



**HAL**  
open science

## Benefits of dual inoculation with arbuscular mycorrhizal fungi and rhizobia on *Phaseolus vulgaris* planted in a low-fertility tropical soil

A.T.E. Razakatiana, Jean Trap, R.H. Baohanta, M. Raherimandimby, C. Le Roux, R. Duponnois, H. Ramanankierana, Thierry Becquer

### ► To cite this version:

A.T.E. Razakatiana, Jean Trap, R.H. Baohanta, M. Raherimandimby, C. Le Roux, et al.. Benefits of dual inoculation with arbuscular mycorrhizal fungi and rhizobia on *Phaseolus vulgaris* planted in a low-fertility tropical soil. *Pedobiologia*, 2020, 83, pp.150685. 10.1016/j.pedobi.2020.150685 . hal-02965344

**HAL Id: hal-02965344**

**<https://hal.inrae.fr/hal-02965344>**

Submitted on 17 Oct 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

1 **Short Communication**

2

3

4 **Benefits of dual inoculation with arbuscular mycorrhizal fungi and rhizobia on**  
5 ***Phaseolus vulgaris* planted in a low-fertility tropical soil**

6

7 A.T.E. Razakatiana<sup>a,b</sup>, J. Trap<sup>c</sup>, R.H. Baohanta<sup>b</sup>, M. Raherimandimby<sup>a</sup>, C. Le Roux<sup>d,e</sup>, R.  
8 Duponnois<sup>e</sup>, H. Ramanankierana<sup>b</sup>, T. Becquer<sup>c,\*</sup>

9

10 <sup>a</sup> Université d'Antananarivo, Faculté des Sciences, Laboratoire de Biotechnologie et de  
11 Microbiologie, BP 906, Antananarivo, Madagascar

12 <sup>b</sup> Centre National de Recherches sur l'Environnement (CNRE), Laboratoire de Microbiologie  
13 de l'Environnement (LME), BP 1739, Antananarivo, Madagascar

14 <sup>c</sup> Eco&Sols, Univ Montpellier, CIRAD, INRA, IRD, Montpellier SupAgro Montpellier,  
15 France

16 <sup>d</sup> CIRAD, UMR LSTM, F-34398 Montpellier, France.

17 <sup>e</sup> LSTM, Univ Montpellier, CIRAD, INRA, IRD, Montpellier SupAgro, Montpellier, France

18

19

20 \*Corresponding author:

21 Thierry Becquer

22 Institut de Recherche pour le Développement (IRD), UMR Eco&Sols, 2 Place Pierre Viala, F-  
23 34060 Montpellier, France

24 *E-mail address:* thierry.becquer@ird.fr

25 **Abstract**

26 The growth response of *Phaseolus vulgaris* to dual inoculation with arbuscular mycorrhizal  
27 (AM) fungi and rhizobia was studied in a low-fertility tropical soil in Madagascar. Two  
28 isolates of AM fungi identified as *Acaulospora* sp. and *Glomus* sp., respectively, along with a  
29 cocktail of ten *Rhizobium* spp. strains were used to conduct a greenhouse experiment in a  
30 fully randomized block design with two factors. The *Phaseolus vulgaris* seedlings received  
31 one of the following inoculation treatments: no inoculation, separate inoculation with each of  
32 the three microbial symbionts (the two AM fungal isolates and the rhizobia), and co-  
33 inoculation with each of the two AM fungal isolates and the mix of rhizobium strains. The  
34 results showed an additive effect of co-infection by AM fungi and rhizobia on plant growth  
35 and on the total N content of the plants, along with a synergistic effect on the total P content,  
36 the number of nodules and the mycorrhizal rate of the plants. Dual symbiosis with native  
37 strains contributes to the success of legumes, especially in harsh environments and low-  
38 fertility tropical soils.

39

40 **Keywords:** Arbuscular mycorrhizal fungi; Rhizobia; Dual inoculation; Native strains; low-  
41 fertility tropical soil

42

## 43 **1. Introduction**

44 The intensive agriculture model, based on the use of synthetic inputs and natural  
45 resources to minimize the effects of production-limiting factors and environmental  
46 heterogeneity, is gradually giving way to an alternative model based on agro-ecological  
47 technologies (Duru and Therond, 2015; Stavi et al., 2016). One such technology relies on  
48 biodiversity management within agro-ecosystems to provide supporting and regulating  
49 ecosystem services in a manner to improve resource-use efficiency and reduce the negative  
50 impacts of conventional agriculture (Duru and Therond, 2015).

