ARBUSCULAR MYCORRHIZA IN *Coffea arabica* L.: REVIEW AND META- ANALYSIS

Franciane Diniz Cogo[1], Paulo Tácito Gontijo Guimarães[2], Enrique Pouyú Rojas[3], Orivaldo José Saggin Júnior[4], Jose Oswaldo Siqueira[5], Marco Aurelio Carbone Carneiro[6]

(Recebido: 04 de maio de 2016; aceito: 16 de novembro de 2016)

ABSTRACT: Coffee, a plant of global economic importance, presents a high degree of micotrophy for nutrients absorption, especially phosphorus, whose sources are scarce, and extremely required in tropical soils. Arbuscular mycorrhizal fungi (AMF) and coffee crop (*Coffea arabica*) have been studied for more than three decades, and therefore, analyzing and gathering these studies in a quantitative and qualitative way by means of meta-analysis and critical review of advances and trends is of great relevance. In this review, aspects such as geographic distribution, ecology, effects on plant growth, mineral nutrition, myotrophism, and symbiotic efficiency and its applications were discussed, with special emphasis on the researches carried out in Brazil. By applying the electronic databases Cab Abstracts, Springerlink, Science Direct, Scielo, Scopus, ISI, Lilascs, Woldcat, 73 studies were analyzed, including papers, dissertations and theses. The meta-analysis showed the importance of AMF for growth, plant nutrition and grain yield. Nevertheless, a gap is still evident in the evaluation of the different management strategies adopted in coffee crop and their effects on AMF. The need to extend the research under field conditions was also detected, in order to confer the real contribution of AMF in coffee biocontrol, and their action as biofertilizers and biostimulants.

Index terms: *Coffea arabica*, plant growth, yield, arbuscular mycorrhizal fungi, symbiotic efficiency, mineral nutrition.

MICORRIZAS ARBUSCULARES EM CAFEEIRO *Coffea arabica* L.: REVISÃO E META-ANÁLISE

***RESUMO*:** *O cafeeiro, planta de importância econômica mundial, apresenta elevado grau de micotrofia para a absorção de nutrientes, em especial de fósforo, cujas fontes são escassas, requeridas em grande quantidade em solos tropicais. Os fungos micorrízicos arbusculares (FMAs) e a cultura do cafeeiro (Coffea arabica) têm sido objeto de estudo há mais de três décadas e, por isso, é relevante analisar e reunir esses estudos de maneira quantitativa e qualitativa, empregando-se meta-análise e revisão crítica dos avanços e tendências. Nesta revisão foi discutido aspecto de distribuição geográfica, ecologia, efeitos no crescimento vegetal, nutrição mineral, micotrofismo, eficiência simbiótica e suas aplicações, com ênfase nas pesquisas realizadas no Brasil. Empregando as bases de dados eletrônicas Cab Abstracts, Springerlink, Science Direct, Scielo, Scopus, ISI, Lilascs, Woldcat, foram 73 estudos analisados entre artigos, dissertações e teses. A meta-análise mostrou a importância dos FMAs para o crescimento, nutrição de plantas e produção de grãos. No entanto, fica evidente ainda uma lacuna na avaliação dos diferentes manejos adotados na cultura do cafeeiro e seus efeitos nos FMAs e a necessidade de ampliar as pesquisas, em condições de campo, para se conferir a contribuição real dos FMAs como biofertilizantes e bioestimulantes e no biocontrole para o cafeeiro.*

Termos para indexação: *Coffea arabica, crescimento de plantas, produtividade, fungos micorrízicos arbusculares, eficiência simbiótica, nutrição mineral.*

1 INTRODUCTION

The occurrence of arbuscular mycorrhizal fungi (AMF) in coffee crops is common, and is naturally identified in nursery (SIQUEIRA et al., 1987) and in the field (ARIAS et al., 2012; BEENHOUWER et al., 2015). Coffee plants present a high degree of mycorrhizal dependence (SIQUEIRA; COLOZZI-FILHO, 1986), mainly in soils with low available P content (KAHILUOTO; KETOJA; VESTBERG, 2012).

AMF form a symbiotic, endophytic, biotrophic, and mutualist association, developed as the roots of vascular plants (BRUNDRETT, 2002; SCHULZ; BOYLE, 2005; SIQUEIRA, 1993). These fungi colonize the cortex of the roots, with inter- and intracellular penetration without visual morphological changes, by means of modifications in the hyphae, forming arbuscules, vesicles and spores (LAMBAIS, 1996; SIQUEIRA, 1993). The extrarradiculares hyphae can explore the soil in microenvironments, which are sites where

[1,6]Universidade Federal de Lavras/UFLA Departamento de Ciência do Solo/DCS - 37.200-000 - Lavras - MG - fdcogo@yahoo.com.br, marcocarbone@dcs.ufla.br
[2]Empresa de Pesquisa Agropecuária de Minas Gerais/EPAMIG - Cx. P. 176 - 37.200-000 - Lavras - MG - paulotgg@ufla.br
[3]Consultor da E.P.R. Consultória Agronômica - Rondonópolis - MT- 78700-000 - epouyu@gmail.com
[4]Empresa Brasileira de Pesquisa Agropecuária - Centro Nacional de Pesquisa de Agrobiologia - 70.770-901 - Seropédica - RJ orivaldo.saggin@embrapa.br
[5]Universidade Federal de Lavras/UFLA - Departamento de Ciência do Solo e Instituto Tecnológico Vale - 66.055-090 - Belém - PA jose.oswaldo.siqueira@itv.org

the roots do not reach, consequently favoring the absorption of water and nutrients by the host plant (SAGGIN-JÚNIOR et al., 1995; TRISTÃO; ANDRADE; SILVEIRA, 2006), especially those of low mobility in the soil, such as phosphorus (ALBÁN; GUERRERO; TORO, 2013).

Phosphorus stands out among the nutrients. Its absorption is favored by AMF for being an ion of slow diffusion in the soil (HINSINGER, 2001), and for the strong fixation with iron and aluminum oxides, which reduces the efficiency of phosphate fertilization (STÜMER; SIQUEIRA, 2013). In addition, natural phosphorus sources are scarce in Brazil, and the nutrient is highly required in tropical soils. Other essential elements absorbed by AMF are zinc (ANDRADE et al., 2009), copper (COLOZZI-FILHO et al., 1994; SIQUEIRA; COLOZZI-FILHO; SAGGIN-JÚNIOR, 1994), and nitrogene (HODGE; CAMPBELL; FITTER, 2001) in the form of nitrate and ammonium (HOOKER; BLACK, 1995).

AMF's fungal hyphae directly protects the plant from the toxicity caused by manganese (SAGGIN-JÚNIOR et al., 1992), copper and zinc (ANDRADE; SILVEIRA; MAZZAFERA., 2010). This great plant nutrition provided by AMF increases plant biomass (TRISTÃO; ANDRADE; SILVEIRA, 2006), and consequently increases yield (COLOZZI-FILHO et al., 1994). In addition, AMF increases soil aggregation (CARNEIRO et al., 2015), and tolerance to disease and pests (VAAST; CASWELL-CHEN; ZASOSKI, 1998), and to water deficit (ANAYA et al., 2011).

Considering the high number of studies on AMF and coffee crop, and that these studies have not yet been collected in a publication, the systematic literature review with meta-analyses becomes extremely important. Meta-analysis consists of a quantitative review that aggregates and synthesizes the literature on a subject, supported by statistical methods (OLKIN, 1995).

To date, three meta-analyses have been performed using mycorrhizal fungi (BARTO; RILLIG, 2010; LEHMANN et al., 2010; MAYERHOFER; KERNAGHAN; HARPER, 2012). The analysis carried out by Barto and Rillig's (2010) was based on 99 experiments extracted from 33 publications, in order to verify the influence of herbivority on carbon transfer to AMF. Lehmann et al. (2010) studied the importance of the year of publication and the response of AMF to root colonization and phosphorus acquisition efficiency. Moreover, Mayerhofer, Kernaghan and Harper (2012) determined the effects of inoculation of root-endophyte fungi on plant biomass and nitrogen concentration.

The above reviews are not focused on a specific agricultural crop, such as coffee. Thus, meta-analysis on AMF and coffee crop provides information value and potential to indicate new advances and trends for this research field.

Therefore, the objective of this work is to present a review with meta-analysis using studies on AMF in coffee plants. In this paper, aspects such as geographic distribution, ecology, effects on plant growth, mineral nutrition, myotrophism, and symbiotic efficiency and its applications were discussed, with special emphasis on researches carried out in Brazil. Advances and trends for future researches were also mentioned, and should indicate the perspectives for the introduction of the technology as a management practice in the coffee production chain.

2 MATERIAL AND METHODS

2.1 Data collection

The electronic databases Cab Abstracts, Springer, Scielo, Scopus, ISI, Lilascs, Woldcat, as well as printed journals, dissertations and theses were used to construct the database, gathering references between the years of 1978 and 2015. The following index terms (key words) were used for the research: [Arbuscular mycorrhizal fungi* (coffee or *Coffea Arabica*, or plant development, or plant nutrition, or phosphate nutrition, or field inoculation, or persistence, or dissemination, or effects on the plant, or phosphorus availability, or coffee seedlings, or nursery seedlings, or seedlings in the field, or nutrient availability, or symbiosis)], and [Coffee* (mycorrhizae, or phosphorus, or root colonization, or native endomycorrhizal, or native mycorrhizal fungi, or symbiosis, or mycorrhizal inoculation)].

Data was extracted from the individual analysis of each publication, by collecting: country of origin, experimental site (laboratory, field, and greenhouse), objectives (biofertilizers, biocontrol, seasonal fluctuation, persistence in the field, yield, and taxonomic idenditication), root colonization, number of spores, AMF species, and plant growth variables (plant height, stem diameter, plant biomass, P content in the shoot). For all variables related to plant growth, the presence (treatment) and absence (control) of mycorrhizae were considered.

When a publication reported more than one variable, this publication was treated as a separate experiment, and when the thesis or dissertation presented data published in papers, these data

were considered only once. The conclusion of this study, the analysis, and the interpretation were based on "Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement" (MOHER et al., 2009), consisting of a support by means of guidelines and checklist.

2.2 Data analysis

2.2.1 Qualitative analysis

The data collected from the country of origin, experiment site, objectives, root colonization, number of spores, and AMF species were analyzed using the method of structuring qualitative content analysis (BARDIN, 1994). This technique consists of decomposing the discourse and identification of units of analysis or groups, by means of pre-analysis, exploration of the material, and treatment of the results, from which significant and valid results can be reconstructed, in order to generate deep knowledge and interpretation of reality, which allows inferences (SILVA; GOBBI; SIMÃO, 2005).

2.2.2 Quantitative analysis

For the colonization and number of spores, the standard error of the mean was calculated for each of the experiments, showing the variability between the studies (BANZATTO; KRONKA, 2013).

In order to compare the effect of AMF on coffee plants growth, the effect size (ES) was calculated in each study. This value is obtained from an analysis that summarizes the differences between experimental and control groups (HARTUNG; KANAPP; SINHA, 2008). The effect size allows measuring the overall effect (significant effect of the treatment compared with the control) and its associated variance (GUREVITCH; HEDGES, 1999; HEDGES; GUREVITCH; CURTIS, 1999). Effect sizes were calculated by the ratio between X^E (experimental treatments) and X^C (control treatment) (NEYELOFF; FUCHS; MOREIRA, 2012).

$$TE = \frac{X^E}{X^C}$$

The choice of the ES is justified, for it has direct biological meaning. Values higher than 1 indicate an increase in the effect on the variables with the inoculation (positive response); values between 0 and 1 indicate a decrease (negative response); and 1 is neutral (treatments with inoculation equal to the treatment without inoculation). The effect size was also calculated individually for each studied AMF species in function of P content in the shoot and grain yield.

