Mycorrhiza (2012) 22:81–97
DOI 10.1007/s00572-011-0419-6

REVIEW

Arbuscular mycorrhizal fungi in national parks, nature reserves and protected areas worldwide: a strategic perspective for their in situ conservation

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Received: 18 July 2011 / Accepted: 18 October 2011 / Published online: 11 November 2011

Abstract Soil fungi play a crucial role in producing fundamental ecosystem services such as soil fertility, formation and maintenance, nutrient cycling and plant community dynamics. However, they have received little attention in the field of conservation biology. Arbuscular mycorrhizal fungi (AMF) are beneficial soil symbionts fulfilling a key function in the complex networks of belowground/aboveground biotic interactions as they live in association with the roots of most (80%) land plant families and influence not only soil fertility but also plant nutrition, diversity and productivity. The diversity of AMF communities can decline due to habitat loss and anthropogenic disturbance, especially in agro-ecosystems, and many valuable ecotypes could become extinct before they are even discovered. Consequently, long-term strategies are urgently needed to ensure their conservation in habitats where they naturally occur and have evolved. Protected areas, where living organisms are under the care of national and international authorities, represent an appropriate place for the in situ conservation of AMF, providing them with adapted situations together with established complex networks of interactions with different components within each specific ecosystem. Here, we review data available about the main present-day threats to AMF and the current state of knowledge about their occurrence in protected sites worldwide, providing a checklist of national parks and nature reserves where they have been reported. The aim was to offer a strategic perspective to increase awareness of the importance of conserving these beneficial plant symbionts and of preserving their biodiversity in the years to come.

Keywords Arbuscular mycorrhizal fungi · In situ microbial conservation · AMF checklist · Protected areas · AMF distribution

Electronic supplementary material The online version of this article (doi:10.1007/s00572-011-0419-6) contains supplementary material, which is available to authorized users.

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Introduction

The dramatic decrease in biodiversity that has arisen as a result of human activities (Pimm and Raven 2000) constitutes a critical environmental problem recognized on a global level (e.g. Johannesburg Sustainable Development Summit 2002; Millenium Ecosystem Assessment 2005; Nagoya Biodiversity Summit 2010). In just two centuries, humans have brought about such massive changes in our planet that now, in the so-called Anthropocene Epoch (Crutzen and Stoermer 2000), measures for the conservation and sustainable use of biodiversity have come to represent a prerequisite for economic and social development efforts (Convention on Biological Diversity 2010). However, soil organisms, especially fungi, have received little attention in the field of conservation biology, although they have a crucial role in producing fundamental ecosystem services such as soil fertility, formation and maintenance, nutrient cycling and plant community dynamics (Gianinazzi et al. 2010; Pringle et al. 2011; van der Heijden and Horton 2009; Wall et al. 2010). These are services that are provided free to human societies, yet possess a high economic value (Balmford et al. 2002; Costanza et al. 1997; Pimentel et al. 1997). For instance, Costanza et al. (1997) estimated that nutrient cycling, in which fungi are deeply involved, supplies over 17 trillion dollars per year, the highest value among ecosystem services. Despite the fact that about 7,000 macrofungal species have been listed in various national Red List assessments (Dahlberg and Mueller 2011), the International Union for Conservation of Nature Red List of threatened species, which is the most valuable guide for estimating endangered species (Rodrigues et al. 2006), includes only one macrofungus and two lichenized fungi (Dahlberg and Mueller 2011). Consequently, fungal species are almost wholly excluded from global conservation programmes.

Fungal species are estimated to range from 0.5 to 9.9 million (Hawksworth 2001). In the context of those producing benefits for ecosystems, arbuscular mycorrhizal (AM) fungi (AMF; phylum Glomeromycota), a key group of plant beneficial symbionts, have been studied and characterized for their fundamental role in the complex networks of biotic interactions which link belowground and aboveground communities. AMF are among the most ecologically significant organisms on the planet (Fitter et al. 2011) since they act as a living connection between soil and plants, influencing soil fertility and plant nutrition, diversity and productivity (Smith and Read 2008; van der Heijden et al. 1998). Plants hosting AMF in their roots show enhanced growth and mineral uptake, and a higher tolerance of biotic and abiotic stresses, compared with non-mycorrhizal plants (Smith and Read 2008). Moreover, AMF contribute to the formation and maintenance of soil structure by the enmeshing action of extraradical hyphae and by the production of a protein, glomalin, which improves soil aggregates stability (Bedini et al. 2009; Gadkar et al. 2006; Wright and Upadhyaya 1998). Belowground AM fungal networks also play an essential role in the distribution of resources in plant communities on account of their ability to establish symbioses with various host plants and to link the roots of contiguous plant species with which they come into contact (Graves et al. 1997; van der Heijden et al. 1998), even between plants belonging to different species, genera and families (Giovannetti et al. 2004). By virtue of these AM fungal activities and functions, their conservation is vital both in natural and agricultural ecosystems.