51 Within this biodiversity, soil microorganisms mostly belonging to the bacteria and fungi  
52 are involved in complex and diverse forms of interactions with terrestrial plants (van der  
53 Heijden et al., 2016). Consequently, plants can no longer be considered as stand-alone  
54 biological entities (Vandenkoornhuyse et al., 2015). Their multiple and complex interactions  
55 with mutualistic symbionts enable them to derive a wide range of benefits (Ossler et al., 2015;  
56 Souza et al., 2015). Indeed, it is widely recognized that soil microorganisms perform crucial  
57 roles in nutrient cycling and are involved in key plant functions, such as nutrition and growth  
58 (Richardson et al., 2009).

59 Two of these complex interactions have been widely described: the close association  
60 between roots and (i) fungi forming the well-known arbuscular mycorrhizal (AM) fungal  
61 association and (ii) bacteria belonging to the genus *Rhizobium* forming the root-nodule with  
62 Fabaceae. AM fungi are obligate plant symbionts that provide resources for plants, primarily  
63 phosphorus (P), in exchange for plant photosynthates (Smith and Read, 2008). Rhizobia are  
64 free-living soil bacteria that colonize the root systems of many legume species and fix  
65 atmospheric nitrogen (N) (Peoples et al., 1995). A key meta-analysis found an overall additive  
66 effect of co-infection by AM fungi and rhizobia on plant growth responses (Larimer et al.,  
67 2010). To our knowledge, few studies have investigated synergistic effects arising from

68 mixed inoculation of Rhizobium-mycorrhiza (e.g. Young et al., 1988). However, according to  
69 Nadeem et al. (2014), synergistic interactions are more likely to be effective in conditions  
70 where biotic or abiotic stresses have occurred.

71 One of the major mechanisms by which inoculation with AM fungus acts on plant  
72 functions seems to be phosphatase activity, involving key enzymes responsible for the  
73 hydrolysis of organic P (Tabatabai, 1994). Indeed, there is a broad consensus on the limitation  
74 of symbiotic N<sub>2</sub> fixation by P availability in terrestrial ecosystems (Augusto et al., 2013) and  
75 the lack of adequate levels of available P in tropical soils, such as in Madagascar, is one of the  
76 major constraints for crop production (Raminoarison et al., 2020). Despite various studies  
77 showing the benefits of the dual inoculation of legumes, such effectiveness in low-fertility  
78 tropical soils with a high P sorption capacity is still poorly documented.

79 The aim of this study was to determine the effects of dual inoculation of both native  
80 microsymbionts, rhizobial bacteria and AM fungi, on *Phaseolus vulgaris* growth in a P- and  
81 N-depleted tropical soil. Given the complementarity of N and P as plant growth-limiting  
82 resources, this study tested the hypothesis that dual inoculation with both symbionts would  
83 have a positive interaction in association with plant roots, and would benefit *Phaseolus*  
84 *vulgaris* growth and productivity. Moreover, we assumed that, whereas most of the time AM  
85 fungi and rhizobia do not interact synergistically (Larimer et al., 2010), it could be more  
86 effective for enhancing N fixation in stressful environments caused by the low availability of  
87 P in tropical soils.

88

## 89 **2. Materials and methods**

90 We conducted a greenhouse experiment in Madagascar with *Phaseolus vulgaris* L. cv.  
91 Ranjonomy as a plant model. A Ferralsol (0-20 cm), typical of the hills of the Malagasy  
92 Highlands, was collected at Lazaina (18°46' S, 47°32' E, North of Antananarivo) from

93 unfertilized long-term grassland fallows. It was an acidic (pH 5.4) sandy clay loam, with total  
94 carbon, N and P contents of 16.4, 0.91 and 0.61 g kg<sup>-1</sup>, respectively (Henintsoa et al., 2017).  
95 Phosphorus availability was very low ( $P_{i\text{water}} = 1.1 \text{ mg P kg}^{-1}$ ) due to its sorption by clay  
96 minerals and iron/aluminium oxides, which amounted to 244 g kg<sup>-1</sup> for kaolinite, 247 g kg<sup>-1</sup>  
97 for gibbsite and 36 g kg<sup>-1</sup> for iron oxides. It was sieved with a 2-mm mesh, mixed (1:1, w/w)  
98 with washed river sand (with total C, N and P contents of 0.17, 0.013, 0.002 g kg<sup>-1</sup>), and  
99 autoclaved at 121°C for 40 min.