Effect sizes were estimated using a Microsoft Excel spreadsheet (NEYELOFF; FUCHS; MOREIRA, 2012). All analyses were performed assuming random effect. The random effect model considers the variation within and between each study, since the studies are connected by a normal probability distribution (RODRIGUES; ZIEGELMAN, 2010). The random effects model was described as:

$$Yj = \Theta m + Zj + \varepsilon j$$

Where Ɛj is the random error of the study j; Zj is the random effect of each study j; and Θm is the meta-analytic measure.

The effect size (ES), the standard error (S_x), the individual confidence interval (CI), and the individual weight (W) and the weight of each group were calculated for this model.

$$ES = \frac{x^E}{x^C}; Sx = \frac{s}{\sqrt{n}}; CI = X \mp (1.96)\frac{s}{\sqrt{n}}; W = \frac{1}{\sqrt{Sx}};$$

In order to validate the basic assumptions of analysis of variance, the I^2 tests (measure of inconsistency to verify the variance heterogeneity) were performed, being described as:

$$I^2 = \frac{Q - (J-1)}{Q} X100$$

Where I^2 is the measure of inconsistency, Q is the Cochran test statistic, and J is the number of studies (HIGGINS; THOMPSN, 2002).

The I^2 test describes the percentage of variation between the studies by means of values that range from 0% to 100%, with negative values equal to zero. Values close to 0% indicate non-heterogeneity between studies; values close to 25% indicate low heterogeneity; values of 50% indicate moderate heterogeneity; and values of 75% indicate high heterogeneity (HIGGINS; THOMPSN, 2002).

3 RESULTS AND DISCUSSION

3.1 Review of published studies

The search in the literature from the list of titles of all databases and other printed sources identified 10,037 bibliographical references and,

of these, 291 publications were selected from their titles and abstracts. However, 218 publications were excluded, since they did not meet the validation criteria for inclusion in a meta-analysis. For instance, some studies did not contain the control plant (not inoculated with AMF), which is important information to perform the meta-analyses. Some publications were related to other agricultural crops, and others did not present the inoculated AMF species. Finally, 61 papers, 10 dissertations, and 3 theses that met the validity criteria for inclusion in the meta-analysis (supplementary material 1) were used.

3.2 Distribution by country, objectives and experimental sites

Studies on AMF and coffee crop were carried out in Brazil, Colombia, Cuba, Ethiopia, India, Mexico, Nigeria, Puerto Rico, Venezuela, and Yemen (Table 1). Although the presence of AMF in coffee (*Coffea arabica*) was first observed by Janse (1897) in Java Island, only after almost 80 years the importance of these fungi for coffee crop was experimentally demonstrated.

In Brazil, the first studies were carried out by Cardoso (1978) with the description and evaluation of the presence of AMF in coffee plants from the state of São Paulo. Then, Lopes et al. (1983a) published studies carried out at the Agronomic Institute of Campinas-SP as part of his PhD thesis. These studies motivated the beginning of research in several other laboratories in Brazil (CALDEIRA; CHAVES; ZAMBOLIM, 1983a, 1983b). In the Federal University of Lavras - UFLA, investigations on AMF in coffee began in the 1980s by Prof. Dr. José Oswaldo Siqueira (UFLA), following the stages of diversity, ecology, effects on growth, nutrition and application, representing a great contribution to the scientific and technological clarification of the importance of this symbiosis for coffee crop.

Most of the studies were carried out in Brazil, being 53.6% of them in the Federal University of Lavras and 17.1% in the College of Agriculture of the University of São Paulo Luiz de Queiroz (ESALQ). This great Brazilian contribution to the study on AMF in coffee is due to the fact that Brazil is one of the largest coffee producers in the world (COMPANHIA NACIONAL DE ABASTECIMENTO - CONAB, 2015), associated with the fact that Brazilian soils present low content of available P and high fixation in iron and aluminum oxide (LOPES; COX, 1977), and with the high degree of mycorrhizal dependence by coffee plants (SIQUEIRA; COLOZZI FILHO, 1986).

Studies on AMF and coffee crop included three sites: greenhouse (54%), field (44%), and laboratory (2%) (Table 1). Most of the studies carried out in greenhouse were related to the biofertilizer function of AMF (87%) for coffee crop, especially at the initial stages of coffee seedlings, in the nursery. Most of the research carried out in greenhouse evaluated the nutritional improvement of coffee seedlings provided by AMF, such as increase in the absorption of several macronutrients and micronutrients, and increase in plant growth (Table 1).

3.3 Effect of disease tolerance

Six studies sought to verify the increase in tolerance to pest and disease (biocontrol), by evaluating the interaction of AMF with *Rhizoctonia solani* (PEREIRA, 1994); *Pratylenchus coffeae* (VAAST; CASWELL-CHEN; ZASOSKI, 1998); *Phoma costarricencis* (AGUILAR, 2002); *Hemileia vastatrix* (THANGARAJU et al., 2008); *Colletotrichum gloeosporioides* and *Cercospora coffeicola* (COLMENÁREZ-BETANCOURT; PINEDA, 2011); and *Meloidoyne exigua* (ALBAN; GUERRERO; TORO, 2013), and indicated the relevance of AMF in reducing the losses caused by diseases, confirming the benefits of AMF. Although AMF do not control diseases, they alleviate damage by improving plant growth and vigor (SIQUEIRA, 1993).

In field conditions, 32 studies were reported, of which 24 sought to identify AMF species that associated with coffee. Three studies verified the relationship between AMF and coffee yield (COLOZZI-FILHO et al., 1994; SIQUEIRA et al., 1993, 1998). Three other studies reported the seasonal fluctuation of mycorrhizal fungi community in the field, and the influence of dry and rainy seasons in the sporulation of native AMF (BONFIM et al., 2010). Another study evaluated coffee from the seedlings inoculated with *Gigaspora margarita*, and reported that five years after planting in the field, the AMF species introduced by the pre-colonized seedlings were still present and interacted with native AMF species, varying the behavior according to the AMF species (BALOTA; LOPES, 1996b). The persistence of the inoculated mycorrhizal fungi in the field decreased over the years after planting (BALOTA; LOPES, 1996a).

TABLE 1 - Distribution by country, experimental site, and objectives of the research.

Country	Experimental site			
	Objectives	**Field**	**Greenhouse**	**Laboratory**
Brazil	Biofertilizer	Colozzi- Filho et al. (1994) and Siqueira et al. (1998)	Andrade, Silveira and Mazzafera (2010), Antunes, Silveira and Cardoso (1988), Caldeira, Chaves and Zambolim (1983a), Cardoso (1978), Clemente (1988), Colozzi-Filho et al. (1994), Colozzi-Filho and Siqueira (1986), França et al. (2014), Konrad (2003), Lopes et al. (1983a), Saggin-Júnior et al. (1992, 1994, 1995a, 1995b), Siqueira and Colozzi-Filho (1986), Siqueira, Colozzi-Filho and Saggin-Júnior (1994), Siqueira et al. (1993, 1995, 1998), Souza et al. (1991), Souza, Oliveira and Carvalho (1989), and Tristão, Andrade and Silveira (2006)	-
	Biocontrol	-	Pereira (1994)	-
	Establishment	-	Siqueira and Colozzi-Filho (1986)	-
	Seasonal fluctuation	Balota and Lopes (1996b) and Bonfim et al. (2010)	-	-
	Persistence	Balota and Lopes (1996a)	-	-
	Yield	Colozzi-Filho et al. (1994) and Siqueira et al. (1993, 1998)	-	-
	Taxonomy	Alves et al. (2014), Andrade et al. (1995), Azevedo (2005), Caldeira, Chaves and Zambolim (1983b), Cardoso et al. (2003), Colozzi-Filho and Cardoso (2000), Fernandes (2009), Fernandes and Siqueira (1989), Lopes et al. (1983b), Oliveira et al. (1990), Siqueira et al. (1986), Souza et al. (1987), Texeira et al. (2010) and Theodoro et al. (2003)	Siqueira et al. (1987)	-
Colombia	Biofertilizer	-	Arango, Ochoa and Rocledo (1989)	-
	Taxonomy	Castro and Conde (2012)	-	-
Cuba	Biofertilizer	-	Esmoris et al. (2011), Rivera et al. (2010) and Sánchez et al. (2005)	-
USA	Biofertilizer	-	Vaast and Zasoski (1991, 1992)	Vaast, Zasoski and Bledsoe (1996)
	Biocontrol	-	Vaast, Caswell-Chen and Zasoski (1998)	-
Ethiopia	Taxonomia	Beenhower et al. (2015), Chanie (2006), Muleta et al. (2007) and Muleta, Assefa and Nemomissa (2008)	-	-

India	Biofertilizer	-	Biradar et al. (2006)	-
	Biocontrol	-	Thangaraju et al. (2008)	-
	Taxonomy	Lakshmipathy, Balakrishna and Bayaraj (2012)	-	-
Mexico	Biofertilizer	-	Aguilar (2002), Aguirre-Medina et al. (2011) and Anaya et al. (2011)	-
	Taxonomy	Arias et al. (2012) and Trejo et al. (2011)	-	-
Nigeria	Biofertilizer	-	Ibiremo, Oloyede and Iremiren (2011)	-
Puerto Rico	Taxonomy	Lebrón, Lodge and Bayman (2012)	-	-
Venezuela	Biocontrol	-	Alban, Guerrero and Toro (2013) and Colmenárez-Betancourt and Pineda (2011)	-
Yemen	Taxonomy	Al-Arequi et al. (2013)	-	-

Only one study was carried out in the laboratory, with *in vitro* propagation of seedlings performed by Vaast, Zasoski and Bledsoe (1996), who observed a 50% increase in plant growth when were inoculated with the species *Acaulospora mellea*, or *Rhizophagus clarus*, in soil of low P availability.

Studies carried out in greenhouse to verify the interactions of coffee seedlings inoculated with AMF with different pathogens showed an increase in root colonization of approximately 38.6% (Figure 1), and higher survival in relation to the non-inoculated plants (AGUILAR, 2002; ALBAN; GUERRERO; TORO 2013; COLMENÁREZ-BETANCOURT; PINEDA, 2011; PEREIRA, 1994; THANGARAJU et al., 2008; VAAST; CASWELL-CHEN; ZOSOSKI, 1998). Vaast, Caswell-Chen and Zasoski (1998) stated that coffee plants previously inoculated with AMF and with the pathogen *Pratylenchus coffeae* showed higher plant survival and greater development of traits related to growth and nutrition, such as leaf area, root length, and leaf phosphorus content.

The presence of root pathogens and AMF provides physiological changes in the root system. These changes in metabolism can promote the plant-fungus interaction, allowing the AMF to colonize the roots more quickly than the pathogen.

The tolerance to the pathogen induced by AMF is also attributed to the physical and physiological changes in the roots, forming barriers such as the activation of metabolites related to the defense of the plant, or physical occupation of infection sites and competition for the absorption of nutrients, making the plants healthier and more resistant to invasion by the pathogen (VAAST; CASWELL-CHEN; ZASOSKI, 1998).

The presence of different pathogens generated the same effect, since plants inoculated with different pathogens presented similar mycorrhizal colonization percentage. Coffee seedlings inoculated with *Rhizoctonia solani* (PEREIRA, 1994), *Pratylenchus coffeae* (VAAST; CASWELL-CHEN; ZASOSKI, 1998), *Phoma costarricencis* (AGUILAR, 2002), and *Meloidoyne exigua* (ALBAN; GUERRERO; TORO, 2013) presented 48.33%, 45.5%, 42.96%, and 40.33% for root colonization, respectively. These results demonstrated that AMF promoted greater tolerance to pathogen attack in the plants (AGUILAR, 2002; ALBAN; GUERRERO; TORO, 2013; PEREIRA, 1994; VAAST; CASWELL-CHEN; ZASOSKI, 1998).