To date, roughly 232 AM fungal species have been formally described, 50 of which were discovered in the last 10 years, some ubiquitous, but others rare or associated with particular plants or habitats. An updated species list is available on http://www.lrz.de/~schuessler/amphylo/. As AMF are obligate plant symbionts, the hypotheses that some fungi could be threatened if a host plant is threatened or, vice versa, that the loss of rare or endemic AMF could produce unpredictable consequences for their hosts should not be disregarded. Some AMF are already known to have declined due to habitat loss and anthropogenic disturbance, especially in agro-ecosystems (Giovannetti and Gianinazzi-Pearson 1994; Helgason et al. 1998). Moreover, Öpik et al. (2010) have shown that most of the SSU rRNA gene virtual taxa that have been localised so far could be endemic to a specific continent, realm or climatic zone, suggesting that individual Glomeromycota taxa may have limited distribution ranges.

Since the risk exists that valuable local AM fungal isolates (ecotypes) could become extinct before they are even studied, long-term strategies are urgently needed to ensure their conservation in habitats where they naturally occur and have evolved. Such habitats are ideally found in protected areas where living organisms are under the care of national and international authorities. These areas, the surface of which has increased worldwide from 3.5% in 1985 to 12.9% in 2009 (Jenkins and Joppa 2009) and for which human society globally spends about 6.5 billion dollars per year (Balmford et al. 2002), represent an appropriate place for in situ conservation of AMF, providing them with adapted situations together with established complex networks of interactions with different components within each specific ecosystem.

The aim of the present review was to increase awareness of the importance of conserving AMF as beneficial plant symbionts and of preserving their biodiversity in the years to come. With this in mind, we (1) overview the main threats to AMF, (2) identify the most threatened AMF, (3) define strategies for their conservation, (4) assess the current state of knowledge on AMF occurring in protected sites worldwide and (5) provide a checklist of national parks and nature reserves detected as natural habitats of AMF.

Threats to AMF

Environmental change drivers such as loss of natural habitats, pollution, invasive species, anthropogenic emissions and global warming are considered to be the main causes of global biodiversity loss (Sala et al. 2000). AM fungal communities are not exempt from such threats, and in the past 20 years, there have been many reports of a reduction in AM fungal diversity in sites experiencing various types of anthropogenic disturbance as compared with natural habitats. For instance, in the 1990s, Sieverding (1991) recorded 5–15 species in agro-ecosystems as compared with 25–30 species in natural ecosystems, and Helgason et al. (1998) found a reduction in AM fungal diversity in an arable field in comparison to a nearby wood. Some data are also available from natural systems concerning the manner in which AM fungal community composition is affected by heavy metal pollution (del Val et al. 1999; Tonin et al. 2001; Turnau et al. 2001; Whitfield et al. 2004; Vallino et al. 2006; Bedini et al. 2010), elevated CO_2 concentrations (Wolf et al. 2003; Klironomos et al.

2005; Drigo et al. 2010) and climate warming (Budge et al. 2011; Dumbrell et al. 2011). For example, it was observed that AMF species diversity decreased in a soil containing high levels of heavy metal as compared with a non-contaminated soil (del Val et al. 1999). Furthermore, a study aimed at estimating the effect of elevated CO_2 concentrations on AMF communities demonstrated that AM fungal species richness decreased by 50% when ambient CO_2 concentration (350 ppm) was abruptly increased to elevated CO_2 concentration (550 ppm), whilst a similar decrease was not evident in response to a gradual increase in CO_2 concentration (10 ppm) over 21 generations (about 6 years in total; Klironomos et al. 2005). Recently, Dumbrell et al. (2011), analysing the spatiotemporal dynamics of an AM fungal community in a British grassland, demonstrated that during summer, when the temperatures are higher and plants produce more carbon compounds through enhanced photosynthetic activities, overdominance of a single taxa is observed, leading to an overall decrease in AMF diversity. These authors hypothesized that global warming could increase the abundance of the dominant taxa, leading to local AM fungal extinctions.

