Chapter 2
Advances in Arbuscular Mycorrhizal Taxonomy

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2.1 Introduction

Taxonomy, the science of classifying organisms, describes names, identifies organisms, and generates tools for taxonomic identification of fungi. A review article by Shenoy et al. (2007) compiled the main activities of fungal systematics. The products of taxonomy are used by taxonomists and ecologists (Hodkinson and Parnell 2007). Correct species names are deliberately used for instance on land management systems to compare ecological interactions between the different components.

Current classification systems of Arbuscular mycorrhizal fungi (AMF, Glomeromycota) involve both morphological and molecular tools and their progress shows in some measure a natural organization and understanding of the relationships among species. Several research groups have been discussing the taxonomy,

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systematics, and evolution of AMF. The researchers may propose their classification system; however, most biologists believe that these developing systems only reflect our knowledge at time (Goto 2014). This chapter presents an overview of data showing AMF classification, and recent advances are here compiled. Our goal was to provide nonspecialists such as researchers in other fields and land managers with information on historical and recent changes in AMF classification.

2.2 Advances in AMF Taxonomy

Taxonomy, the identifies and describes names, generating tools for taxonomic identification of fungi. The products of taxonomy (species lists, descriptions of formally delimited species, and identification keys, among others) are used by taxonomists and ecologists (Hodkinson and Parnell 2007). As previously stated, a review article by Shenoy et al. (2007) compiled the main activities of fungal systematics before and after the twentieth century.

With regard to the classification of AMF, it was based mostly in the spore morphologies (see Morton et al. 2004; Stürmer 2012). However, delimitation of taxa is very difficult and new information is continuously added. Stürmer (2012) reviewed the AMF systematics suggesting four periods, which the phylum Glomeromycota (Schüßler et al. 2001) has passed, that is, the discovery, alpha taxonomy, cladistics, and phylogenetic synthesis periods. The increasing AMF species reported within the course of time are shown in Table 2.1. One of the most widely accepted classification system for AMF proved to be that of Oehl et al. (2011a, b) (Table 2.2), who intended a further division of three AMF classes and the establishment of a fifth order, namely Gigasporales. They based their classification system on morphological (such as spore morphology and spore formation, and mycorrhizal and mycelial structures including staining processes) and genetic features (β-tubulin and rRNA sequences). A few important advances have been presented since then, e.g., in the Glomerales (e.g., Sieverding et al. 2014; Błaszkowski et al. 2015), in the Gigasporales (Silva et al. 2012; Pontes et al. 2013; Marinho et al. 2014), in the Diversisporales (Błaszkowski 2012; Medina et al. 2014), and in the Archaeosporales (Oehl et al. 2015). Therefore, we suggest the classification proposed by Oehl et al. (2011a) including the most recent progress for better understanding of the natural classification of AMF (see also Aguilera et al. 2015; www.agroscope.ch/saf).

Table 2.1 Number of arbuscular mycorrhizal species reported by periods

Period	Number of AMF species	References
1845–1974	>30	Gerdemann and Trappe (1974)
1975–1989	~97	Schenck and Perez (1988)
1990–2000	39	Stürmer (2012)
2001–2011	65	Oehl et al. (2011a)
2012 to present	~40	Goto (2014)
Total of species	~270	Goto (2014)

Table 2.2 Some recent reviews and papers dealing with arbuscular mycorrhizal fungi classification, identification, and phylogeny

Focus	References
DNA-based detection and identification of Glomeromycota	Öpik et al. (2013)
Classification of arbuscular mycorrhizal fungi	Redecker et al. (2013)[a]
Systematic and phylotaxonomy of arbuscular mycorrhizal fungi	Krüger et al. (2012)[a]
A molecular guide to the taxonomy of arbuscular mycorrhizal fungi	Young (2012)[a]
A history of the taxonomy and systematics of arbuscular mycorrhizal fungi	Stürmer (2012)
Glomeromycota taxonomy	Oehl et al. (2011a)
Advances in Glomeromycota taxonomy	Oehl et al. (2011b)[a]
Glomerospores: a new denomination for the spores of Glomeromycota	Goto and Maia (2006)
Molecular phylogeny, taxonomy, and evolution of *Geosiphon pyriformis* and arbuscular mycorrhizal fungi	Schüßler (2002)

[a]Review

Table 2.3 Journal articles dealing with arbuscular mycorrhizas and their taxonomy and ecology

Key words	Number of journal articles
AMF	>4800
AMF + ecology	>450
AMF + taxonomy	>100
New AMF species	129

Database survey conducted on April 2015 (SCOPUS database since 1947) and other bases; *AMF*, arbuscular mycorrhizal fungi

Additionally, fungal taxonomists have recently integrated the modernization of its nomenclatural rules. The prerequisites of Latin descriptions, endorsement of electronic publication, and the use of the dual system of nomenclature (different names for the sexual and asexual phases of pleomorphic species) have ceased to be used (Hibbett and Taylor 2013).