Considering the benefits of AMF on the tolerance of coffee plants to nematodes, inoculation of nursery seedlings is highly recommended, mainly because the change in the substrates did not alter the behavior of AMF in tolerance to pathogen attack. In addition, AMF reduced the time required for seedling formation in the nursery and contributed to seedling growth and nutrition (SIQUEIRA et al., 1993), which may also favor seedlings planting in areas infested with the pathogen.

3. 3 Symbiosis functioning: mycorrhizal colonization and number of spores

Twenty-four studies analyzed root colonization in roots collected in nursery or in greenhouse (ALVES et al., 2014; ANAYA et al., 2011; ANDRADE; SILVEIRA; MAZZAFERA, 2010; ANTUNES; SILVEIRA; CARDOSO,

1988; CALDEIRA; CHAVES; ZAMBOLIM, 1983a; CLEMENTE, 1988; COLOZZI-FILHO et al., 1994; ESMORIS et al., 2011; FRANÇA et al., 2014; IBIREMO; OLOYEDE; IREMIREN, 2011; KONRAD, 2003; LOPES et al., 1983b; RIVERA et al., 2010; SAGGIN-JÚNIOR et al., 1992, 1994, 1995b; SIQUEIRA; COLOZZI, 1986; SIQUEIRA; COLOZZI-FILHO; SAGGIN-JÚNIO, 1994; SIQUEIRA et al., 1987, 1995; SOUZA et al., 1991; SOUZA; OLIVEIRA; CARVALHO, 1989; TRISTÃO; ANDRADE; SILVEIRA, 2006; VAAST; ZASOSKI, 1992), and five studies analyzed the number of AMF spores (KONRAD, 2003; LOPES et al., 1983a; RIVERA et al., 2010; SIQUEIRA et al., 1987, 1995) at the stage of coffee seedling formation in greenhouse or nursery.

Studies on root colonization and number of AMF spores presented 7.2% minimum mean, and 70% maximum mean, and 8 to 43 spores per 50 mL of substrate. Such variations can be attributed to substrate diversity, AMF species, and to the use of soil fumigation (KONRAD, 2003; SIQUEIRA et al., 1987; THANGARAJU et al., 2008).

Colonization data and number of spores in coffee seedlings without AMF inoculation were collected from a study carried out by Siqueira et al. (1987) with 288 samples collected in 72 commercial nurseries, distributed in 29 municipalities located in the south of the state of Minas Gerais (Figure 1). Despite being a unique study, the mean is representative, and thus, it was compared with the other studies in figure 1.

These results indicate that the inoculation of coffee seedlings with efficient AMF species at nursery stage contributes to the increase of colonization of coffee seedlings by AMF, and consequently to the development of healthier seedlings, which are more tolerant to transplant stress. This effect associated with AMF remains for 12 months after planting in the field (COLOZZI-FILHO et al., 1994). Coffee seedlings inoculated with AMF have greater survival capacity and initial growth after transplanting to the field, which is a critical stage in the formation of coffee crops (VALLONE et al., 2010).

Eighteen studies evaluated root colonization in roots collected in the field (AL-AREQUI et al., 2013; ALVES et al., 2014; ANDRADE et al., 1995; AZEVEDO, 2005; BALOTA; LOPES, 1996a, 1996b; BONFIM et al., 2010; CHANIE, 2006; COLOZZI et al., 1994; FERNANDES, 2009; FERNANDES; SIUEIRA, 1989; LAKSHMIPATHY; BALAKRISHA; BAGYARAJ, 2012; LAMMEL et al., 2014; SIQUEIRA et al., 1986, 1993, 1998; THEODORO et al., 2003; TREJO et al., 2011); and 22 evaluated the number of spores in the field (AL-AREQUI et al., 2013; ALVES et al., 2014; ANDRADE et al., 1995; ARIAS et al., 2012; AZEVEDO, 2005; BALOTA; LOPES, 1996a, 1996b; BONFIM et al., 2010; CARDOSO et al., 2003; CASTRO; CONDE, 2012; COLOZZI-FILHO et al., 1994; FERNANDES, 2009; FERNANDES; SIQUEIRA, 1989; LAKSHMIPATHY; BALAKRISHNA; BAGYARAJ, 2012; LAMMEL et al., 2014; LÉBRON; LODGE; BAYMAN, 2012; LOPES et al., 1983b; MULETA; ASSEFA; NEMOMISSA, 2008; MULETA et al., 2007; OLIVEIRA et al., 1990; SIQUEIRA et al., 1986; TEXEIRA et al., 2010). Of these, four studies (BALOTA; LOPES, 1996a; COLOZZI et al., 1994; SIQUEIRA et al., 1993, 1998) are related to seedlings inoculated with AMF and transported to the field. These seedlings had a percentage of colonization similar to that of uninoculated seedlings; however, the number of spores was higher. These results demonstrated great variation among the studies regarding the number of spores in the field, ranging from 2 to 287 spores per 50 mL of substrate. These results showed that the effects of inoculation of efficient AMF species in the form of coffee plant seedlings does remain two years after planting in the field (BALOTA; LOPES, 1996a, 1996b; SIQUEIRA et al., 1993a).

Over time, native AMF species become more competitive for the plant, which explains the dominance of occurrence of certain species in coffee. Another critical point of seedling innoculation is the field environment, which is very different from the conditions of each vegetation where the fungus was efficient. This leads to a lack of adaptation of the fungus to the new field conditions. In addition, the crops undergo extensive soil modifications for planting (plowing, liming, plastering, phosphating, and the use of agrochemicals), which also affect the inoculated AMF species, making it necessary to identify efficient species adapted to coffee management system in the field.

In this sense, the knowledge on the factors that control mycorrhizal colonization in the field is of great importance, since the plant's response to mycorrhization is complex, and it is difficult to relate the factors of the fungus, plant and environment (FERNANDES; SIQUEIRA, 1989).

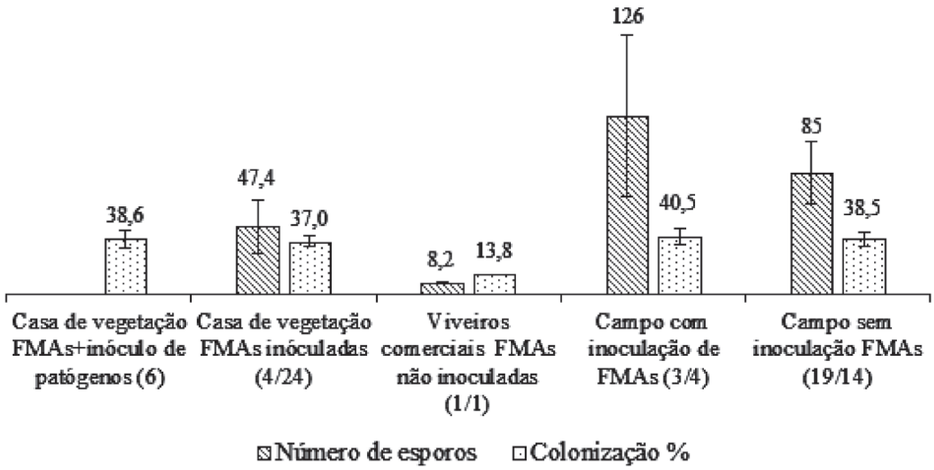

FIGURE 1 - Mean values for colonization and number of spores of different studies. In parentheses, the number of studies analyzed for number of spores and root colonization, respectively.

The use of molecular and biochemical techniques are supposed to identify the effect of fungus species and their contribution to coffee in the field. These techniques will allow the control of the action of AMF inoculated in seedlings in the field; the evaluation of the interaction between AMF and other soil microorganisms, such as phosphate solubilizers, diazotrophic bacteria, biological control agents, and soil fauna; and the proposal of researches for the development of commercial inoculants or improvement of crop management in order to maximize the use of native AMF community. Techniques of this nature would elucidate the behavior of the coffee seedlings inoculated throughout the development in the field, and thus, they would make the benefits provided by this symbiosis be used by the coffee producers.

3.4 FMA community in coffee crops

The specific richness of AMF associated with coffee plants is distributed as follows: 22 species of the genus *Glomus*, 18 species of the genus *Acaulospora*, 7 species of the genus *Scutellospora*, 6 species of the genus *Rhizophagus*, 5 species of the genus *Gigaspora,* 3 species of the genus *Funneliformis,* 2 species of the genus *Ambispora,* 2 species of the genus *Claroideoglomus*, 2 species of the genus *Sclerocystis*, 1 species of the genus *Entrophospora,* 1 species of the genus *Paraglomus,* and 1 species of the genus *Archaeospora* (supplementary material 2).

Based on the studies analyzed, the genus *Glomus* presented higher occurrence, and showed greater adaptability and ability to survive, colonize and multiply, demonstrating its importance for terrestrial ecosystems, mainly for coffee crop (COLOZZI-FILHO; CARDOSO, 2000; COLOZZI-FILHO et al., 1994; FERNANDES; SIQUEIRA, 1989; OLIVEIRA et al., 1990).

Studies carried out in the southern state of Minas Gerais consider the species *Acaulospora scrobiculata*, *Acaulospora morrowiae,* and *Acaulospora mellea* as dominant. This result reveals the high adaptability of these three species to the prevailing edaphoclimatic conditions in coffee agroecosystems (FERNANDES; SIQUEIRA, 1989; OLIVEIRA et al., 1990; SIQUEIRA et al., 1986; THEODORO et al., 2003). The predominance of these species does not depend on the coffee cultivar and on the type of management used, and reflects the characteristics of the ecosystem and of the combination with the coffee plant, since they are also found in the commercial nurseries, where these species are also predominant (SIQUEIRA et al., 1987).

The general occurrence of some genera certainly reflects their adaptation to the cultivation and crop management conditions (SIQUEIRA; COLOZZI-FILHO, 1986), and to soil use, soil correction, fertilization, and agrochemicals (SIQUEIRA et al., 1986, 1990). In addition, some genera adapt to other abiotic factors, such as humidity, temperature, luminosity, and aeration, which vary according to the crop management, such as addition of organic matter and plant cover

between rows (ARIAS et al., 2012; BONFIM et al., 2010; SOUZA et al., 1987).

Among 14 studies (supplementary material 1), a total of 70 AMF species (supplementary material 2) were identified in coffee plants rhizosphere. According to Siqueira et al. (2010), these results demonstrate that the cultivation system used in coffee crop has a low impact on the diversity of AMF in relation to other cultivation systems, such as eucalyptus (52 species), pasture (54 species), and also presented the same number of species in revegeted areas (SIQUEIRA et al., 2010). This is due to the fact that coffee plant is very mycotrophic, and not specific in its association with AMF, indicating that soil edaphic conditions do not interfere with mycorrhizal symbiosis. Tillage is only carried out at crop implantation, generating less impact in the AMF community, and the use of correctives improves the root environment, which favors AMF's establishment (SIQUEIRA, 1993).

Brazil presents the highest number of AMFs genus and species found in coffee crops (SAGGIN-JÚNIOR; SIQUEIRA, 1996). The great interest in this subject has placed Brazil in the ranking of mycorrhizal studies, with 82% of the studies involving AMF and coffee crop, and also revealed the Brazilian mycorrhizal diversity, making Brazil known as a country of high mycotrophic diversity (SIQUEIRA et al., 2010). However, the diversity of AMF in Brazil is the result of few researches in some Brazilian states, as reported by Siqueira et al. (2010).

3.5. Meta-analysis results

The I^2 test (inconsistency measure) ranged from zero to 15.8, indicating that the model of random effects is satisfactory for these data. Thus, no substantial changes were reported between the studies analyzed, as presented in Table 2.

The inoculation of coffee plants with AMF significantly increased plant response when compared with uninoculated control, showing the importance of AMF for growth, plant nutrition, and grain yield (Table 2). Effect size was different from 1 for all the variables under study, and indicated the significant mycorrhizal effect on the growth of coffee plant seedlings over the 213 studies (Table 2).