100 Native strains of rhizobia and AM fungi were isolated from the roots and rhizospheric  
101 soil of bean (*Phaseolus vulgaris*), respectively, taken from an experimental design with  
102 intercropped bean and rice growing in the same soil at Lazaina. Two AM fungal isolates  
103 extracted by the wet sieving and decanting method (Gerdemann and Nicolson, 1963) were  
104 selected. They were identified according to their morphological features (colour, size and  
105 shape), and by using the key provided by the International Culture Collection of Vesicular  
106 Arbuscular Mycorrhizal Fungi (INVAM, <http://www.invam.wvu.edu>): M1, with 50- $\mu\text{m}$   
107 brown spores, consisting of *Acaulospora* sp. and M2, with 80- $\mu\text{m}$  black spores, consisting of  
108 *Glomus* sp. The rhizobial inoculum S1 corresponded to a cocktail of ten *Rhizobium* spp.  
109 strains from bioassays carried out on a collection of infective isolates, selected for their  
110 greater symbiotic effectiveness.

111 The experiment was a fully randomized block design with two factors, inoculations of  
112 AM fungus (coded “M”) and rhizobia (coded “S”), and four replications. The design  
113 comprised a negative control without inoculation (coded “S0/M0”), and treatments with  
114 inoculation by the two AM fungal strains, *Acaulospora* sp. (“M1”) or *Glomus* sp. (“M2”), and  
115 by the rhizobial mixture (“S1”), either alone or together.

116 One bean seed was sown in 1-litre mesocosms with 1 kg of a sterile soil-sand mixture  
117 placed in a greenhouse with a 12-hour photoperiod and 28/18°C day/night temperature. Tap

118 water was supplied every two days to adjust moisture to nearly 80% of water-holding  
119 capacity, i.e. 31 g of water per 100 g of the dry soil-sand mixture. The soils were inoculated  
120 on sowing with AM fungi and/or one week after sowing with rhizobia. For AM fungi, the  
121 strains were maintained on *Sorghum* sp. grown for 6 weeks in sterilised sand, and a sand  
122 inoculum (1 g of chopped AM-colonized sorghum roots (75% infection levels) and 50 g of  
123 sand) was placed in a 5-cm slot made near the seedling (Duponnois et al., 2001). For rhizobia,  
124 5 ml of liquid inoculum, grown on yeast mannitol broth (YMB) for 24 h, was applied to the  
125 base of each seedling. The negative controls (S0 and M0) were managed in the same way as  
126 the positive ones, but without inocula, i.e. by adding 5 ml of YMB for S0 or a mixture of sand  
127 and non-mycorrhizal sorghum roots for M0.

128 Plants were harvested two months after sowing. Shoots and roots were gently separated  
129 and washed to remove the soil, and their biomass was determined after drying at 65°C for  
130 48 h. The N and P contents of the shoot biomass were determined by the Kjeldahl method and  
131 by colorimetry (molybdenum blue) after acid digestion, respectively. Nodules were separated  
132 from fresh roots and counted. Fresh roots were stained with Trypan Blue (Phillips and  
133 Hayman 1970) and the percentage of root length colonized by the mycorrhizal fungus was  
134 quantified by the Giovannetti and Mosse method (1980) using 30 root segments. Soil  
135 phosphatase activity was measured by the Tabatabai method (1994), using the hydrolysis of  
136 p-nitrophenylphosphate (p-NPP), buffered at pH 6.0 for acid phosphatase measurement, and  
137 pH 11 for alkaline phosphatase measurement, respectively, using a citrate-phosphate buffer  
138 (i.e. McIlvain buffer). Means and standard deviations were calculated per treatment for all  
139 variables. In order to test the interaction significance between plant mutualists, we performed  
140 a two-way ANOVA with AM fungi and rhizobia inoculations as factors, including three  
141 treatments for the AM fungus factor (None, M1 and M2) and two treatments for rhizobia (S0,  
142 S1). The two-way ANOVAs were followed by Tukey HSD post hoc tests to localize the

143 significant differences between treatments and display letters of pair-wise comparisons. When  
144 the interaction was significant, the Tukey HSD post hoc results from the interaction were  
145 displayed. When the interaction was not significant, the Tukey HSD post hoc results for the  
146 main effects were displayed. The ANOVA residuals were checked for normality using Wilk-  
147 Shapiro tests. All tests were performed using R software (R Core Team, 2015) at  $P < 0.05$ .

