old-growth grasslands. These ancient grassland ecosystems characterized by high
91 species richness, high endemism, and unique species composition (Veldman et al. 2015) have had time to develop
92 species-specific relationships with soil organisms (Tscherko et al. 2005; Bauer et al. 2015).

93
94 Such old-growth grasslands (e.g. dehesa in Spain or continental steppes in Siberia) are particularly threatened.
95 Technical progress in agronomy in the last century allowed agricultural intensification in low-productivity
96 ecosystems (Huston 2005). Understanding how such changes in land-use can alter these ecosystems is important,
97 especially when environmental authorities aim to stop biodiversity loss and target 15% ecosystem restoration
98 (Millennium Ecosystem Assessment 2005; Convention on Biological Diversity 2011). In this context,
99 abandonment of intensive land-use can be viewed as an opportunity both to restore former ecosystems and to study
100 ecosystem natural recovery (Prach and Walker 2011). While old-growth grasslands usually show poor recovery
101 after severe anthropogenic disturbance (Forey and Dutoit 2012; Veldman et al., 2015), little seems to be known
102 about the recovery of other ecosystem components, such as soil or AMF.

103 Cultivation can be seen as a severe anthropogenic disturbance for natural or semi-natural plant communities:
104 during cultivation, disturbance occurs over a large scale exceeding plant community processes (Peterson et al.
105 1998; Huston 1999) and its strength (i.e. the force of the disturbance; Sousa 1984) is high. The severity of
106 disturbance (i.e. the damage caused by the disturbance; Sousa 1984) is also high, as the majority of mature plants
107 initially present are killed prior to and during a cultivation event. As a consequence, anthropogenic disturbance
108 such as cultivation is followed by low recovery in many ecosystems, such as grasslands, heathlands or forests
109 (Bellemare et al. 2002; Dupouey et al. 2002; Römermann et al. 2005; Elmore et al. 2007; Gustavsson et al. 2007).
110 In the medium term (i.e. decades), vegetation recovery has been proven to be very poor (Römermann et al. 2005;
111 Buisson et al. 2006). Cultivation disturbance generally leads to leaching of amended nutrients and therefore a
112 progressive recovery of soil chemical properties, except for phosphorus, which is known to remain in soil (Smits
113 et al. 2008; Henkin et al. 2010). Due to their low dispersal and competitive abilities, most steppe plant species can
114 recolonize only a few meters from remnant steppe patches (Buisson et al. 2006). This means recovery of vegetation
115 composition is usually poor even when abandoned fields are surrounded by remnant steppe patches.

116 To address AMF recovery dynamics, we chose the La Crau area of south-eastern France, an old-growth
117 Mediterranean dry grassland or steppe plant community impacted by thousands of years of interaction between (1)
118 Mediterranean climate, (2) a particularly well-draining soil and (3) extensive sheep grazing (Devaux et al. 1983;
119 Buisson and Dutoit, 2006). Almost 20% of this species-rich plant community was once cultivated and then
120 abandoned. As AMF root colonization depends not only on AMF dispersal abilities but also on host abundance
121 and soil conditions, our hypothesis was that the more recent and intense the disturbance is, the less AMF root
122 colonization recovers.

123 We assessed AMF root colonization on four plant species from this Mediterranean steppe after three disturbance
124 events (a vineyard abandoned for 150 years, a melon field abandoned for 35 years and an intensive orchard
125 abandoned for 2 years), compared to an undisturbed ecosystem, to determine whether AMF root colonization
126 recovers after cultivation disturbance.