TABLE 2 - I^2 test, effect size (ES), standard error (SE), and confidence interval (CI) for growth parameters of coffee plant seedlings and grain yield.

Treatments	Site	Number of experiments	DF	I^2	ES	SE	-95 % CI	+95 % CI	P –value (t test)
Plant height	greenhouse	36	35	0	1.46	0.06	1.35	1.58	<0.001
Plant height	field	10	9	12.6	1.19	0.03	1.14	1.25	<0.001
Leaf area	greenhouse	8	7	15.8	2.13	0.24	1.65	2.61	0.007
Stem diameter	greenhouse	16	15	0	1.24	0.12	1.01	1.47	0.034
SDMW	greenhouse	47	46	5.4	1.81	0.10	1.60	2.01	0.029
RDMW	greenhouse	12	11	0	3.09	0.61	1.89	4.29	<0.001
Grain yield	field	48	47	35.5	1.28	0.18	1.10	1.46	ns
P contente in the shoot	greenhouse	36	35	0	2.82	0.81	1.22	4.41	0.058
Total		213							

DF: degrees of freedom; SDMW: shoot dry matter weight, RDMW: root dry matter weight.

This result allowed the consistent verification of the magnitude of the direct effects of AMF on growth and yield of coffee plant. These effects can be attributed to the direct action AMF in nutients absorption (TRISTÃO; ANDRADE; SILVEIRA, 2006), heavy metals, salinity, water stress (ANAYA et al., 2011), and root system pathogens, as described above.

The researches showed that AMF present a positive response to coffee seedlings, and no evidence of negative responses was verified. Another important point observed in all the studies on AMF that evaluated growth variables of coffee plants was that the positive results varied according to their amplitude as a function of the AMF species, of the coffee cultivar, of the substrate composition, and of the presence of pathogens. Despite this positive result, attention should be given to AMF species that have proved to be efficient.

In this sense, the growth variables shoot and root dry matter weight in greenhouse was positively affected by the inoculation of the AMF, and presented the greatest effects when compared with the other growth variables (Table 2). Results of the studies indicate that the inoculated AMF species affects the plant response. Plants inoculated with the genera *Glomus* and *Gigaspora* tended to present better growth characteristics when compared with the other genera inoculated alone or in combinations (SAGGIN-JÚNIOR et al., 1995; SIQUEIRA et al., 1993; TRISTÃO; ANDRADE; SILVEIRA, 2006). The species *Gigaspora margarita* (ANTUNES; SILVEIRA; CARDOSO, 1988; LOPES et al., 1983a; SIQUEIRA et al., 1993, 1995)*, Ambispora leptoticha* (ANTUNES; SILVEIRA; CARDOSO, 1988), *Rhizophagus clarus* (SIQUEIRA et al., 1993, 1995), and *Claroideoglomus etunicatum* (SIQUEIRA et al., 1993) presented better responses, mainly for shoot dry matter weight and root dry matter weight in greenhouse.

Therefore, AMF species affect plant response, which indicates that symbiotic efficiency has practical implications for a program of massive use of AMF. Efficient fungi strains adapted to the edaphoclimatic conditions and to the type of coffee management should be selected (SIQUEIRA; COLOZZI-FILHO; SAGGIN-JÚNIOR, 1994).

Thirty-five experiments originated from eleven studies (Table 3) carried out in greenhouse showed the benefit of AMF in the P absorption of the soil evaluated by leaf P content. Of all the positive effects, the contribution of AMF to the absorption of nutrients that are not very mobile in the soil has the most practical interest, since these nutrients, especially phosphorus, have low accessibility to the absorbent roots, slow diffusion in the soil, forming a depletion zone around the roots. Moreover, in the case of P, sources are scarce and the nutrient is required in large quantity by crops, including coffee plants in tropical soils (SIQUEIRA, 1990, 1993).

The contribution of AMF to P absorption is of great social and economic interest, since it allows greater efficiency in the use of phosphate fertilizers, generating cost reduction and preservation of water sources of eutrophication. In addition to phosphorus, this symbiosis contributes to the increase in the absorption of other nutrients, such as K, Ca, Mg, S, Cu, and the reduction of Mn and Zn when at toxic levels (SAGGIN-JÚNIOR et al., 1995a; SIQUEIRA et al., 1995), which becomes the most important contribution of AMF to the plants, being extremely relevant to the increase in coffee yield, since most coffee crops are under highly weathered soils, where nutrients are scarce and phosphorus (P), copper (Cu), and zinc (Zn) have low mobility (FURTINI et al., 2001). The presence of AMF in agricultural systems can contribute to their sustainability, especially during the years of coffee monoculture.

The meta-analysis also showed that coffee plants inoculated with AMF presented better yields when compared with uninoculated control (Table 4). The large variation in effect size (ES) is remarkable, and this can be attributed to the species of inoculated AMF and to the dose of phosphorus applied to the pit during tillage.

The lowest yields ranged from 6 to 58 g of benefited coffee per plant at zero dose of phosphorus at planting (SIQUEIRA et al., 1998). This result demonstrates that phosphorus-deficient soils impaired grain yield, but did not inhibit root colonization by AMF, being considered high, ranging from 43 to 55% (SIQUEIRA; COLOZZI-FILHO, 1986). However, phosphatic fertilization favored the symbiosis, with variations in this contribution. For instance, when 7.80 g of P per plant were applied, grain yield was 197 g per plant in the third crop (COLOZZI-FILHO, 1994), while application of 8.73; 17.5; 34.9; and 69.8 g per plant yielded, respectively, 176; 250; 447 and 550 g of benefited coffee per plant in the fifth harvest. Nevertheless, colonization and number of spores linearly decreased with the increase in the phosphorus dose (SIQUEIRA et al., 1998).

TABLE 3 - Phosphorus Content (%) in the shoot of coffee plants inoculated or not with AMF, Effect Size (ES), and Confidence Interval (CI) for seedlings in greenhouse

Author, year	AMF species	Treat-P %	P content %	ES	-95% CI	+95% CI
Antunes, Silveira and Cardoso (1988)	*Gigaspora sp.; Funneliformis mosseae; Funneliformis geosporum; Rhizophagus intraradices*	0,650	0,630	1,03	1,00	1,3
Antunes, Silveira and Cardoso (1988)	*Scutellospora heterogama*	0,580	0,500	1,16	1,05	1,5
Antunes, Silveira and Cardoso (1988)	*Gigaspora margarita*	0,660	0,630	1,05	1,01	1,3
Antunes, Silveira and Cardoso (1988)	*Appendicispora leptoticha*	0,550	0,500	1,10	1,03	1,5
Arango, Ochoa and Robledo (1989)	*Rhizophagus manihotis; Paraglomus occultum;Rhizophagus fasciculatus; Acaulospora sp.*	0,410	0,130	3,15	2,77	3,2
Arango, Ochoa and Robledo (1989)	*Rhizophagus manihotis; Paraglomus occultum;Rhizophagus fasciculatus; Acaulospora myriocarpa*	0,180	0,130	1,38	1,32	2,8
Colozzi-Filho and Siqueira (1986)	*Gigaspora margarita*	0,220	0,180	1,22	1,17	2,4
Colozzi-Filho et al. (1994)	*Glomus macrocarpum*	0,230	0,050	4,60	4,35	4,7
Colozzi-Filho et al. (1994) *Gigaspora margarita*		0,200	0,050	4,00	3,79	4,7
Colozzi-Filho et al. (1994)	*Rhizophagus clarus; Gigaspora margarita*	0,220	0,050	4,40	4,16	4,7
Colozzi-Filho et al. (1994)	*Rhizophagus clarus*	0,230	0,050	4,60	4,35	4,7
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	0,190	0,050	3,80	3,61	4,7
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum;Acaulospora longula*	0,240	0,050	4,80	4,54	4,7
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata*	0,200	0,050	4,00	3,79	4,7
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata; Paraglomus occultum*	0,200	0,050	4,00	3,79	4,7
Lopes et al. (1983a)	*Gigaspora margarita*	0,090	0,090	1,00	1,00	3,3
Lopes et al. (1983a)	*Funneliformis mosseae*	0,095	0,090	1,06	1,05	3,3
Lopes et al. (1983a)	*Scutellospora heterogama*	0,094	0,090	1,04	1,04	3,3
Lopes et al. (1983a)	*Glomus macrocarpum*	0,094	0,090	1,04	1,04	3,3
Pereira (1994)	*Gigaspora margarita*	0,084	0,044	1,91	1,85	4,8
Saggin-Júnior et al. (1992)	*Acaulospora scrobiculata; Acaulospora morrowae; Acaulospora longura; Rhizophagus clarus; Claroideoglomus etunicatum e Gigaspora margarita*	0,105	0,060	1,75	1,69	4,1
Saggin-Júnior et al. (1995a)	*Rhizophagus clarus; Gigaspora margarita*	2,100	0,700	3,00	1,06	3,1
Saggin-Júnior et al. (1995a)	*Claroideoglomus etunicatum*	2,900	0,700	4,14	1,09	4,2
Siqueira et al. (1993)	*Rhizophagus clarus; Gigaspora margarita*	0,220	0,040	5,50	5,25	5,2
Siqueira et al. (1993)	*Acaulospora longula; Gigaspora margarita; Acaulospora morrowae*	0,150	0,040	3,75	3,60	5,2
Siqueira et al. (1993)	*Acaulospora scrobiculata*	0,230	0,040	5,75	5,49	5,3
Siqueira et al. (1993)	*Acaulospora scrobiculata*	0,220	0,040	5,50	5,25	5,2

Siqueira et al. (1993)	*Acaulospora longula; Gigaspora margarita; Acaulospora morrowae*	0,170	0,040	4,25	4,07	5,2
Siqueira et al. (1993)	*Acaulospora scrobiculata*	0,210	0,040	5,25	5,01	5,2
Siqueira, Colozzi-Filho and Saggin-Júnior (1994)	*Gigaspora margarita*	0,168	0,060	2,80	2,65	4,2
Siqueira et al. (1995)	*Rhizophagus clarus; Gigaspora margarita*	0,160	0,040	4,00	3,83	5,2
Vaast, Zasoski and Bledsoe (1998)	*Acaulospora mellea*	0,141	0,055	2,56	2,44	4,4
Vaast, Zasoski and Bledsoe (1998)	*Rhizophagus clarus*	0,093	0,055	1,69	1,64	4,3
Vaast, Zasoski and Bledsoe (1998)	*Acaulospora mellea*	0,072	0,055	1,31	1,29	4,3
Vaast, Zasoski and Bledsoe (1998)	*Rhizophagus clarus*	0,064	0,055	1,16	1,15	4,3
Random effect model ($I^2 = 0$)						

TABLE 4 - Phosphorus (g / plant) applied in the pit during planting, grain yield (g / plant) in coffee seedlings inoculated or not with AMF, Effect Size (ES), confidence interval (CI).