148

### 149 **3. Results**

150 After two months of growth, shoot biomass was significantly impacted by the inoculation  
151 of rhizobia ( $P$ -value 0.012) and mycorrhiza ( $P$ -value 0.021), without any significant  
152 interaction ( $P$ -value 0.251) between these two factors (Table 1). The inoculation of rhizobia  
153 (S1) and AM fungus (M1, M2), alone or together, induced higher shoot biomass (around 50%  
154 more) than the controls (S0 and M0). The total plant biomass showed similar patterns with the  
155 highest values for treatments S1 (0.29 g) and M1 (0.30 g). In contrast, we did not find any  
156 significant changes in root biomass or in the shoot:root ratio between the treatments. A slight  
157 increase ( $P$ -value  $< 0.001$ ) in the total N content of the plant was observed with the inoculation  
158 of both rhizobia (+ 13%) and mycorrhiza (+7%). Thus, the amount of N accumulated in plant  
159 biomass increased by 70% after inoculation with rhizobia or mycorrhiza. Alkaline  
160 phosphatase activity exhibited the same trend as shoot and total plant biomass, i.e. higher  
161 values for the inoculation of rhizobia ( $P$ -value 0.013) and mycorrhiza ( $P$ -value 0.001),  
162 without any significant interaction ( $P$ -value = 0.401). AM fungal isolate M2 was more  
163 efficient than M1.

164 The plant P content, the number of nodules, the mycorrhizal rate of the plants and acid  
165 phosphatase activity were affected by inoculation with both AM fungi and rhizobia, with  
166 significant interactions (Table 1). The plant P content, which was  $0.85 \text{ g kg}^{-1}$  without  
167 inoculation (S0-M0), increased to  $1.57 \text{ g kg}^{-1}$  with dual inoculation (S1-M2), corresponding to



168 an amount of P accumulated in plant biomass that was three times greater. The nodule  
169 number, which was zero in the absence of inoculation with the rhizobium strains, reached 134  
170 nodules per plant after inoculation. However, co-inoculation of soil with mycorrhizal strains  
171 increased nodulation by 77-89%. The mycorrhization rate, which was also zero in the absence  
172 of inoculation, increased slightly (12%) following inoculation with rhizobia. The  
173 mycorrhization rate increased from 30-63% for inoculation with mycorrhiza alone to 80-95%  
174 for inoculation with both mycorrhiza and rhizobia, i.e. an increase of 28-216% (Table 1).

175

#### 176 **4. Discussion**

177 We showed positive responses of legumes to rhizobial and AM symbioses, as often found  
178 (Xie et al., 1995; Ndoye et al., 2015), despite strong N and P depletion in these tropical soils.  
179 Based on greenhouse experiments, a meta-analysis showed an increase in yield of 59% for  
180 rhizobial inoculation, 45% for AM fungi and 44% for rhizobial and AM fungi (Kaschuk et al.,  
181 2010), in line with our results. However, we found a synergistic effect of dual inoculation on  
182 plant P content, nodulation, mycorrhizal rate and acid phosphatase activity. Few data have  
183 shown a similar synergistic effect of dual inoculation (e.g. Chalk et al., 2006; Ossler et al.,  
184 2015), with most results showing that the effects of dual inoculation are only additive (see the  
185 quantitative review of Larimer et al. 2010). Synergistic benefits of dual inoculation are  
186 thought to occur mostly in soils with both limited N and P availability (Mortimer et al., 2012).  
187 According to the stress-gradient hypothesis for plant communities predicting an increasing  
188 importance of facilitative mechanisms relative to competition along gradients of increasing  
189 environmental stress (Maestre et al., 2009), it is possible that dual inoculation is likely to  
190 produce synergistic effects in severely nutrient-depleted Malagasy soils. This hypothesis is  
191 supported by the fact that the main mechanism by which inoculation with AM fungi acts on  
192 plant functions seems to be improved phosphatase activity, particularly that of acid