127 Materials and methods

128 Study area

129 The La Crau area is the last xeric steppe of south-eastern France (ca. 10,000ha). It is shaped by i) a dry
130 Mediterranean climate, ii) a 40cm-deep soil with about 50% of siliceous stones overlying an almost impermeable
131 conglomerate layer, making the alluvial water table unavailable to plant roots and iii) itinerant sheep grazing over
132 a period of several thousand years (Devaux et al. 1983; Buisson and Dutoit 2006). This has led to a unique and
133 species-rich vegetation association composed mainly of annuals and dominated by *Brachypodium retusum* Pers.
134

135 and *Thymus vulgaris* L.. The steppe, which experienced recurring anthropogenic disturbance until 400 BP from
136 sheep grazing and pastoral fires, has lost more than 80% of its original 45,000 ha area due to other anthropogenic
137 disturbances such as intensive cultivation (Buisson and Dutoit 2006). Our study focuses on three types of
138 cultivation, all initiated on the original steppe, applied for several years and today abandoned: (1) a vineyard
139 abandoned approximately 150 years ago (AF-150) as revealed from consultation of old cadastral maps and land
140 registers (Dutoit et al. 2005), (2) two melon fields, cultivated for one year only before being abandoned 35 years
141 ago (AF-35) (Römermann et al. 2005) and an orchard cultivated for 17 years, abandoned in 2006 and which
142 underwent its last disturbance comparable to ploughing in 2009, two years before sampling (Jaunatre et al. 2014)
143 (AF-2) (Fig. 1). The control was the surrounding steppe, whose available history (Cassini et al. 1778) showed no
144 severe anthropogenic disturbance. The three types of cultivation represent a gradient both of time since
145 abandonment and of disturbance intensity: the vineyard probably underwent only one ploughing and no herbicide
146 applications (Dutoit et al. 2005), the melon field underwent one ploughing and one fertilizer and herbicide
147 application (Römermann et al. 2005), while the orchard underwent repeated ploughing, fertilizer and herbicide
148 applications (Jaunatre et al. 2014).

149 2.2. Sampling

150 We concentrated our sampling areas around the former vineyard (AF-150, n=3) and the former orchard (AF-2,
151 n=3) as they are unique in the La Crau area (Fig. 1). Two steppe sites (ST-6000, n=6) and two sites in fields
152 abandoned for 35 years (AF-35, n=6) were selected, one of each in proximity to either AF-150 or AF-2. The
153 imbalance in design is due to the fact that there was only one site abandoned for 150 years before sampling and
154 only one site abandoned for 2 years before sampling in the entire La Crau area (10 000 ha). We considered the
155 distance between sampling areas (>70m; Fig 1c) sufficient because of the very weak dispersal ability of La Crau
156 plant species (i.e. after 19 years of abandonment, half the species had colonized less than a few meters, Buisson
157 and Dutoit 2004; Buisson et al., 2006). In each of the six sites selected, three sampling areas were set up to sample
158 AMF root colonization, vegetation and soil (Fig. 1d).

159 AMF root colonization

160 Colonization by AMF was assessed from roots of four species occurring over almost the entire gradient described
161 above: i) *Carthamus lanatus* L, an Asteraceae more abundant in the steppe, ii) *Carduus pycnocephalus* L, an
162 Asteraceae more abundant in the abandoned fields, iii) *Brachypodium distachyon* (L.) P. Beauv, a Poaceae more
163 abundant in the steppe and iv) *Bromus madritensis* L, a Poaceae more abundant in the abandoned fields. When
164 possible, in each sampling area three individuals of each species were collected; however, some species were not
165 present in some sampling areas. Air-dried roots were colored with black Schaeffer ink using the vinegar coloration
166 method (Vierheilig et al. 1998). For total percentage AMF root colonization, internal hyphae, vesicles or arbuscules
167 were counted with the magnified intersections method using 100 intersections (McGonigle et al. 1990).

168 Soil analyses

169 In each sampling area, three 70g sub-samples of soil were taken from depths of 1-10cm (Fig. 1d) and pooled to
170 constitute one soil sample. Soil was sieved (2mm mesh) for analyses carried out by INRA (*Institut National de la*
171 *Recherche Agronomique, Arras, France*). Granulometry without decarbonation (percentage content of clay
172 (<0.002 mm), fine silt (0.002-0.02 mm), coarse silt (0.02-0.05 mm), fine sand (0.05-0.2 mm) and coarse sand (0.2-
173 2 mm)), nutrients (organic C, total N, P₂O₅ (Olsen et al. 1954), CaO, and K₂O) and pH were measured according
174 to the methods described in Baize (2000).