2.3 Implications

In 2009, a total of 214 AMF species were described simply by morphological tools (few of them were successfully cultured) (Krüger et al. 2009). However, molecular characterization and morphological observations showed that AMF diversity is greater than the present estimations (Kottke et al. 2008; Öpik et al. 2008; Sudová et al. 2015).

A robust system of AMF classification will facilitate the research for specialists and nonspecialists (Table 2.3). There is a need to further explore the natural and nonnatural ecosystems for so far unknown AMF species and to describe them. This is for instance because almost all reports include a significant number of non-identified AMF species, often attributed to the genus *Glomus*, but also in other genera, such as *Acaulospora* and *Gigaspora*, we are still aware of several to many unidentified species (e.g., Velázquez and Cabello 2011; Zangaro et al. 2013; Silva et al. 2014; Coutinho et al. 2015). Such studies will facilitate the AMF identification in the different studied ecosystems as well as their utilization and management. AMF biodiversity in natural ecosystems such as tropical forests or permanent grasslands is typically higher than in conventional agricultural systems, because of higher number of plant species and more complex habitats that can support a wider diversity. In tropical regions such as Brazil the number of accepted new AMF species is increasing (Błaszkowski et al. 2013; Goto et al. 2013; Mello et al. 2013; Lima et al. 2014). Also in regions with few studies, such as aquatic sites with macrophytes, new AMF species such as *Rhizoglomus melanum* are found (Sudová et al. 2015).

Since 1990, when molecular analyses to AMF species identification have started (Table 2.1), more new AMF species (~143, Goto 2014) have been described than in the previous 150 years (~127) (Schenck and Perez 1988). Some authors estimate that the number of species can reach 300–1600 (Öpik et al. 2013; Kivlin et al. 2011; Sudová et al. 2015). The discovery, isolation, and morphological/molecular description of new species to science are required due to increase of environmental impacts in preserved areas, as well as the potential uses of these fungi as bio-inoculants (Sieverding et al. 2014). In this sense, studies need a better assessment of the AMF communities in natural, managed reforested and agronomic areas (Fig. 2.1).

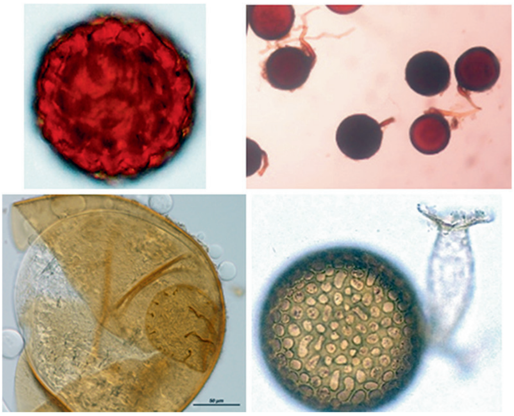

Fig. 2.1 Spores of non-identified, difficult to identify, and recently identified AMF species found in field conditions: clockwise from upper left: unidentified spore, *Septoglomus furcatum* identified from semiarid region of Brazil, *Acaulospora* sp. found in Minas Gerais, and *Fuscutata aurea* from Amazonia. Photo credit: M. Pagano; Camilla M.R. Pereira

2.4 Conclusion

We briefly described advances in AMF classification based on both morphological and molecular characters and faster progress attained. We have mentioned that different research groups naturally adopt their preferred taxonomic system, which have been steadily improved by newly acquired knowledge. The different systems, however, have been approaching each other due to the concomitant progresses on morphological and molecular characterization of species belonging to the phylum. Both morphological and molecular characterization have still to be developed further. Moreover, a large portion, and probably the majority, of AMF species have still remained undiscovered and undescribed. Thus, AMF taxonomy and classification consequently have to develop further for at least another 50–100 years on both lower and higher taxon levels attempting to diminish the current knowledge gaps.

An advanced Glomeromycota system will facilitate ecological research and efforts to accrue benefits from mycorrhizas. Consequently, a better diagnosis of new AMF species will help to achieve maximum benefits from these microorganisms.