193 phosphatases responsible for organic P hydrolysis (Tabatabai, 1994) and involved in  
194 supplying the high P requirements of N<sub>2</sub>-fixing nodules (Sulieman and Tran, 2015). However,  
195 according to Zhang et al. (2016), phosphatase activity would not seem to be due to the AM  
196 fungus itself, but to a free-living phosphate-solubilizing bacterium associated with AM fungi.  
197 Our study, carried out on a tropical soil with high P-fixing capacity and poor N availability,  
198 supported the hypothesis of a contribution of acid phosphatase activity and showed a highly  
199 significant positive interaction between the two symbionts on the number of nodules and the  
200 mycorrhization rate. However, the costs and benefits associated with these interactions for the  
201 plant are context-dependent, with AM fungi and rhizobia being less beneficial to plants in  
202 environments high in P (Hoeksema et al., 2010) or N (Herridge et al., 1984) (in Larimer et al.,  
203 2014). However, dual symbioses with AM fungus and rhizobia contribute to the success of  
204 legumes, especially in a harsh environment and on low-fertility soils (Franco and de Faria,  
205 1997; van der Heijden et al., 2016).

206 We also highlighted the positive effect of native symbiotic microorganisms selected from  
207 the soils of the Malagasy Highlands. Native microorganisms can display better adaptability to  
208 soil and environmental stress under harsh conditions (e.g. Kawaka et al., 2014), with the M2  
209 strain displaying greater efficiency. As the quality of the commercial products used as  
210 biofertilizers is sometimes questionable (Herrmann and Lesueur, 2013) and the potential  
211 negative consequences of introducing microorganisms into the soil is poorly understood  
212 (Thomsen and Hart, 2018), commercial inoculants should be used with caution, especially in  
213 ecosystems like Madagascar, which are hotspots of endemic biodiversity that need to be  
214 protected (Mittermeier et al., 2011).

215

216 **Acknowledgements**

217 This research was supported by Agropolis Fondation (France) under reference ID 321  
218 1001-009 through the “Investissements d’Avenir” programme (Labex Agro: ANR-10-LABX-  
219 322 0001-01). We acknowledge Agropolis Fondation for financial support and for the PhD  
220 grant provided to A.T.E. Razakatiana to conduct this research. The authors wish to thank  
221 Peter Biggins, a professional translator/reviser at CIRAD, for reviewing the English of the  
222 manuscript.

223

## 224 **References**

- 225 Augusto, L., Delerue, F., Gallet-Budynek, A., Achat, D.L., 2013. Global assessment of  
226 limitation to symbiotic nitrogen fixation by phosphorus availability in terrestrial  
227 ecosystems using a meta-analysis approach. *Glob. Biogeochem. Cycle* 27, 804-815.
- 228 Chalk, P.M., Souza, R.D.F., Urquiaga, S., Alves, B.J.R., Boddey, R.M., 2006. The role of  
229 arbuscular mycorrhiza in legume symbiotic performance. *Soil Biol. Biochem.* 38, 2944-  
230 2951.
- 231 Duponnois, R., Plenchette, C., Bâ, A.M., 2001. Growth stimulation of seventeen fallow  
232 leguminous plants inoculated with *Glomus aggregatum* in Senegal. *Eur. J. Soil Biol.* 37,  
233 181-186.
- 234 Duru, M., Therond, O., 2015. Livestock system sustainability and resilience in intensive  
235 production zones: which form of ecological modernization? *Reg. Environ. Change* 15,  
236 1651-1665.
- 237 Franco, A.A., de Faria, S.M., 1997. The contribution of N<sub>2</sub>-fixing tree legumes to land  
238 reclamation and sustainability in the tropics. *Soil Biol. Biochem.* 29, 897-903.
- 239 Gerdemann, J.W., Nicolson, T.H., 1963. Spores of mycorrhizal *Endogone* species extracted  
240 from soil by wet sieving and decanting. *Trans. Brit. Mycol. Soc.* 46, 235-244.

241 Giovannetti, M., Mosse, B., 1980. An evaluation of techniques for measuring vesicular  
242 arbuscular mycorrhizal infection in roots. *New Phytol.* 84, 489-500.

243 Henintsoa, M., Becquer, T., Rabeharisoa, L., Gérard, F., 2017. Geochemical and microbial  
244 controls of the effect of citrate on phosphorus availability in a ferralsol. *Geoderma* 291,  
245 33-39.

246 Herridge, D.F., Roughley, R.J., Brockwell, J., 1984. Effect of rhizobia and soil nitrate on the  
247 establishment and functioning of the soybean symbiosis in the field. *Aust. J. Agric. Res.*  
248 35, 149–161.