175 Vegetation survey

176 Vegetation relevés were performed on three 2x2m quadrats for each sampling area using Braun-Blanquet
177 coefficients (Braun-Blanquet et al. 1952). In addition, average vegetation height (i.e. height of the dominant
178 stratum) and cover (in percentage) were estimated in each quadrat.

179 Data analysis

180 Generalized Linear Mixed Models (GLMM) were used to determine whether the cultivation disturbance continued
181 to affect AMF root colonization, soil chemical variables and plant community characteristics. We compared two
182 models: in the first, age was implemented as a categorical fixed factor and blocks (i.e. around the AF-2 or around
183 AF-150; Fig. 1) as a categorical random factor; the second contained neither a fixed factor nor blocks as a
184 categorical random factor. If the first model containing age had a lower Aikake Information Criterion (AIC) with
185 a difference greater than 2, age effect was declared significant (Burnham and Anderson 2004) and difference
186 between ages was assessed by a multiple comparison test using Tukey's method. To obtain a global overview of
187 soil parameters and of plant communities, we ran a Principal Component Analysis (PCA) for soil parameters and
188 a Correspondence Analysis (CA) for plant community (Borcard et al. 2011). To measure similarity of plant
189 communities to those of the undisturbed control, we used the normalized Community Structure Integrity Index
190 (CSII_{norm}) and the Higher Abundance Index (HAI) to distinguish the percentage of recovery of reference species
191 abundances (CSII_{norm}) from new abundances not occurring in this reference (HAI) (Jaunatre et al., 2013).

192 All analyses were performed with R 2.13.0 (R Development Core Team 2011), univariate analyses with its package
193 "lme4" and "multcomp" (Hothorn et al. 2008; Bates et al. 2012) and multivariate analyses with its packages "ade4"
194 (Chessel et al. 2004; Dray and Dufour, 2007; Dray et al. 2007) and "vegan" (Oksanen et al. 2008).

195 **Results**

196 *AMF root colonization*

197 AMF root colonization recovered to ST-6000 values (approximately 90%) in all three abandoned fields for forbs
198 (*Carthamus lanatus* and *C. pycnocephalus*; Fig. 2, Table 1). However, both grasses did not recover in all the
199 locations: *Bromus madritensis* shows lower AMF root colonization in AF-2 (40.7 ± 3.8) than in ST-6000 (63.9 ± 4.2)
200 (Fig. 6, Table 1) and *B. distachyon* shows a significant difference in AMF root colonization between AF-35
201 (51.4 ± 5.9) and ST-6000 (64.2 ± 2.1) (no *B. distachyon* was found in AF-2).

202 *Soil analyses*

203 The PCA of soil properties (Fig. 3) clearly discriminates among the four locations. The first axis (35.2%) shows a
204 clear distinction in age between the field abandoned 2 years previously (AF-2) and the three other locations, with
205 higher concentrations of P₂O₅, pH and K₂O (Fig. 4), although only pH is significantly higher (Table 1). The second
206 axis (24.5%) discriminates the steppe (ST-6000) from the longest-abandoned field (AF-150), with higher carbon
207 and nitrogen content (Fig. 4), although only carbon differences are significant (Table 1).

208 *Vegetation survey*

209 Compared to the reference, all three abandoned fields have significantly different values for composition and
210 structure (Table 1, Fig. 5). Their CSII_{norm} is lower: AF-150 and AF-35 have recovered less than 60% of the
211 vegetation structure, while AF-2 has recovered less than 20%. Their HAI is higher: in AF-150 and AF-35, 50% of
212 the structure is composed of species whose abundances are higher than in ST-6000 (both new species and the same
213 species); while in AF-2, more than 70% of species have abundances higher than in ST-6000. These differences in
214 plant community variables are also discernible on the correspondence analysis (Fig. 6): AF-2 is dominated by
215 *Bromus madritensis* L., *Bromus lanceolatus* Roth and *Carduus pycnocephalus* L.. AF-35 is also characterized by
216 Poaceae and Asteraceae (*Bromus hordeaceus* L., *Bromus rubens* L., *Carthamus lanatus* L. etc.). AF-150 and ST-
217 6000 share many species (e.g. *Aegilops ovata* L., *Brachypodium distachyon* (L.) P. Beauv., *Carlina corymbosa* L.,
218 *Erodium cicutarium* (L.) L'Hérit. or *Plantago bellardii* All.), although i) some dominant ST-6000 species are
219 absent from AF-150 (e.g. *Brachypodium retusum* (Pers.) P. Beauv.) and ii) some AF-150 species are absent from
220 ST-6000 (e.g. *Bothriochloa ischaemum* (L.) Keng, *Crucianella angustifolia* L.). The species richness of AF-150
221 is not significantly different from that of ST-6000; however, it is significantly lower for AF-35 and AF-2. All the
222 abandoned field locations except AF-2 have recovered ST-6000 average height and vegetation cover, while AF-2
223 shows significantly higher values (Table 1, Fig. 5).