Although some new data concerning the effects of climate-changing parameters on AM fungal communities are becoming available, so far, most of the data on anthropogenic effects on AMF biodiversity mainly involve comparisons between agricultural and natural systems. A number of studies have demonstrated that AMF diversity is adversely affected by the excessive use of chemical fertilisers and pesticides as well as intensive agricultural managements (e.g. monocropping) or practices (e.g. tillage). The intensity of agricultural management may differentially affect AM fungal spore communities (Oehl et al. 2003a, 2004, 2005; Hijri et al. 2006). For example, low-input agricultural systems, such as organic farming, where the use of chemical fertilisers and pesticides is not allowed, tend to promote higher AM fungal diversity than conventional agriculture (Oehl et al. 2004), whilst fields where conventional practices like intensive tillage and monoculture prevail show a lower AM fungal diversity (Hijri et al. 2006). Such an effect was observed in maize monoculture where a very low number of AM fungal spores were found as compared with grassland or a poplar grove (Bedini et al. 2007), supporting the postulate of a negative impact of intensive agricultural practices on this group of beneficial symbionts. This has recently been enforced by a comparative analysis of AM fungal communities in semi-natural grasslands, organically and conventionally managed fields based on terminal restriction fragment length polymorphism fingerprinting, and which showed that AMF diversity was higher in grasslands and in organic farming systems than in conventionally managed fields (Verbruggen et al. 2010). A reduction in AMF diversity was also observed in other disturbed agricultural or semi-natural grassland soils (Antunes et al. 2009; Schnoor et al. 2011).

No data on AM fungal invasiveness are available at present, although the deliberate transfer of AM fungal isolates is increasing due to the extensive use of non-native AM fungal inocula. The potential costs of such global mycorrhizal fungal transfer have recently been discussed by Schwartz et al. (2006).

Threatened AMF

In addition to a reduction in AMF diversity caused by anthropogenic disturbance, a range of studies, based either on spore characterization or on molecular methods, have shown that some AM fungal families, e.g. Gigasporaceae and Acaulosporaceae, are particularly vulnerable to threats from agricultural practices. Studies based on spore morphology found that 8 years of chemical fertilization decreased spore abundance of *Gigaspora gigantea*, *Gigaspora margarita*, *Scutellospora calospora* and *Paraglomus occultum* ecotypes whilst increasing that of *Glomus intraradices* (Johnson 1993). Other authors found that ecotypes of *Scutellospora*, *Acaulospora* and *Entrophospora* were lacking in tilled compared with no-tilled soils (Jansa et al. 2002). Interestingly, two ecotypes of *Scutellospora* were abundant in deep soil layers of intensively managed corn fields, suggesting a tendency to develop in soil niches less exposed to antropogenic (mechanical and chemical) disturbance (Oehl et al., 2005). Recently, an ecotype of *Racocetra beninensis* (Gigasporaceae) frequently occurring in natural soils of western African savannas (Tchabi et al. 2008) was found to be highly vulnerable to agricultural practices as it was not recovered under monocropped groundnut or in intensively managed cotton fields, even after 37 years fallow (Tchabi et al. 2009).

Molecular analyses have demonstrated that members of the Gigasporaceae and Acaulosporaceae can be particularly threatened by intensive land use. For instance, Helgason et al. (1998) observed the predominance of *Glomus* sequences (92%) in maize roots grown in an arable field, whilst *Acaulospora* and *Scutellospora* sequences were mainly present in a nearby woodland. Such data may reflect the adverse effects of ploughing, through the mechanical disruption of hyphae, on AMF that are unable to reestablish hyphal interconnections via anastomosis formation, such as those belonging to the Gigasporaceae (Giovannetti et al. 1999; Daniell et al. 2001). Subsequent molecular studies have shown that members of the Gigasporaceae may also be sensitive to high levels of chemical fertiliser and pesticides. Thus, *Acaulospora* and *Scutellospora* sequences were found to be absent from maize roots in intensive conventional monoculture (Hijri et al. 2006), whereas a high level of AM fungal diversity was observed where low levels of chemical fertiliser and pesticides were used, and *Acaulospora* and *Scutellospora* sequences were detected in 33% and 66% of the samples, respectively (Hijri et al. 2006). Recently, Verbruggen et al. (2010) showed that some AM fungal sequences, corresponding to *G. intraradices*, *Glomus mosseae* and *Glomus coronatum*, were as much present in grassland and organic farming as in conventionally managed fields, occurring in 79%, 70% and 67% of all root samples, respectively, whilst sequences of Gigasporaceae were retrieved only from grasslands and organic fields. These data suggest that Gigasporaceae and Acaulosporaceae may be affected by a number of threats (e.g. tillage, chemical fertilisers and pesticides) which may exert additional negative forces.