Author (first), year	AMF species	P	Treatment	Control	ES	95% CI	95% CI
			Grain yield				
[1]Colozzi-Filho et al. (1994)	*Gigaspora margarita; Rhizophagus clarus*	12	110	93	1.18	0.96	1.40
Colozzi-Filho et al. (1994)	*Rhizophagus clarus*	12	135	93	1.45	1.20	1.69
Colozzi-Filho et al. (1994)	*Gigaspora margarita*	12	179	93	1.91	1.63	2.19
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata;Paraglomus occultum*	12	130	93	1.39	1.15	1.63
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	12	126	93	1.35	1.12	1.59
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora longula*	12	139	93	1.49	1.24	1.74
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	12	181	93	1.94	1.65	2.22
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata*	12	214	93	2.29	1.98	2.60
Colozzi-Filho et al. (1994)	*Glomus occultum*	12	180	93	1.93	1.64	2.21
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata*	12	183	93	1.96	1.68	2.24
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	12	119	93	1.27	1.05	1.50
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata*	12	139	93	1.49	1.24	1.74
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	12	157	93	1.69	1.42	1.95
Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum; Acaulospora scrobiculata*	12	148	93	1.58	1.33	1.84

Colozzi-Filho et al. (1994)	*Claroideoglomus etunicatum*	12	115	93	1.23	1.01	1.46
[2]Siqueira et al. (1993)	*Rhizophagus clarus, Claroideoglomus etunicatum; Acaulospora scrobiculata; Acaulospora longula; Gigaspora margarita; Acaulospora morrowiae*	8	122	74	1.66	1.36	1.95
Siqueira et al. (1993)	*Rhizophagus clarus;Claroideoglomus etunicatum*	8	135	74	1.83	1.52	2.14
Siqueira et al. (1993)	*Rhizophagus clarus; Claroideoglomus etunicatum*	8	334	74	4.54	4.05	5.03
[3]Siqueira et al. (1998)	*Gigaspora margarita; Rhizophagus clarus*	0	6	25	0.24	0.05	0.43
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	0	58	25	2.33	1.73	2.93
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	0	18	25	0.71	0.38	1.05
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	0	5	25	0.19	0.02	0.36
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	0	2	25	0.08	-0.03	0.19
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	0	19	25	0.75	0.41	1.08
Siqueira et al. (1998)	*Gigaspora margarita; Rhizophagus clarus*	9	404	133	3.04	2.75	3.34
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	9	105	133	0.79	0.64	0.94
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	9	137	133	1.04	0.86	1.21
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	9	106	133	0.80	0.65	0.95
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	9	166	133	1.25	1.06	1.45
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	9	140	133	1.06	0.88	1.23
Siqueira et al. (1998)	*Gigaspora margarita; Rhizophagus clarus*	17	246	323	0.76	0.67	0.86
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	17	280	323	0.87	0.76	0.97
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	17	313	323	0.97	0.86	1.08
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	17	202	323	0.63	0.54	0.71
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	17	177	323	0.55	0.47	0.63
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	17	285	323	0.88	0.78	0.98

Siqueira et al. (1998)	*Gigaspora margarita; Rhizophagus clarus*	35	609	653	0.93	0.86	1.01
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	35	583	653	0.89	0.82	0.96
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	35	377	653	0.58	0.52	0.64
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	35	351	653	0.54	0.48	0.59
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	35	487	653	0.75	0.68	0.81
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	35	276	653	0.42	0.37	0.47
Siqueira et al. (1998)	*Gigaspora margarita; Rhizophagus clarus*	70	467	373	1.25	1.14	1.37
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	70	285	373	0.76	0.67	0.85
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	70	742	373	1.99	1.84	2.13
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	70	864	373	2.31	2.16	2.47
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	70	350	373	0.94	0.84	1.04
Siqueira et al. (1998)	*Claroideoglomus etunicatum*	70	294	373	0.79	0.70	0.88

Obs.: [1]first harvest; [2] third harvest; [3]fifth harves

The best yields of inoculated AMF were obtained with the inoculation of *Claroideoglomus etunicatum,* with 864 g per plant when 70 g P were applied per plant, and 609 g per plant when 35 g of P per plant were applied, both in the fifth harvest. After fertilization, inoculation was performed with a mixture of *Rhizophagus clarus* and *Claroideoglomus etunicatum*, yielding 404 g per plant when 9 g of P were applied per plant (SIQUEIRA et al., 1998). In these results, the difference between the contributions by species associated with the dose of phosphorus is evident, demonstrating the complexity of the application of phosphorus in relation to mycorrhization. The continuity of studies of this nature aiming to improve crop and soil management is of great importance, since the use of AMF in large-scale agriculture significantly contributes to yield increase.

3.6. Advances and trends

The results obtained for the growth and mineral nutrition, especially due to the increase in the phosphorus absorption by coffee seedlings, indicate that the AMF species used as inoculants positively affect the response of the coffee seedling (ANTUNES; SILVEIRA; CARDOSO, 1988; LOPES et al., 1983a; SAGGIN-JÚNIOR et al., 1995; SIQUEIRA et al., 1993, 1995; TRISTÃO; ANDRADE; SILVEIRA, 2006). These results showed the importance of including the inoculation with AMF in the routine of coffee seedlings production, since they contributed to the formation of well-nourished plants that better withstand the adversities of the field, such as drought and pest and pathogen attack (ALBAN; GUERRERO; TORO, 2013; MULETA; ASSEFA; NEMOMISSA, 2008). The formation of coffee seedlings with quality is the basis for the successful implantation of coffee crops.

As shown in this review, few studies address inoculation with arbuscular mycorrhizal fungi in coffee in the field due to the difficulties of obtaining sufficient quantities of good quality inoculants, to the high production cost of these inoculants, and also because the arbuscular mycorrhizal are found in most soils in sufficient quantities. In spite of these obstacles, inoculation with arbuscular mycorrhizal fungi in the nursery can be successfully practiced, especially when associated with modern technologies of seedling production, such as the tubetes. In this sense, a protocol was developed for the use of arbuscular mycorrhizal fungi in coffee plants described in Saggin Junior and Siqueira (1996), and demonstrated in Figure 2.

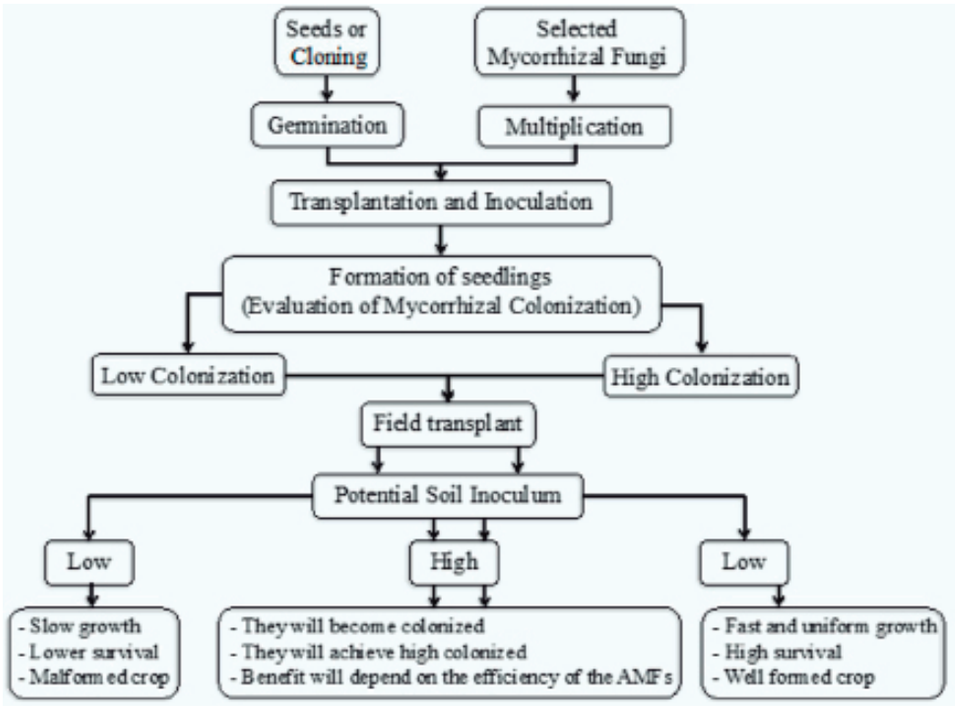

FIGURE 2 - Protocol for application of arbuscular mycorrhizal fungi in coffee crop, developed and tested at the Federal University of Lavras (UFLA) (SAGGIN JUNIOR; SIQUEIRA, 1996).

The results regarding the efficiency of the AMF in the inoculated coffee seedlings introduced in the field show favorable effects at the initial stage of growth and grain yield. They show that the persistence of the fungus inoculated in the field decreases with the years after planting (BALOTA; LOPES, 1996a). No difference in response was observed in the field two years after planting (SIQUEIRA et al., 1993). The identification of AMF that are effective in the field is of actual interest, since they provide favorable effects, such as increase in nutrient availability (SAGGIN-JÚNIOR et al., 1995a), tolerance to pests and diseases (VAAST; CASWELL-CHEN; ZASOSKI, 1998), and improvement in the water-soil-plant relationship (AUGÉ, 2001).

In this context, encouraging researches to use molecular and biochemical techniques to identify and associate the effect of AMF in the field is fundamental. In addition, researches should determine how and how much the symbiosis between AMF and coffee plant acts on the efficiency and cost reduction of phosphate fertilization, controlling the action of the inoculated

Finally, studies that improve crop and soil management aimed at the development of native AMF community should be prioritized, since the symbiosis between AMF and coffee roots contributes to greater coffee yield.

4 CONCLUSIONS

This review showed the importance of AMF for growth, plant nutrition and coffee grain yield. It also confirmed that few studies that evaluate the different soil and coffee crop management in the native AMF community are found in the literature. Further researches under field conditions are necessary in order to confer the real contribution of AMF as biofertilizers, biostimulants, and biocontrol agents for coffee plants.

5 ACKNOWLEDGMENTS

The authors thank the Scientific and Technological Development Council (CNPq) for the doctorate scholarship granted to the first author, and the productivity scholarship granted to the other authors; the Minas Gerais State Research Foundation (FAPEMIG); the Brazilian Consortium for Research and Development of Coffee; the National Coffee Science and Technology Institute and EMBRAPA CAFÉ, for the financial support for this project.

6 REFERENCES

AGUILAR, M. A. E. **Interaccion de plantas de café fertilizadas com fósforo e inoculadas com hongosmicorrizico arbusculares y *Ph*omacostarricencis Echandi**. 2002. 106 p. Dissertação (Mestrado em Biotecnologia)-Universidade de Colina, Colina, 2002.

AGUIRRE-MEDINA, J. F. et al. Hongo endomicorrizo y bacteria fijadora de nitrogeno inoculadas a *Coffe arabica* en vivero. **Agronomía Meso Americana**, Alajuela, v. 22, p. 71-80, 2011.

AL-AREQUI, A. H. N. et al. Diversity of arbuscular mycorrhizal fungi in the rhizosphere of Coffea arabica in the Republic of Yemen. **Journal of Applied Biosciences**, Nairobi, v. 64, p. 4888-4901, 2013.

ALBÁN, R.; GUERRERO, R.; TORO, M. Interactions between a root knot nematode (*Meloidoyne exigua)* and arbuscular mycorrhizae in coffee plant development (*Coffea arabica*). **American Journal of Plant Sciences**, Boca Raton, v. 4, p. 19-23, 2013.

ALVES, M. J. et al. Efeito da adubação verde com espécies herbáceas e arbóreas na micorrização do cafeeiro. **Revista Brasileira de Agropecuária Sustentável**, Viçosa, v. 4, n. 1, p. 11-16, 2014.

ANAYA, M. L. A. et al. Biofertilización de café orgánico en etapa de vivero en rachia, México**. Revista Mexicana de Ciencias Agrícolas**, Texcoco, v. 2, n. 31, p. 417-431, 2011.

ANDRADE, S. A. L. et al. Review Arbuscular mycorrhizal association in coffee. **Journal of Agricultural Science**, Toronto, v. 147, p. 105-115, 2009.

ANDRADE, D. S. et al. Atividade microbiana em função da calagem em um solo cultivado com cafeeiro. **Revista brasileira de Ciência do Solo**, Campinas, v. 19, p. 191-196, 1995.

ANDRADE, S. A. L.; SILVEIRA, A. P. D.; MAZZAFERA, P. Arbuscular mycorrhiza alters metal uptake and the physiological response of Coffea arabica seedlings to increasing Zn and Cu concentrations in soil. **Science of the Total Environment**, Amsterdam, v. 408, p. 5381-5391, 2010.