224 **Discussion**

225 It takes a very long time to recover ecosystem characteristics. This has been proved for many different old-growth
226 grassland types, such as Midwest prairie, Scandinavian semi-natural grasslands, Mediterranean steppe or limestone
227 grassland (Tomanek et al. 1955; Bonet et Pausas 2004; Öster et al. 2009; Forey and Dutoit 2012), and our study
228 confirms it. Most of these low-resilient ecosystems have similar characteristics: harsh environmental conditions,
229 which are attenuated by the disturbance event (i.e. nutrient or water availability is increased). In such a context,
230 some plant species adapted to higher nutrient content can colonize and generate relatively stable mutualistic
231 associations with soil organisms, such as AMF or microbial communities, thus slowing down the potential
232 recovery of the original state (Spiegelberger et al. 2006; Wardle et al. 2014). Our study shows that it is not only
233 vegetation and soil components that are durably affected by a severe anthropogenic disturbance such as cultivation:
234 there is an impact on AMF root colonization too. The results also confirm our hypothesis that the more recent and
235 intense the disturbance is, the less AMF root colonization recovers. Our findings are in line with those from studies
236 on different components under harsh environmental conditions, which reacted in a similar way (Hejcman et al.
237 2007; Spiegelberger et al. 2010, 2006). However, new evidence is provided here on ecosystem recovery via the
238 recovery of AMF root colonization, rarely studied in parallel with soil and plant communities.

239 *AMF root colonization*

240 AMF root colonization can decrease due to any soil disturbance (Jasper et al. 1989). Agricultural practices in
241 particular are known to impact AMF communities, modifying their abundance, their diversity and their
242 composition (Douds et al. 1995; Jansa et al. 2003), and their reproduction dynamics (Oehl et al. 2009). Areas
243 cultivated with more fertilizer show less AMF root colonization (Douds et al. 1995; Mäder et al. 2000). In our
244 study, the AMF root colonization rate increases with time since cultivation abandonment for two plant species out
245 of four. It has previously been shown that AMF root colonization can recover with time (Eriksson 2001; Gibson-
246 Roy et al. 2014) but that this depends on plant community composition (Fitzsimons et al. 2008). This is supported
247 by our results: AMF root colonization recovered and was no longer significantly different from the steppe after 35
248 years, except for *B. distachyon*, and the field abandoned for 35 years showed over 50% recovery of plant
249 community structure (Figure 5). It should be noted that the major finding here is the difference between AMF root
250 colonization in abandoned fields and in the reference. The similar values found here for AMF root colonization
251 may in fact mask an absence of recovery of certain AMF species, since it is likely that different AMF species are
252 involved. This hypothesis is supported by the fact that AMF community composition can be altered by a change
253 in plant community composition (Klamer and Hedlund, 2004), and such a change occurred in our abandoned fields.
254 We did not find any difference in root colonization recovery between species more abundant in the steppe (*C.*

255 *lanatus* and *B. distachyon*) and species more abundant in the abandoned fields (*C. pycnocephalus* and *B.*
256 *madritensis*). We found, however, that grasses (*B. distachyon* and *B. madritensis*) have higher average mycorrhizal
257 root colonization and higher recovery of mycorrhizal root colonization than forbs (*C. lanatus* and *C.*
258 *pycnocephalus*), which confirms that plant functional type is the most important driver of plant response to
259 mycorrhizal fungi (Hoeksema et al. 2010).