References

Aguilera P, Cumming J, Oehl F, Cornejo P, Borie F (2015) Diversity of arbuscular mycorrhizal fungi in acidic soils and their contribution to aluminum phytotoxicity alleviation. In: Panda SK, Baluška F (eds) Aluminum stress adaption in plants. Signaling, communication in plants, vol 24. ISBN: 978-3-319-19967-2. doi:10.1007/978-3-319-19968-9_11

Błaszkowski J (2012) Glomeromycota. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, p 303

Błaszkowski J, Chwat G, Kovács GM, Gáspár BK, Ryszka P, Orłowska E, Pagano MC, Araújo FS, Wubet T, Buscot F (2013) *Septoglomus fuscum* and *S. furcatum*, two new species of arbuscular mycorrhizal fungi (Glomeromycota). Mycologia 105(3):670–680

Błaszkowski J, Chwat G, Góralska A, Ryska P, Kovács GM (2015) Two new genera, *Dominikia* and *Kamienska*, and *D. disticha* sp. nov. in Glomeromycota. Nova Hedwig 100:225–238

Coutinho ES, Fernandes GW, Berbara RLL, Valério HM, Goto BT (2015) Variation of arbuscular mycorrhizal fungal communities along an altitudinal gradient in rupestrian grasslands in Brazil. Mycorrhiza 25(8):627–38. doi:10.1007/s00572-015-0636-5

Gerdemann JW, Trappe JM (1974) The Endogonaceae in the Pacific Northwest. Mycol Mem 5:1–76

Goto BT (2014) Aspectos gerais da classificação. Laboratório de Biologia de Micorrizas. Available at: http://glomeromycota.wix.com/lbmicorrizas#!c1/c229i

Goto BT, Maia LC (2006) Glomerospores, a new denomination for the spores of Glomeromycota, a group molecularly distinct from Zygomycota. Mycotaxon 96:129–132

Goto BT, Pereira CMR, Nobre CP, Zatorre NP, Covacevich F, Berbara LL, Maia LC (2013) *Acaulospora endographis* (*Glomeromycetes*), a new fungus with a complex spore wall. Mycotaxon 123:403–408

Hibbett DS, Taylor JW (2013) Fungal systematics: is a new age of enlightenment at hand? Nat Rev Microbiol 11(2):129–133

Hodkinson TR, Parnell JAN (2007) Reconstructing the tree of life: taxonomy and systematics of species rich taxa, vol 72, Systematics association, special series. Taylor and Francis/CRC Press, Boca Raton

Kivlin SN, Hawkes CV, Treseder KK (2011) Global diversity and distribution of arbuscular mycorrhizal fungi. Soil Biol Biochem 43:2294–2303

Kottke I, Haug I, Setaro S, Pablo Suarez J, Weiss M, Preussing M, Nebel M, Oberwinkler F (2008) Guilds of mycorrhizal fungi and their relation to trees, ericads, orchids and liverworts in a neotropical mountain rain forest. Basic Appl Ecol 9:13–23

Krüger M, Stockinger H, Krüger C, Schüßler A (2009) DNA-based species level detection of Glomeromycota: one PCR primer set for all arbuscular mycorrhizal fungi. New Phytol 183:212–223

Krüger M, Krüger C, Walker C, Stockinger H, Scüβler A (2012) Phylogenetic reference data for systematic and phylotaxonomy of arbuscular mycorrhizal fungi from phylum to species level. New Phytol 193:970–984

Lima LL, Kozovits AR, Assis DMA, da Silva GA, Oehl F (2014) *Cetraspora auronigra*, a new glomeromycete species from Ouro Preto (Minas Gerais, Brazil). Sydowia 66(2):299–308

Marinho F, Silva GA, Ferreira ACA, Veras JSN, Sousa NMF, Goto BT, Maia LC, Oehl F (2014) *Bulbospora minima*, new genus and new species in the Glomeromycetes from semi-arid Northeast Brazil. Sydowia 66:313–323

Medina J, Cornejo P, Borie F, Meyer S, Palenzuela J, Vieira HEE, Ferreira ACA, Silva GA, Sánchez-Castro I, Oehl F (2014) *Corymbiglomus pacificum*, a new glomeromycete from a saline lakeshore in Chile. Mycotaxon 127:173–183

Mello CMA, da Silva GA, Assis DMA, Pontes JS, Ferreira ACA, Leão MPC, Vieira HEE, Maia LC, Oehl F (2013) *Paraglomus pernambucanum* sp. nov. and *Paraglomus bolivianum* comb. nov., and biogeographic distribution of *Paraglomus* and *Pacispora*. J Appl Bot Food Qual 86:11–125