249 Herrmann, L., Lesueur, D., 2013. Challenges of formulation and quality of biofertilizers for  
250 successful inoculation. *Appl. Environ. Biotechnol.* 97, 8859-8873.

251 Hoeksema, J.D., Chaudhary, V.B., Gehring, C.A., Johnson, N.C., Karst, J., Koide, R.T.,  
252 Pringle, A., Zabinski, C., Bever, J.D., Moore, J.C., Wilson, G.W.T., Klironomos, J.N.,  
253 Umbanhowar, J., 2010. A meta-analysis of context-dependency in plant response to  
254 inoculation with mycorrhizal fungi. *Ecol. Lett.* 13, 394–407.

255 Kaschuk, G., Leffelaar, P.A., Giller, K.E., Alberton, O., Hungria, M., Kuyper, T.W., 2010.  
256 Responses of legumes to rhizobia and arbuscular mycorrhizal fungi: a meta-analysis of  
257 potential photosynthate limitation of symbioses. *Soil Biol. Biochem.* 42, 125-127.

258 Kawaka, F., Dida, M.M., Opala, P.A., Ombori, O., Maingi, J., Osoro, N., Muthini, M.,  
259 Amoding, A., Mukaminega, D., Muoma, J., 2014. Symbiotic efficiency of native rhizobia  
260 nodulating common bean (*Phaseolus vulgaris* L.) in soils of Western Kenya. *Int. Sch.*  
261 *Res. Not.* 258497.

262 Larimer, A.L., Bever, J.D., Clay, K., 2010. The interactive effects of plant microbial  
263 symbionts: a review and meta-analysis. *Symbiosis* 51, 139-148.

264 Larimer, A.L., Clay, K., Bever, J.D., 2014. Synergism and context dependency of interactions  
265 between arbuscular mycorrhizal fungi and rhizobia with a prairie legume. *Ecology* 95,  
266 1045-1054.

267 Maestre, F.T., Callaway, R.M., Valladares, F., Lortie, C.J., 2009. Refining the stress-gradient  
268 hypothesis for competition and facilitation in plant communities. *J. Ecol.* 97, 199-205.

269 Mittermeier, R.A., Turner, W.R., Larsen, F.W., Brooks, T.M., Gascon, C., 2011. Global  
270 biodiversity conservation: the critical role of hotspots. In: Zachos, F.E., Habel, J.C.  
271 (Eds.), *Biodiversity hotspots*. Springer-Verlag, Berlin, Heidelberg, pp. 3-22.

272 Mortimer, P.E., Pérez-Fernández, M.A., Valentine, A.J., 2012. Arbuscular mycorrhiza  
273 maintains nodule function during external  $\text{NH}_4^+$  supply in *Phaseolus vulgaris* (L.).  
274 *Mycorrhiza* 22, 237-245.

275 Nadeem, S.M., Ahmad, M., Zahir, Z.A., Javaid, A., Ashraf, M., 2014. The role of  
276 mycorrhizae and plant growth promoting rhizobacteria (PGPR) in improving crop  
277 productivity under stressful environments. *Biotechnol. Adv.* 32, 429-448.

278 Ndoye, F., Kane, A., Diedhiou, A.G., Bakhom, N., Fall, D., Sadio, O., Sy, M.O., Noba, K.,  
279 Diouf, D., 2015. Effects of dual inoculation with arbuscular mycorrhizal fungi and  
280 rhizobia on *Acacia senegal* (L.) Willd. Seedling growth and soil enzyme activities in  
281 Senegal. *Int. J. Biosci.* 6, 36-48.

282 Ossler, J.N., Zielinski, C.A., Heath, K.D., 2015. Tripartite mutualism: Facilitation or trade-  
283 offs between rhizobial and mycorrhizal symbionts of legume hosts. *Am. J. Bot.* 102,  
284 1332-1341.

285 Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: an efficient  
286 source of nitrogen for sustainable agricultural production? *Plant Soil* 174, 3-28.

287 Phillips, J.M., Hayman, D.S., 1970. Improved procedures for clearing roots and staining  
288 parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection.  
289 Trans. Brit. Mycol. Soc. 55, 158-161.

290 R Core Team, 2015. R: A Language and Environment for Statistical Computing. R  
291 Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.