260 *Soil parameters*

261 The different abandoned fields are found to have contrasting soil properties. The former vineyard, which is the
262 longest abandoned field, has the lowest pH and potassium and phosphorus content. However, the difference in
263 fertilization practices can also introduce biases; fertilizer use was more sparing and more organic-based 150 years
264 ago than 3 years ago (Dutoit et al. 2005). Annual, and therefore cumulative, fertilizer quantities are difficult to
265 estimate. Despite these potential biases, our results are consistent with findings from other studies: as in Wong et
266 al. (2010), potassium and phosphorus content tend to decrease with time since last cultivation, and as in studies on
267 Mediterranean or calcareous grasslands (Smits et al. 2008; Henkin et al. 2010), high soil phosphorus content is
268 maintained even 35 years after cessation of fertilization. Soil properties are known to be very important in
269 determining plant community diversity, structure and composition. For instance, Kulmatiski et al. 2006 showed
270 how soil legacies impact invasive plant species distributions and Janssens et al. (1998) suggested that 5 mg of
271 phosphorus per 100 g of dry soil is a threshold value limiting establishment of species-rich plant communities.
272 Despite the fact that in our abandoned fields current soil phosphorus content remains close to (AF-2) or below this
273 level (AF-35 and AF-150), it is possible that a previous higher phosphorus content had a long-term effect which
274 can still be observed, even after the recovery of lower values (Semelová et al. 2008).

275 *Plant communities*

276 As with soil, the longer the time since abandonment, the more plant community characteristics in abandoned fields
277 differ from the reference. More recently abandoned fields have lower species richness or CSII, while they have
278 higher HAI, average vegetation height and cover. Moreover, vegetation composition, which is mainly dominated
279 by grasses such as *Bromus* spp. in the most recently abandoned fields, gains in species richness and in the number
280 of forbs with time since abandonment. Similar slow recolonization was observed in other ecosystems after severe
281 disturbances (Tomanek et al. 1955; Coffin et al. 1996; Meiners et al. 2002; Bonet and Pausas 2004). However after
282 150 years, while the vegetation composition of the abandoned field is close to that of the steppe it is still slightly
283 different, notably due to the absence of *B. retusum*, the dominant steppe species. Interestingly, the species with the
284 lowest AMF root colonization recovery rate (*B. distachyon*) is phylogenetically closest to *B. retusum* (The
285 Angiosperm Phylogeny Group 2009). *B. retusum* is not present in any part of this long-abandoned field, although
286 it is the dominant steppe species and occurs at the abandoned field boundaries, and despite the fact that all measured
287 environmental characteristics are not significantly different. Low seed production and fertility, and hence poor
288 dispersal abilities, have already been hypothesized (Buisson et al. 2006; Coiffait-Gombault et al. 2012). The slow
289 recovery of AMF root colonization rates in a phylogenetically close species would suggest that *B. retusum* not
290 only has low seed production (Caturla et al. 2000) but also suffers from a lack of AMF interaction. This interaction
291 would likely enhance its growth by higher phosphorus uptake (López-Sánchez et al. 1992), enabling it to establish
292 in abandoned fields.