Morton JB, Koske RE, Stürmer SL, Bentivenga SP (2004) Mutualistic arbuscular endomycorrhizal fungi. In: Mueller GM, Bills GF, Foster MS (eds) Biodiversity of fungi: inventory and monitoring methods. Smithsonian Institution Press, Washington, DC, pp 317–336

Oehl F, Da Silva GA, Goto BT, Maia LC, Sieverding E (2011a) Glomeromycota: two new classes and a new order. Mycotaxon 116:365–379

Oehl F, Sieverding E, Palenzuela J, Ineichen K, da Silva GA (2011b) Advances in Glomeromycota taxonomy and classification. IMA Fungus 2(2):191–199

Oehl F, Sánchez-Castro I, Palenzuela J, Silva GA (2015) *Palaeospora spainii*, a new arbuscular mycorrhizal fungus from Swiss agricultural soils. Nova Hedwigia 101:89–102

Öpik M, Moora M, Zobel M, Saks Ü, Wheatley R, Wright F, Daniell T (2008) High diversity of arbuscular mycorrhizal fungi in a boreal herb-rich coniferous forest. New Phytol 179:867–876

Öpik M, Zobel M, Cantero JJ, Davison J, Facelli JM, Hiiesalu I, Jairus T, Kalwij JM, Koorem K, Leal ME et al (2013) Global sampling of plant roots expands the described molecular diversity of arbuscular mycorrhizal fungi. Mycorrhiza 23:411–430

Pontes JS, Sánchez-Castro I, Palenzuela J, Maia LC, Silva GA, Oehl F (2013) *Scutellospora alterata*, a new gigasporalean species from the semi-arid Caatinga biome in Northeastern Brazil. Mycotaxon 125:169–181

Redecker D, Schüßler A, Stockinger H, Stürmer SL, Morton JB, Walker C (2013) An evidence-based consensus for the classification of arbuscular mycorrhizal fungi (Glomeromycota). Mycorrhiza 23:515–531

Schenck NC, Perez Y (1988) Manual for identification of vesicular-arbuscular mycorrhizal fungi. INVAM, Gainesville, FL

Schüßler A (2002) Molecular phylogeny, taxonomy, and evolution of *Geosiphon pyriformis* and arbuscular mycorrhizal fungi. Plant Soil 244:75–83

Schüßler A, Schwarzott D, Walker C (2001) A new fungal phylum, the Glomeromycota: phylogeny and evolution. Mycol Res 105:1413–1421

Shenoy BD, Jeewon R, Hyde KD (2007) Impact of DNA sequence-data on the taxonomy of anamorphic fungi. Fungal Divers 26:1–54

Sieverding E, Silva GA, Berndt R, Oehl F (2014) *Rhizoglomus*, a new genus in the Glomeraceae. Mycotaxon 129:373–386

Silva GA, Maia LC, Oehl F (2012) Phylogenetic systematics of the Gigasporales. Mycotaxon 122:207–220

Silva IRD, Mello CMAD, Ferreira Neto RA, Silva DKAD, Melo ALD, Oehl F, Maia LC (2014) Diversity of arbuscular mycorrhizal fungi along an environmental gradient in the Brazilian semiarid. Appl Soil Ecol 84:166–175

Stürmer SL (2012) A history of the taxonomy and systematics of arbuscular mycorrhizal fungi belonging to the phylum Glomeromycota. Mycorrhiza 22:247–258

Sudová R, Sýkorová Z, Rydlová J, Čtvrtlíková M, Oehl F (2015) *Rhizoglomus melanum*, a new arbuscular mycorrhizal fungal species associated with submerged plants in freshwater lake Avsjøen in Norway. Mycol Prog 14:9

Velázquez S, Cabello MN (2011) Occurrence and diversity of arbuscular mycorrhizal fungi in trap cultures from El Palmar National Park soils. Eur J Soil Biol 47:230–235

Young (2012) A molecular guide to the taxonomy of arbuscular mycorrhizal fungi. New Phytol 193:823–826

Zangaro W, Rostirola LV, de Souza PB, Alves AR, Lescano LEAM, Rondina AB, Nogueira MA, Carrenho R (2013) Root colonization and spore abundance of arbuscular mycorrhizal fungi in distinct successional stages from an Atlantic rainforest biome in southern Brazil. Mycorrhiza 23:221–233

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