ANTUNES, A.; SILVEIRA, A. P.; CARDOSO, E. J. Interação entre diferentees tipos de Solo e Fungos Micorrízicos-Arbusculares na produção de mudas de café (*Coffea arabica* L.). **Turrialba**, San José, v. 38, n. 2, p. 117-127, 1988.

ARANGO, C.; OCHOA, G.; ROBLEDO, A. Evaluacion de dos fuentes de inoculo de micorrizas MVA y dos dosis de fósforo em almacigos de café variedade Colômbia. **Agronomía**, Manizales, v. 5, n. 1, p. 25-28, 1989.

ARIAS, R. M. et al. Diversity and abundance of arbuscular mycorrhizal fungi spores under different coffee production systems and in a tropical montane cloud forest patch in Veracruz, Mexico. **Agroforestry Systems**, Dorchecht, v. 85, p. 179-193, 2012.

AUGÉ, R. M. Water relations, drought and vesicular-arbuscular mycorrhizal symbiosis. **Mycorrhiza**, Heidelberg, v. 11, p. 3-42, 2001.

AZEVEDO, L. C. B. **Avaliação Fenotípica e molecular (PCR/RFLP) de fungos glomerales em cafeeiro (*Coffea arabica*)**. 2005. 76 p. Dissertação (Mestrado em Ciência do Solo)-Universidade Federal de Lavras, Lavras, 2005.

BALOTA, E. L.; LOPES, E. S. Introdução de fungo micorrízico arbuscular no cafeeiro em condições de campo: I., Persistência e interação com espécies nativas. **Revista Brasileira Ciência do Solo**, Campinas, v. 20, p. 217-223, 1996a.

BALOTA, E. L.; LOPES, E. S. Introdução de fungo micorrízico arbuscular no cafeeiro em condições de campo: II., flutuação sazonal de raízes, de colonização e de fungos micorrízicos arbusculares associados. **Revista brasileira de Ciência do Solo**, Campinas, v. 20, p. 225-232, 1996b.

BANZATTO, D. A.; KRONKA, S. N. **Experimentação agrícola**. Jaboticabal: FUNEP, 2013. 247 p.

BARDIN, I. **Análise de conteúdo**. Lisboa: Edições Setenta, 1994. 226 p.

BARTO, E. K.; RILLIG, M. C. Does herbivory really suppress mycorrhiza?: a meta-analysis. **Journal of Ecology**, London, v. 98, p. 745-753, 2010.

BEENHOUWER, M. et al. DNA pyrosequencing evidence for large diversity differences between natural and managed coffee mycorrhizal fungal communities. **Agronomy for Sustainable Development**, Dordrecht, v. 35, p. 241-249, 2015.

BIRADAR, B. I. et al. Effect of bio-fertilizers and pgprs on growth and development of coffee seedlings. **Journal Coffee Research**, Austin, v. 34, p. 57-63, 2006.

BONFIM, J. A. et al. Fungos micorrízicos arbusculares (FMA) e aspectos fisiológicos em cafeeiros cultivados em sistema agroflorestal e a pleno sol. **Bragantia**, Campinas, v. 69, n. 1, p. 201-206, 2010.

BRUNDRETT, M. C. Coevolution of roots and mycorrhizas of land plant. **New Phytologist**, Oxford, v. 154, n. 2, p. 275-304, 2002.

CALDEIRA, F. F.; CHAVES, G. M.; ZAMBOLIM, L. Associação de micorriza vesicular-arbuscular com café, limão-rosa e capim gordura. **Pesquisa Brasileira Agropecuária**, Brasília, DF, v. 18, n. 3, p. 223-228, 1983a.

CALDEIRA, F. F.; CHAVES, G. M.; ZAMBOLIM, L. Observações de micorrizas vesicular-arbuscular em diferentes espécies de plantas. **Revista Ceres**, Viçosa, v. 30, n. 167, p. 19-24, 1983b.

CARDOSO, E. J. B. N. Ocorrência de micorriza em café. **Summa Phytopathologica**, Campinas, v. 4, n. 2/4, p. 136-137, 1978.

CARDOSO, I. M. et al. Distribution of mycorrhizal fungal spores in soils under agroforestry and monocultural coffee systems in Brazil. **Agroforestry Systems**, Dorchecht, v. 58, p. 33-43, 2003.

CARNEIRO, M. A. C. et al. Arbuscular mycorrhizal fungi in soil aggregates from fields of 'murundus' converted to agriculture. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 50, p. 313-321, 2015.

CASTRO, A. L. F.; CONDE, M. R. G. Caracterización de las endomicorrizas y siete grupos de microorganismos en agrossistemas del piedemonte amazónico, rachiar. **Acta Biológica Colombiana**, Bogotá, v. 17, p. 349-362, 2012.

CHANIE, T. **Arbuscular mycorrhizal fungal diversity of coffee and shade trees of Bonga forest, South Western Ethiopia**. 2006. 72 p. Dissertation (Master of Biology)-University School of Graduate Studies, Addis Ababa, 2006.

CLEMENTE. C. M. **Nutrição mineral e crescimento de mudas de cafeeiro sob influência de Gigaspora margarita (Becker & Hall), matéria orgânica e fósforo**. 1988. 169 p. Dissertação (Mestrado em Agronomia)-Universidade Federal de Lavras, Lavras, 1988.

COLMENÁREZ-BETANCOURT, F.; PINEDA, J. B. Relación entre la aplicación de inóculo Brachiaria y fósforo con la infección por *colletotrichum Gloesporioides*en cafeto. **Fitopatología Venezolana**, Santiago de León de Caracas, v. 24, n. 1, p. 18-21, 2011.

COLOZZI-FILHO, A. et al. Efetividade de diferentes fungos endomicorrízicos na formação, crescimento pós-transplante e produção do cafeeiro. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 29, n. 9, p. 1397-1406, set. 1994.

COLOZZI FILHO, A.; CARDOSO, E. J. B. N. Detecção de fungos micorrízicos arbusculares em raízes de cafeeiro e de crotalária cultivada na entrelinha. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 35, n. 1, p. 2033-2042, jan. 2000.

COLOZZI-FILHO, A.; SIQUEIRA, J. O. Micorrizas vesículo-arbusculares em mudas de cafeeiro: I., efeitos de Gigaspora margarita e adubação fosfatada no crescimento e nutrição. **Revista Brasileira de Ciência do Solo**, Campinas, v. 10, p. 199-205, 1986.

COMPANHIA NACIONAL DE ABASTECIMENTO. **Levantamento CONAB da safra de café**. Brasília, DF, 2015. Disponível em: <http://www.conab.gov.br/OlalaCMS/uploads/arquivos/12_01_10_10_54_22_boletim_cafe_1a_estimativa.pdf >. Acesso em: 7 nov. 2015.

ESMORIS, E. A. et al. Abonos verdes e inoculación micorrízica de posturas de cafeto sobre suelosferralíticos rojos lixiviados. **Cultivos Tropicales**, Havana, v. 32, n. 3, p. 11-17, 2011.

FERNANDES, A. B.; SIQUEIRA, J. O. Micorrizas vesicular-arbusculares em cafeeiros da região Sul do Estado de Minas Gerais. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 24, n. 12, p. 1489-1498, dez. 1989.

FERNANDES, R. A. **Impacto de usos de um Latossolo Vermelho de cerrado sobre a diversidade de fungos micorrízicos arbusculares**. 2009. 82 p. Dissertação (Mestrado em Agronomia)-Universidade Federal de Goiás, Goiânia, 2009.

FRANÇA, A. C. et al. Crescimento de mudas de cafeeiro inoculadas com fungos micorrízicos arbusculares.

Revista Brasileira de Ciências Agrárias, Recife, v. 9, n. 4, p. 506-511, 2014.

FURTINI NETO, A. E. et al. **Fertilidade do solo**. Lavras: FAEPE, 2001. 252 p.

GUREVITCH, J.; HEDGES, L. V. Statistical issues in ecological meta-alyses. **Journal of Ecology**, London, v. 80, p. 1142-1149, 1999.

HARTUNG, J.; KANAPP, G.; SINHA, B. K. **Statistical meta-analysis with applications**. New Jersey: Willey, 2008. 288 p.

HEDGES, L.; GUREVITCH, V. J.; CURTIS, P. S. The meta-analysis of response ratios in experimental ecology. **Journal of Ecology**, London, v. 80, p. 1150-1156, 1999.

HIGGINS, J. P.; THOMPSON, S. G. Quantifying heterogeneity in a meta-analysis. **Statistics Medical**, Ontario, v. 21, p. 1539-1558, 2002.

HINSINGER, P. Biologyavailability of soil inorganic P in the rhizosphere as affected by root-induced chemical changes: a review. **Plant and Soil**, Dordrecht, v. 237, n. 2, p. 173-195, 2001.

HODGE, A.; CAMPBELL, C. D.; FITTER, A. H. An arbuscular mycorrizal fungi accelerates decomposition and acquires nitrogen directiy from organic material. **Nature**, London, v. 413, n. 20, p. 297-299, 2001.

HOOKER, J. E.; BLACK, K. E. Arbuscular mycorrhizal fungi as components of sustainable soilplant systems. **Critical Review in Biotechnology**, London, n. 15, p. 201-212, 1995.

IBIREMO, O. S.; OLOYEDE, M. A.; IREMIREN, G. O. Growth of coffee seedlings as influenced by Arbuscular mycorrhizal inoculation and phosphate fertilizers in two soils in Nigeria. **Journal of Plant Science**, Boca Raton, v. 2, n. 6, p. 160-165, 2011.

JANSE, J. M. Les endophytes radicaux de quelques plantes javanaises. **Annual Jardin Botanique**, Buitenzorg, v. 54, p. 53-201, 1897.

KAHILUOTO, H.; KETOJA, E.; VESTBERG, M. Plant-available P supply is not the main factor determining the benefit from arbuscular mycorrhizato crop P nutrition and growth in contrasting cropping systems. **Plant and Soil**, Dordrecht, v. 350, n. 1, p. 85-98, 2012.

KONRAD, M. L. F. **Crescimento do cafeeiro sob influência do alumínio em solução nutritiva e em solo ácido, inoculado com micorrizas arbusculares**. 2003. 112 p. Tese (Doutorado em Biologia)-Universidade Estadual de Campinas, Campinas, 2003.

LAKSHMIPATHY, R.; BALAKRISHNA, N. A.; BAGYARAJ, D. J. Abundance and diversity of AM fungi across a gradient of land use intensity and their seasonal variations in niligiri biosphere of the Western Ghats, India. **Journal of Agricultural Science and Technology**, Tehran, v. 14, p. 903-918, 2012.

LAMBAIS, M. R. Aspectos bioquímicos e moleculares da relação fungo-planta em micorrizas arbusculares. In: SIQUEIRA, J. O. (Ed.). **Avanços em fundamentos e aplicação de micorrizas**. Lavras: Ed. UFLA, 1996. p. 5-38.

LAMMEL, D. R. et al. Microbiological and faunal soil attributes of coffee cultivation under different management systems in Brazil. **Brazilian Journal of Biology**, São Carlos, v. 75, n. 4, p. 894-905, 2014.

LÉBRON, L.; LODGE, D. J.; BAYMAN, P. Differences in arbuscular mycorrhizal fungi among three coffee cultivars in Puerto Rico. **Agronomy**, Madison, v. 2012, p. 1-7, 2012.

LEHMANN, A. et al. Mycorrhizal responsiveness trends in annual crop plants and their wild relatives-a meta-analysis on studies from 1981 to 2010. **Plant and Soil**, Dordrecht, v. 355, p. 231-250, 2010.

LOPES, A. S.; COX, F. R. A survey of the fertility status of soils under cerrado vegetation in Brazil. **Soil Science Society of America Journal**, Madison, v. 41, p. 742-747, 1977.

LOPES, E. S. et al. Efeito da inoculação do cafeeiro com diferentes espécies de fungos micorrízicos vesicular arbusculares. **Revista Brasileira de Ciência do Solo**, Campinas, v. 7, p. 137-41, 1983b.