293 *Ecosystem recovery*

294 Our results on vegetation are consistent with previous studies, where: vegetation was still affected 70 years after a
295 fertilization event, even though the soil almost recovered its properties (Spiegelberger et al. 2006); only half the
296 species were able to colonize abandoned fields 50 years later (Öster et al. 2009); or differences in plant
297 communities were still significant more than 2000 years after a cultivation event in a forest community (Dupouey
298 et al. 2002). The filter model is often used to describe vegetation dynamics (Keddy 1992; Lortie et al. 2004): i)
299 plant species have to be able to disperse, which depends on species dispersal abilities and proximity of source site
300 (Gibson and Brown 1991; Pärtel and Zobel 1999; Lindborg and Eriksson 2004; Hérault and Thoen 2009); ii) plant
301 species have to be able to withstand environmental constraints, which depends both on historical environmental
302 conditions and on disturbance legacies (Foster et al. 2003) and iii) the first two filters will be modified by biotic
303 interactions and will depend on the presence of facilitators or competitors in the community (Bruno et al. 2003).
304 This model explains the low resilience of plants after cultivation in the La Crau area: species have low dispersal
305 abilities and no permanent seed bank (Graham and Hutchings 1988; Römermann et al. 2005), soil nutrient content
306 is still different in recently abandoned fields, and finally, some species are better competitors under higher nutrient
307 conditions (Baeten et al. 2009; Öster et al. 2009), especially if they arrived first due to chance or better dispersal
308 abilities (Fukami et al. 2005).

309 It should be feasible to apply a similar model to AMF, to explain their recovery after a severe anthropogenic
310 disturbance, as suggested by Lekberg et al. (2007). If AMF have been eliminated during the cultivation event
311 (Douds et al. 1995; Jansa et al. 2003), they have to disperse through the disturbed area. Wind seems to be a poor
312 long-distance disperser (Egan et al., 2014), but faunal agents may also provide some local-scale dispersal (Warner
313 et al. 1987; Allen 1989; Harinikumar and Bagyaraj 1994). Hyphae not killed by cultivation can also be a rich
314 source of AMF; however, they are highly affected by soil disturbance (Jasper et al. 1989; Brundrett and Abbott,

1994). AMF root colonization thus depends on environmental conditions: the more available nutrients are, the less roots are colonized by AMF (Koide, 1991). Our findings support this: AMF root colonization was higher in the abandoned fields with lower soil nutrient content. Finally, AMF root colonization depends on biotic interactions. In our study, the abandoned field with the highest vegetation average height and the highest vegetation cover (AF-2) was found to have the lowest mycorrhizal root colonization. These results are in accordance with the negative relationship between vegetation biomass and AMF biomass already found in abandoned fields (Hedlund et al., 2003). Despite the fact that mechanical soil disturbance plays a greater role than plant communities in shaping AMF communities (Schnoor et al. 2011), plant species richness has been shown to increase the diversity and fitness of AMF (Burrows and Pflieger, 2002). Moreover, the diversity of AMF infecting an individual plant depends on the diversity of the whole plant community (van de Voorde et al. 2010), and the composition of the plant community has a significant effect on the composition of the AMF community (Johnson, 1993; Eom et al. 2000; Hiiesalu et al., 2014).

Our study is a first step towards exploring the relationship between a proxy of AMF (AMF root colonization), soil conditions and plant communities. In accordance with our hypotheses, recovery of these three ecosystem components differs, increasing from vegetation (lowest recovery) to AMF root colonization (intermediate recovery), to soil conditions (highest recovery). All three components assessed are moving towards the undisturbed state, but full, unassisted recovery is highly unlikely within a human lifetime.

Feedbacks occurring between different ecosystem components, as in a panarchy model, need to be taken into account to understand the overall recovery process. One component starts to recover while being influenced by another component; based on these dynamics, the recovery of the first component is affected, and in turn the recovery of other components is further influenced (Allen et al. 2014). To our knowledge, although few studies have measured the recovery of different components of an ecosystem after disturbance, most of them found, like us, staggered responses for each component (García-Tejero et al. 2013; Wardle and Jonsson, 2013). Determining the limiting components able to affect, slow down or stop the recovery dynamics of the whole ecosystem would be of particular interest in a restoration context. AMF communities affect plant communities in complex ways: like plants, not all AMF species play the same role in ecosystems (Hart et al. 2003). The effects of AMF on plants are species-specific (Hoeksema et al. 2010; Endresz et al. 2013), but also depend on environmental conditions (Grime et al. 1987; Hartnett and Wilson, 1999; Kytöviita et al. 2003), and higher AMF root colonization is not always linked with better vegetation recovery (Richter et al. 2002). Further research is required to explore how different ecosystem components can affect overall ecosystem recovery, and how they could be used to facilitate or to accelerate this recovery in a restoration context (Allen, 1989; Herrera et al. 1993; Callaway et al. 2001; Kardol et al. 2009).