292 Raminoarison, M., Razafimbelo, T., Rakotoson, T., Becquer, T., Blanchart, E., Trap, J., 2020.  
293 Multiple-nutrient limitation of upland rainfed rice in Ferralsols: a greenhouse nutrient  
294 omission trial. J. Plant Nutr. 43, 270-284.

295 Richardson, A.E., Barea, J.M., McNeill, A.M., Prigent-Combaret, C., 2009. Acquisition of  
296 phosphorus and nitrogen in the rhizosphere and plant growth promotion by  
297 microorganisms. Plant soil 321, 305-339.

298 Smith, S.E., Read, D.J., 2008. Mycorrhizal symbiosis. Third edition. Academic Press, London

299 Souza, R., Ambrosini, A., Passaglia, L.M.P., 2015. Plant growth-promoting bacteria as  
300 inoculants in agricultural soils. Genet. Mol. Biol. 38, 401-419.

301 Stavi, I., Bel, G., Zaady, E., 2016. Soil functions and ecosystem services in conventional,  
302 conservation, and integrated agricultural systems. A review. Agron. Sustain. Dev. 36, 1-  
303 12.

304 Sulieman, S., Tran, L.S.P., 2015. Phosphorus homeostasis in legume nodules as an adaptive  
305 strategy to phosphorus deficiency. Plant Sci. 239, 36-43.

306 Tabatabai, M.A., 1994. Soil enzymes. In: Weaver, R.W., Angle, JS, Bottomley P.S. (Eds),  
307 Methods of Soil Analyses. Part 2. Microbiological and Biochemical Properties. Soil  
308 Science Society of America, Madison, pp 775–833.

309 Thomsen, C.N., Hart, M.M., 2018. Using invasion theory to predict the fate of arbuscular  
310 mycorrhizal fungal inoculants. Biol. Invasions 20, 2695-2706.

311 Vandenkoornhuyse, P., Quaiser, A., Duhamel, M., Le Van, A., Dufresne, A., 2015. The  
312 importance of the microbiome of the plant holobiont. *New Phytol.* 206, 1196-1206.

313 van der Heijden, M.G., de Bruin, S., Luckerhoff, L., van Logtestijn, R.S., Schlaeppi, K., 2016.  
314 A widespread plant-fungal-bacterial symbiosis promotes plant biodiversity, plant  
315 nutrition and seedling recruitment. *ISME J.* 10, 389-399.

316 Xie, Z.P., Staehelin, C., Vierheilig, H., Wiemken, A., Jabbouri, S., Broughton, W.J., Vogeli-  
317 Lange, R., Boller, T., 1995. Rhizobial nodulation factors stimulate mycorrhizal  
318 colonization of nodulating and nonnodulating soybeans. *Plant Physiol.* 108, 1519-1525.

319 Young, C.C., Juang, T.C., Chao, C.C., 1988. Effects of Rhizobium and vesicular-arbuscular  
320 mycorrhiza inoculations on nodulation, symbiotic nitrogen fixation and soybean yield in  
321 subtropical-tropical fields. *Biol. Fertil. Soils* 6, 165-169.

322 Zhang, L., Xu, M., Liu, Y., Zhang, F., Hodge, A., Feng, G., 2016. Carbon and phosphorus  
323 exchange may enable cooperation between an arbuscular mycorrhizal fungus and a  
324 phosphate-solubilizing bacterium. *New Phytol.* 210, 1022-1032.