LOPES, E. S. et al. Occurrence and distribution of vesicular arbuscular mycorrhizal fungi in coffee (*Coffea arabica* L.) plantations in central Sao Paulo State, Brazil. **Turrialba**, San José, v. 33, p. 417-422, 1983a.

MAYERHOFER, M. S.; KERNAGHAN, G.; HARPER, A. K. The effects of fungal root endophytes on plant growth: a meta-analysis. **Mycorrhiza**, Heidelberg, v. 22, p. 29-39, 2012.

MOHER, D. et al. For the PRISMA group: preferred reporting Items for systematic reviews and meta-anlayses the PRISMA statement. **Annals of Internal Medicine Journal**, Philadelphia, v. 151, p. 65-94, 2009.

MULETA, D.; ASSEFA, F.; NEMOMISSA, S. Distribution of arbuscular mycorrhizal fungi spores in soils of smallholder agroforestry and monocultural coffee systems in southwestern Ethiopia. **Biology and Fertility of Soils**, Heidelberg, v. 44, p. 653-659, 2008.

MULETA, D. et al. Composition of coffee shade tree species and density of indigenous arbuscular mycorrhizal fungi (AMF) spores in Bonga natural coffee forest, southwestern Ethiopia. **Forest Ecology and Managementv**, Amsterdam, v. 241, p. 145-154, 2007.

NEYELOFF, J.; FUCHS, S. C.; MOREIRA, L. B. Meta-analyses and Forest plots using a brachiari excel spreadsheet: step-by-step guide focusing on descriptive data analysis. **BioMed Central**, London, v. 5, p. 1-6, 2012.

OLIVEIRA, E. et al. Ocorrência de fungos micorrízicos vesículo-arbusculares em cafeeiro em cafeeiro das regiões do Alto Paranaíba e Triângulo no Estado de Minas Gerais. **Hoehnea**, São Paulo, v. 17, n. 2, p. 117-125, 1990.

OLKIN, I. Meta-analysis: reconciling the results of independent studies. **Statistics in Medicine**, Washington, v. 14, n. 5/7, p. 457-472, 1995.

PEREIRA, L. A. A. **Desenvolvimento de mudas cafeeiro (*Coffea arabica* L.) na presença de *Gigaspora margarita* Becker & Hall e *Rhizoctonia solani, Kuhn***. 1994. 61 p. Dissertação (Mestrado em Ciência do Solo)-Universidade Federal de Lavras, Lavras, 1994.

RIVERA, R. et al. Abonos verdes e inoculación micorrízica de posturas de cafeto sobre suelos fersialíticos rojos lixiviados. Cultivos. **Tropicales**, Havana, v. 31, n. 3, p. 75-81, 2010.

RODRIGUES, C. L.; ZIEGELMANN, P. K. Meta-análise: um guia prático: meta-analysis: a practicalguide. **Revista do Hospital Clínicas de Porto Alegre**, Porto Alegre, v. 30, n. 4, p. 435-447, 2010.

SAGGIN-JÚNIOR, O. J. et al. Avaliação da eficiência simbiótica de fungos endomicorrízicos para o cafeeiro. **Revista Brasileira de Ciência do Solo**, Campinas, v. 19, p. 221-228, 1995a.

SAGGIN-JÚNIOR, O. J. et al. Colonização do cafeeiro por diferentes fungos micorrízicos: efeito na formação das mudas e no crescimento em solo fumigado. **Revista Brasileira Ciência do Solo**, Campinas, v. 19, p. 213-220, 1995b.

SAGGIN-JÚNIOR, O. J. et al. A infestação do solo com fungos micorrízicos no crescimento pós-transplante de mudas de cafeeiro não micorrizadas. **Revista Brasileira Ciência do Solo**, Campinas, v. 16, n. 1, p. 39-46, 1992.

SAGGIN-JÚNIOR, O. J. et al. Interação fungos micorrízicos versus superfosfato e seus efeitos no crescimento e teores de nutrientes do cafeeiro em solo não fumigado. **Revista Brasileira de Ciência do Solo**, Campinas, v. 18, p. 209-213, 1994.

SAGGIN-JÚNIOR, O. J.; SIQUEIRA, J. O. Micorrizas arbusculares em cafeeiro. In: SIQUEIRA, J. O. (Ed.). **Avanços em fundamentos e aplicação de micorrizas**. Lavras: DCS/DCF, 1996. p. 203-254.

SANCHEZ, C. et al. Comportamiento de 15 cepas de hongos micorrizogenos (HMA) sobre el desarrollo de posturas de cafeto en un suelo pardo gleyzoso. **Revista Forestal Latino Americana**, Bogotá, v. 38, p. 83-95, 2005.

SCHULZ, B.; BOYLE, C. The endophytic continuum. **Mycological Research**, London, v. 109, p. 661-686, 2005.

SILVA, C. R.; GOBBI, B. C.; SIMÃO, A. A. O uso da análise de conteúdo como uma ferramenta para a pesquisa qualitativa: descrição e aplicação do método. **Organizações Rurais Agroindustriais**, Lavras, v. 7, n. 1, p. 70-81, 2005.

SIQUEIRA, J. O. **Biologia do solo**. Lavras: Ed. UFLA/FAEPE, 1993. 230 f.

SIQUEIRA, J. O.; COLOZZI FILHO, A. Micorrizas vesículo-arbusculares em mudas de cafeeiro: II., efeito do fósforo no estabelecimento e funcionamento da simbiose. **Revista Brasileira de Ciência do Solo**, Campinas, v. 10, p. 207-211, 1986.

SIQUEIRA, J. O.; COLOZZI-FILHO, A.; SAGGIN-JÚNIOR, O. J. Efeitos da infecção de plântulas de cafeeiro com quantidades crescentes de esporos do fungo endomicorrízico *Gigaspora margarita.* **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 29, n. 6, p. 875-883, jun. 1994.

SIQUEIRA, J. O. et al. Arbuscular mycorrhizal inoculation and superphosphate application influence plant development and yield of coffee in Brazil. **Mycorrhiza**, Heidelberg, n. 7, p. 293-300, 1998.

SIQUEIRA, J. O. et al. Crescimento de mudas e produção do cafeeiro sob influência da inoculação com fungos micorrízicos e aplicação de superfosfato. **Revista Brasileira de Ciência do Solo**, Campinas, v. 17, n. 1, p. 53-60, 1993.

SIQUEIRA, J. O. et al. Influência do substrato de formação e da micorriza no crescimento de mudas de cafeeiro transplantadas. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 30, n. 12, p. 1417-1425, dez. 1995.

SIQUEIRA, J. O. et al. **Micorrizas:** 30 anos de pesquisa no Brasil. Lavras: Ed. UFLA, 2010. v. 1, 310 p.

SIQUEIRA, J. O. et al. The relationship between vesicular-arbuscular mycorrhiza and lime: associated effects on the growth and nutrition of brachiaria grass (*Brachiaria decumbens*). **Biology and Fertility of Soils**, Heidelberg, v. 10, p. 65-71, 1990.

SIQUEIRA, O. S. et al. Influência de cultivar e adubação fosfatada de plantio sobre a ocorrência de micorrizas vesicular arbusculares em cafeeiro (*Coffea arabica L.*). **Ciência Prática**, Lavras, v. 10, n. 3, p. 325-335, 1986.

SIQUEIRA, O. S. et al. Micorrizas vesicular-arbusculares em mudas de cafeeiro produzidas no sul do Estado de Minas Gerais. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 22, n. 1, p. 31-38, jan. 1987.

SOUZA, A. S. S. et al. Crescimento e nutrição do cafeeiro micorrizadas. **Pesquisa Agropecuária Brasileira**, Brasília, DF, v. 26, n. 11/12, p. 1989-2005, nov./dez. 1991.

SOUZA, C. A. S. et al. Influência de micorrizas vesicular-arbusculares o crescimento de mudas de cafeeiro (*Coffea arabica* L.) em substrato com e sem matéria orgânica e diferentes doses de superfosfato simples. **Ciência Prática**, Lavras, v. 11, n. 2, p. 177-189, 1987.

SOUZA, C. A. S.; OLIVEIRA, E.; CARVALHO, M. M. Desenvolvimento de mudas de cafeeiro (*Coffea arabica* cv.Catuaí) micorrizadas nas condições de viveiro comercial, em substrato com e sem matéria orgânica e diferentes doses de superfosfato simples. **Ciência e Prática**, Lavras, v. 13, p. 269-278, 1989.

STÜMER, S. L.; SIQUEIRA, J. O. Fungos micorrízicos. In: MOREIRA, F. S. (Ed.). **O ecossistema solo**. Lavras: Ed. UFLA, 2013. p. 289-310.

TEXEIRA, M. E. et al. Ocorrência de fungos micorrízicos arbusculares, nematoides e ácaros em solos sob diferentes sistemas de cultivo de cafeeiro no sul de Minas Gerais. **Agrogeoambiental**, Muzambinho, v. 2, n. 1, p. 101-108, 2010.

THANGARAJU, M. et al. Microbial consortium and its effect on controlling coffee root-lesion nematode (*Pratylenchus coffeae)* under nursery conditions. **Journal of Biological Control**, Bangalore, v. 22, n. 2, p. 425-432, 2008.

THEODORO, V. C. A. et al. Carbono biomassa e micorriza em solo sob mata nativa e agroecossistemas cafeeiros. **Acta Scientiarum:** Agronomy, Maringá, v. 25, n. 1, p. 147-153, 2003.

TREJO, D. et al. Efectividad de siete brachiaria nativos de hongos micorrízicos arbusculares en plantas de café en condiciones de invernadero y campo. **Revista Chilena de Historia Natural**, London, v. 84, p. 23-31, 2011.

TRISTÃO, F. S. M.; ANDRADE, S. A. L.; SILVEIRA, A. P. D. Fungos micorrízicos arbusculares na formação de mudas de cafeeiro, e, substrato orgânico comerciais. **Bragantia**, Campinas, v. 65, n. 4, p. 649-658, 2006.

VAAST, P.; CASWELL-CHEN, E. P.; ZASOSKI, R. J. Influences of a root-lesion nematode, Pratylenchus coffeae, and two arbuscular mycorrizal fungi, *Acaulospora mellea* and *Rhizophagus clarus* on coffee (*Coffea arabica* L.). **Biology and Fertility of Soils**, Heidelberg, v. 26, p. 130-135, 1998.

VAAST, P.; ZASOSKI, R. J. Effect of nitrogen sources and mycorrhzal inoculation different species on growth and nutrient composition of young arabica seedlings. **Café Cacao Thé**, Paris, v. 35, n. 2, 1991.

VAAST, P.; ZASOSKI, R. J. Effects of VA-mycorrhizae and nitrogen sources on rhizosphere soil characteristics, growth and nutrient acquisition of coffee seedlings (*Coffea arabica* L.). **Plant Soil**, The Hague, v. 147, p. 31-39, 1992.

VAAST, P.; ZASOSKI, R. J.; BLEDSOE, C. Effects of vesicular-arbuscular mycorrhizal inoculation at different soil P availabilities on growth and nutrient uptake of in vitro propagated coffee (*Coffea arabica* L.) plants. **Mycorrhiza**, Heidelberg, v. 6, p. 493-497, 1996.

VALLONE, H. S. et al. Diferentes recipientes e substrato na produção de mudas de cafeeiros. **Ciência e Agrotecnologia**, Lavras, v. 34, n. 1, p. 55-60, jan./fev. 2010.