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606 **Tables**

607 Table 1: Aikaike Information Criterion of Generalized Linear Mixed Models, one including Age as a fixed effect
 608 and Block as a random effect, the other including only Block as a random effect. Stars preceding variable names
 609 indicate that the model including age is better (i.e. $\Delta AIC > 2$; Burnham and Anderson, 2004) and age can
 610 therefore be considered as affecting the variable.

	Variable	AIC <i>Age+Block</i>	AIC <i>Block</i>
Mycorrhizal root colonization	* <i>Brachypodium distachyon</i>	276.1	289.8
	* <i>Bromus madritensis</i>	344.2	368.5
	* <i>Carthamus lanatus</i>	274.7	286.0
	* <i>Carduus pycnocephalus</i>	187.0	198.1
Vegetation	*Species-richness	364.7	472.6
	*CSII	-50.5	40.8
	*HAI	-110.5	-14.9
	*Average height	351.5	410.0
	*Vegetation cover	430.7	474.5
Soil	*Carbon	69.2	76.8
	*pH	9.5	19.5
	C:N	23.2	25.0
	Nitrogen	3.1	-6.9
	Phosphorus	-54.8	-69.8
	Potassium	-30.8	-40.3

611

612 **Figure Captions**
613

614 **Fig. 1** Study site and sampling design. a: location of La Crau area in France. b: location of study area in La Crau
615 area. c: location of sites: the two steppe sites (ST-6000) and the field sites abandoned for 150 (AF-150), 35 (AF-
616 35) and 2 (AF-2) years. Dark grey areas represent sampled abandoned fields. d: detailed scheme of design per
617 sampling area, large circle represents the area prospected for individuals of the four species for mycorrhizal root
618 colonization assessment, grey squares represent the three 2x2m quadrats where plant species abundances were
619 recorded and black dots represent the three soil samples before pooling for soil physical and chemical analyses
620 **Fig. 2** Mean mycorrhizal root colonization for the four species in steppe (white, ST-6000) and abandoned fields
621 (grey, AF-2/35/150). Error bars represent standard error; bars having a common letter are not significantly different
622 (Tukey; $p>0.05$). Numbers inside plots indicate the number of individual plants on which mycorrhizal root
623 colonization was counted. Missing bars indicate that the species was not found in any plot of the abandoned field
624 **Fig. 3** Ordination plot of the Principal Component Analysis based on soil granulometry and nutrient content in
625 steppe (white, ST-6000) and abandoned fields (grey, AF-2/35/150). Arrows represent soil variables (coarse sand,
626 fine sand, coarse silt, fine silt, clay, organic matter, C:N: Carbon/Nitrogen ratio; C: total carbon; N: total nitrogen;
627 K_2O : potassium, P_2O_5 : Olsen phosphorus; CaO: Calcium oxide and pH). Polygons surround the points
628 corresponding to one age class
629 **Fig. 4** Soil nutrient content in steppe (white, ST-6000) and abandoned fields (grey, AF-2/35/150). Mean values \pm
630 standard error of carbon (C), nitrogen (N), C/N ratio (C/N), phosphorus (P_2O_5), and potassium (K_2O) in steppe
631 (ST-6000) and abandoned fields (AF-2/35/150). Bars having a common letter are not significantly different
632 (Tukey; $p>0.05$)
633 **Fig. 5** Mean species richness per 4 m² (a), normalized Community Structure Integrity (b), Index Higher Abundance
634 Index (c), average height (d) and percentage of vegetation cover (e) in steppe (white, ST-6000) and abandoned
635 fields (grey, AF-2/35/150). Error bars represent standard error; bars having a common letter are not significantly
636 different (Tukey; $p>0.05$)
637 **Fig. 6** Ordination plot of the Correspondence Analysis based on vegetation abundances on steppe (white, ST-6000)
638 and abandoned fields (grey, AF-2/35/150). Based on 54 relevés and 110 species, showing the 35 most correlated
639 with the axes. Polygons surround the points corresponding to one age class
640