Variables	Unit	Factors												
		Rhizobium inoculation treatments						Mycorrhiza inoculation treatments						Interaction
		S0	S1	P-value			M0	M1	M2	P-value			P-value	
Shoot biomass	g	0.14 (0.05)	<b>x</b>	0.21 (0.07)	<b>y</b>	<b>0.012*</b>	0.13 (0.05)	<b>α</b>	0.21 (0.04)	<b>β</b>	0.20 (0.09)	<b>αβ</b>	<b>0.021*</b>	0.251
Root biomass	g	0.07 (0.03)	<b>x</b>	0.07 (0.04)	<b>x</b>	0.330	0.05 (0.03)	<b>α</b>	0.08 (0.04)	<b>α</b>	0.07 (0.02)	<b>α</b>	0.202	0.661
Total biomass	g	0.23 (0.09)	<b>x</b>	0.29 (0.10)	<b>y</b>	<b>0.034*</b>	0.18 (0.09)	<b>α</b>	0.30 (0.08)	<b>β</b>	0.26 (0.11)	<b>αβ</b>	<b>0.034*</b>	0.521
Shoot:Root	/	2.77 (0.94)	<b>x</b>	3.30 (1.31)	<b>x</b>	0.294	2.98 (0.87)	<b>α</b>	3.09 (1.33)	<b>α</b>	3.09 (1.39)	<b>α</b>	0.982	0.228
Plant N content	g kg <sup>-1</sup>	18.8 (0.82)	<b>x</b>	21.3 (1.05)	<b>y</b>	<b>&lt;0.001***</b>	19.1 (1.37)	<b>α</b>	20.4 (1.15)	<b>β</b>	20.6 (1.86)	<b>β</b>	<b>&lt;0.001***</b>	0.225
Plant P content	g kg <sup>-1</sup>	1.09 (0.19)		1.33 (0.23)			0.95 (0.12)		1.30 (0.08)		1.38 (0.23)			<b>0.006**</b>
Alkaline phosphatase	μg-pNP h <sup>-1</sup> g <sup>-1</sup>	0.9 (0.8)	<b>x</b>	1.5 (0.7)	<b>y</b>	<b>0.013*</b>	0.5 (0.4)	<b>α</b>	1.1 (0.6)	<b>α</b>	2.0 (0.6)	<b>β</b>	<b>0.001*</b>	0.401
Mycorrhization rate	%	30.9 (29.0)		62.2 (38.8)			40 (42.7)		71.2 (13.6)		67.1 (34.7)			<b>&lt;0.001***</b>
Nodule number	Number	0.0 (0.0)		208.3 (59.0)			67.1 (72.3)		118.5 (128.6)		145.0 (136.0)			<b>&lt;0.001***</b>
Fluorescein diacetate	μg-FDA h <sup>-1</sup> g <sup>-1</sup>	179.1 (25.6)		171.5 (108.8)			104.1 (80.2)		197.6 (49.9)		224.3 (39.3)			<b>&lt;0.001***</b>
Acid phosphatase	μg-pNP h <sup>-1</sup> g <sup>-1</sup>	2.8 (3.0)		5.0 (3.3)			0.91 (1.1)		5.0 (2.6)		5.8 (3.4)			<b>0.036*</b>
<b>Significant interaction</b>		<b>Treatments</b>												
		S0-M0	S1-M0	S0-M1	S1-M1	S0-M2	S1-M2							
Plant P content	g kg <sup>-1</sup>	0.85 (0.02)	<b>d</b>	1.05 (0.07)	<b>bc</b>	1.24 (0.06)	<b>c</b>	1.36 (0.05)	<b>ab</b>	1.17 (0.12)	<b>cd</b>	1.57 (0.08)	<b>a</b>	
Mycorrhization rate	%	0.0 (0.0)	<b>d</b>	11.5 (14.4)	<b>cd</b>	62.5 (14.2)	<b>b</b>	80.0 (4.8)	<b>ab</b>	30.0 (2.0)	<b>c</b>	95.0 (1.6)	<b>a</b>	
Nodule number	Number	0.0 (0.0)	<b>c</b>	134.2 (14.0)	<b>b</b>	0.0 (0.0)	<b>c</b>	253.7 (15.4)	<b>a</b>	0.0 (0.0)	<b>a</b>	237.0 (34.6)	<b>a</b>	
Fluorescein diacetate	μg-FDA h <sup>-1</sup> g <sup>-1</sup>	175.8 (18.4)	<b>ab</b>	32.3 (18.2)	<b>c</b>	168.7 (38.9)	<b>b</b>	226.5 (46.9)	<b>a</b>	192.96 (17.4)	<b>ab</b>	255.7 (24.6)	<b>a</b>	
Acid phosphatase	μg-pNP h <sup>-1</sup> g <sup>-1</sup>	0.06 (0.07)	<b>bc</b>	1.76 (1.09)	<b>bc</b>	5.49 (3.44)	<b>ab</b>	4.55 (2.34)	<b>abc</b>	3.01 (1.68)	<b>bc</b>	8.77 (1.30)	<b>a</b>	

When the interaction was not significant, letters "x, y" and "α, β" indicate main effect significance within rhizobium and mycorrhiza treatments, respectively. When the interaction was significant, letters "a, b, c, d and e" indicate significant difference among cross-treatments according to Tukey HSD test (P < 0.05, n=5).

\*P < 0.05; \*\*P < 0.01; \*\*\*P < 0.001