Supplementary Material 1
Lista de publicações utilizadas para a revisão e meta-análise
List of publications used for the review and meta-analysis

Author (first) /year	Source	Country
Aguilar (2002)	Universidade de Colima/dissertação	Mexico
Al-arenqi (2013)	Journal of Applies Bioscience v.64, p.4888-4901	Yemen
Alban (2013)	American Journal of Plant Sciences, v.4, p.19-23	Venezuela
Alves (2014)	Rev. Brasileira de Agropecuária Sustentável.v.4, n.1, p.11-16	Brazil
Anaya (2011)	Rev. Mexicana de Ciencias Agrícolas, v.3, p.417-431	Mexico
Andrade (1995)	Revista brasileira de Ciência do Solo v.19, p.191-196	Brazil
Andrade (2010)	Science of the Total Environment, v.408, p.5381-5391	Brazil
Antunes (1988)	Revista Turrialba, v.38, p.117-122	Brazil
Arango (1989)	Agronomia v.5, p.25-28	Colombia
Arias et al. (2012)	Agroforest Systems v.85, p.179-193	Mexico
Azevedo (2005)	Universidade Federal de Lavras/dissertação	Brazil
Balota (1989)	Universidade de São Paulo/dissertação	Brazil
Balota (1996)	Revista Brasileira de Ciência do Solo, v.20, p.217-223	Brazil
Balota (1996)	Revista Brasileira de Ciência do Solo, v.20, p.225-232	Brazil
Beenhouwer (2015)	Agron. Sustain. Dev. v.35 p.241-249	Ethiopia
Biradar (2006)	Journal of Coffee Research, n.34, p.57-63	India
Bonfim (2010)	Bragantia, v.69, p.201-206	Brazil
Caldeira (1983)	Pesquisa Agropecuária Brasileira v.18, p.223-228	Brazil
Caldeira (1983)	Revista Ceres v.167, p.19-24	Brazil
Cardoso (1978)	Summa Phytopathologiva, v.4, p.2-4	Brazil
Cardoso (2003)	Agroforest Systems, v.58, p.33-43	Brazil
Castro (2012)	Acta Biológica Colombiana, v.17, p.349-362	Colombia
Chanie (2006)	Universidade Addis Ababa/dissertação	Ethiopia
Clemente (1988)	Universidade Federal de Lavras/dissertação	Brazil
Colozzi-Filho (1999)	Universidade de São Paulo/tese	Brazil
Colozzi-Filho (1986)	Revista Brasileira de Ciência do Solo, v.10, p.199-205	Brazil
Colozzi-Filho (1994)	Pesquisa Agropecuária Brasileira v.29, p.1397-1406	Brazil
Colozzi-Filho (2000)	Pesquisa Agropecuária Brasileira v.35, p.2033-2042	Brazil
Colmenárez-Betancourt (2011)	Fitopatologia Venezuelana, n.24, v.1, p.20-24	Venezuela
Esmoris (2011)	Cultivos Tropicales, v.3, p.11-17	Cuba
Fernandes (2009)	Universidade Federal de Goiás/dissertação	Brazil
Fernandes (1989)	Pesquisa Agropecuária Brasileira, v.24, p.1489-1498	Brazil
França (2014)	Revista Brasileira de Ciência Agrária, n.4, v,9, p.506-511	Brazil
Konrad (2003)	Universidade Estadual de Campinas/tese	Brazil
Ibiremo (2011)	Journal of Plant Science, v.6, p.160-165	Nigeria
Lammel (2015)	Brazilian Journal of Biology, n.4, v.75, p.894-905	Brazil

Lakshmipathy (2012)	Journal of Agricultural Science and Technology, v.14, p.903-918	India
Lébron (2012)	International Scholarly Research Network p.1-7	Puerto Rico
Lopes (1983)	Revista Brasileira de Ciência do Solo, v.7, p.137-141	Nigeria
Lopes (1983)	Revista Turrialba, v.33, p.417-422	Brazil
Medina (2011)	Agronoma Mesoamericana, v.22, p.71 -80	Mexico
Muleta (2007)	University of Agricultural Sciences/tese	Ethiopia
Muleta (2007)	Forest Ecology and Management, v.241, p.145-154	Ethiopia
Muleta (2008)	Biology and Fertility of Soils, v.44, p.653:659	Ethiopia
Oliveira (1990)	Hoehnea, v.17, p.117-125	Brazil
Panneerselvam (2008)	Journal Biological Control, v.22, p.425-432	India
Pereira (1994)	Universidade Federal de Lavras/dissertação	Brazil
Rivera (2010)	Cultivos Tropicales, v.31, n.3, p.75-81	Cuba
Saggin-Júnior (1992)	Universidade Federal de Lavras/dissertação	Brazil
Saggin-Júnior (1992)	Revista Brasileira de Ciência do Solo, v.16, p.39-46	Brazil
Saggin-Júnior (1994)	Revista Brasileira de Ciência do Solo, v.18, p.27-36	Brazil
Saggin-Júnior (1995)	Revista Brasileira de Ciência do Solo, v.19, p.213-220	Brazil
Saggin-Júnior (1995)	Revista Brasileira de Ciência do Solo, v.19, p.221-228	Brazil
Sánchez (2005)	Revista Forestal Latino americana, v.38, p.83–95	Cuba
Siqueira (1986)	Ciência Prática, v.10, p.325-335	Brazil
Siqueira (1986)	Revista Brasileira de Ciência do Solo, v10, p.207-211	Brazil
Siqueira (1987)	Pesquisa Agropecuária Brasileira v.22 p.31-38	Brazil
Siqueira (1993)	Revista Brasileira de Ciência do Solo, v.17 p.53-60	Brazil
Siqueira (1994)	Pesquisa Agropecuária Brasileira v.29, p.875-883	Brazil
Siqueira (1995)	Pesquisa Agropecuária Brasileira v.30, p.1417-1425	Brazil
Siqueira (1998)	Mycorrhiza v.7, p.293:300	Brazil
Souza (1987)	Universidade Federal de Lavras/dissertação	Brazil
Souza (1987)	Ciência Prática, v.11, p.177-189	Brazil
Souza (1991)	Pesquisa Agropecuária Brasileira v.26, p.1989-2005	Brazil
Texeira (2010)	Revista Agrogeoambiental v.2, p.101-108	Brazil
Theodoro (2003)	Acta Scientiarum: Agronomy v.25, p.147-153	Brazil
Trejo (2011)	Revista Chilena de História Natural, v.84, p.23-31	Mexico
Tristão (2005)	Universidade Estadual de Campinas/dissertação	Brazil
Tristão (2006)	Revista Bragantia, v.65, p.649-658	Brazil
Vaast (1991)	Café Cacao Thé, v.2, p.121-132	USA
Vaast (1992)	Plant and Soil, v.147, p.31-39	USA
Vaast (1996)	Mycorrhiza, v.6, p.493:497	USA
Vaast (1998)	Biology and Fertility of Soils, v.26, p.130:135	USA

Supplementary Material 2

List of AMF genera and species, and their occurrence in coffee crops per country

AMF species	Countries					
	Brazil	India	Mexico	Puerto Rico	Yemen	[1]TNC
Acaulospora bireticulata Rothwell & Trap		+	+			2
Acaulospora colombiana (Spain & Schenck) Kaonongbua, Morton & Bever	+					1
Acaulospora dilatata Morton		+	+			2
Acaulospora excavata Ingleby & Walker			+			1
Acaulospora foveata Trappe & Janos	+		+			2
Acaulospora gedanensis Blaszkowski	+					1
Acaulospora lacunosa Morton		+				1
Acaulospora laevis Gerdemann & Trappe	+	+	+			3
Acaulospora longula Spain & Schenck	+					1
Acaulospora mellea Spain & Schenck	+		+			2
Acaulospora morrowiae Spain & Schenck	+					1
Acaulospora myriocarpa Spain, Sieverding & Schenck	+					1
Acaulospora scrobiculata Trappe	+	+	+			3
Acaulospora spinosa Walker & Trappe	+		+			2
Acaulospora sporocarpia Berch					+	1
Acaulospora sppendicula	+					1
Acaulospora tuberculata Janos & Trappe	+					1
Ambispora appendicula (Spain, Sieverd. & Schenck) Walker	+					1
Ambispora leptoticha (Schenck & Smith) Walker, Vestberg & Schuessler	+	+	+			3
Archaeospora trappei (Ames & Linderman) J.B. Morton & D. Redecker	+					1
Claroideoglomus claroideum (Schecnk & Smith) Walker & Schüssle			+		+	2
Claroideoglomus etunicatum Becker & Gerd.) Walker & Schüssler	+		+			2
Entrophospora infrequens (I.R. Hall) Ames & Schneid	+		+			2
Funneliformis constrictum (Trappe) Walker & Schüßler			+			1
Funneliformis coronatum (Giovann.) Walker & Schüßler			+			1
Funneliformis mosseae (Nicolson & Gerd.) Walker & Schüßler	+	+	+			3

Gigaspora albida Schenck & Smith	+				1
Gigaspora decipiens Hall & Abbott	+				1
Gigaspora gigantea (Nicolson & Gerdemann) Gerd. & Trappe	+				1
Gigaspora margarita Becker & Hall	+	+			2
Gigaspora rosea Nicolson & Schenck	+				1
Glomus aggregatum Schenck & Smith	+	+	+		3
Glomus albidum Walker & Rhodes	+				1
Glomus citricola Tang & Zang		+			2
Glomus clavisporum (Trappe) Almeida & Schenck	+	+			2
*Glomus coremioide*s (Berk. & Broome) Redecker & Morton			+		1
Glomus deserticola Trappe, Bloss & Menge	+	+			2
Glomus halonatum Rose & Trappe		+			1
Glomus heterosporum Smith & Schenck		+			1
Glomus invermaium Hall		+			1
Glomus lacteum Rose & Trappe		+			1
Glomus macrocarpum Tulasne & Tulasne	+		+	+	3
Glomus magnicaule Hall		+			1
Glomus microaggregatum Koske, Gemma & Olexia			+		1
Glomus microcarpum Tulasne & Tulasne	+				1
Glomus monosporum Gerdemann & Trappe		+			1
Glomus multicaule Gerdemann & Bakshi		+			1
Glomus radiatum (Thaxter) Trappe & Gerdemann		+			1
Glomus rubiforme (Gerd. & Trappe) Almeida & Schenck			+		1
Glomus sinuosum (Gerd. & Bakshi) Almeida & Schenck	+		+	+	3
Glomus tenebrosum (Thaxter) Berch		+			1
Glomus tortuosum Schenck & Smith	+				1
Glomus hoi Berch & Trappe		+			1
Paraglomus occultum (Walker) Morton & Redecker	+				1
Racocetra verrucosa (Koske & Walker) Oehl, Souza & Sieverd	+				1
Rhizophagus clarus (Nicolson & Schenck) C. Walker & Schüßler	+		+		2
Rhizophagus diaphanum (Morton & Walker) Walker & Schüßler	+	+	+		3
Rhizophagus fasciculatus (Thaxt.) Walker & Schüßler	+	+	+		3

Rhizophagus intraradices (Schenck & Sm.) Walker & Schüßler	+	+	+			3
Rhizophagus manihotis (Howeler, Sieverd. & Schenck) Walker & Schüßler	+					1
Rhizophagus proliferus (Dalpé & Declerck) C. Walker & Schüßler					+	1
Sclerocystis coremioides Berk. & Broome	+					1
Sclerocystis sinuosa Gerd. & B.K. Bakshi	+					1
Scutellospora biornata Spain, Sieverd. & Toro			+			1
Scutellospora cerradensis Spain & JMiranda	+					1
Scutellospora dipapillosa (Walker & Koske) Walker & Sanders	+		+			2
Scutellospora gilmorei (Trappe & Gerd.) Walker & Sanders	+					1
Scutellospora heterogama (Nicolson & Gerd.) Walker & Sanders	+	+				2
Scutellospora nigra (Redhead) Walker & Sanders					+	1
*Scutellospora pellucid*a (Nicolson & Schenck) Walker & Sanders	+					1
[2]TNSC	45	26	27	2	4	
[3]TNS:						70

[1]TNC: total number of countries per species; [2]TNSC; total number os species per country; [3]TNS: total number os species