In addition, members of the Acaulosporaceae and Gigasporaceae appear to be sensitive to elevated CO_2 levels. Klironomos et al. (2005) observed that ecotypes of *Gigaspora* and *Scutellospora*, unlike *Glomus* ecotypes, decreased severely when ambient CO_2 concentration (350 ppm) was abruptly increased to elevated CO_2 concentration (550 ppm). Recently, Drigo et al. (2010) noted a complete shift in the dominant AMF occurring under ambient conditions in which the presence of AM fungal sequences affiliated to Acaulosporaceae was detected, versus elevated CO_2 levels, which showed the presence of sequences affiliated to Glomeraceae. The question as to whether ecotypes of such families are generally more sensitive to contemporary environmental threats remains to be investigated. Deeper insight into AM fungal biology (e.g. knowledge of hyphal interconnectedness and intraspecific genetic and functional diversity, biogeography) could enhance our understanding of the role played by the various taxa in the complex network of interactions occurring in natural and agricultural ecosystems.

Ex situ and in situ conservation of AMF

Conservation projects should take into account different strategies designed to preserve AMF for future generations, e.g. the establishment and maintenance of ex situ collections and the assessment of AMF occurrence in protected sites, with the aim of promoting the creation of in situ germplasm reserves. Ex situ collections are maintained in living cultures, together with their host plants, in all the laboratories where AMF are studied. Three official International AM fungal collections have been set up: the International Culture Collection of (Vesicular) Arbuscular Mycorrhizal Fungi (INVAM; http://www.invam.caf.wvu.edu/), the International Bank for the Glomeromycota (IBG; http://www.kent.ac.uk/bio/beg/englishhomepage.htm) and the Glomeromycota In Vitro Collection (GINCO; http://emma.agro.ucl.ac.be/ginco-bel). INVAM is a large collection located in West Virginia, USA, where more than 1,000 living accessions belonging to 109 species are reproduced. IBG is a collection without walls maintaining a number of different isolates (233 accessions belonging to 53 species) in a number of laboratories, with a core collection located in Dijon, France. In the GINCO in vitro collection, some AM fungal cultures of *Glomus*, *Acaulospora*, *Scutellospora* and *Gigaspora* isolates have been established on transgenic Ri T-DNA carrot roots, which represent a potentially important tool for fundamental research and for long-term maintenance of high-quality cultures in a sterile environment.

Ex situ collections do, however, present two main drawbacks. The first concerns the strong selective pressure on fungal isolates due to the standardized in vivo and in vitro conditions, which may lead to a genetic drift. Secondly, by definition, culture collections do not reproduce unculturable AM fungal species, which are the majority of AMF in nature (Öpik et al. 2010). To overcome these constraints, in situ conservation strategies have been pursued with the aim of preserving AM fungal genetic resources in habitats where they naturally occur and have evolved, such as protected areas, natural parks and reserves (Hawksworth 1991; Giovannetti and Gianinazzi-Pearson 1994). Recently, the first in situ collection of AMF was established in an integrally protected area within the UNESCO Biosphere Reserve “Selva Pisana” in Italy, with the aim of preserving the AM fungal diversity occurring in an Italian sand dune ecosystem, in particular valuable *Scutellospora* ecotypes (Turrini et al. 2008). In this collection, two *Scutellospora* species (*Scutellospora fulgida* and *Scutellospora persica*) are reported to be regular components of *Ammophila arenaria* and *Helichrysum stoechas* rhizospheres (Turrini et al. 2008).

AMF in protected areas worldwide

Data collection

In order to checklist AMF in protected areas worldwide, we conducted a survey of scientific articles that analysed AM fungal communities using either spore morphological characters or DNA sequences, together with data on the mycorrhizal colonisation of plants in parks, protected areas and natural reserves. Information was obtained from bibliographical databases such as CAB Abstracts (CABI Publishing, UK), ISI Current Contents (Thomson Scientific), or Scopus_Basic search (Elsevier B.V.). Search terms used were: “arbuscular mycorrhizal fungi”, “park”, “reserve” and “protected area”. All the papers listed in the species list web site at http://www.lrz.de/~schuessler/amphylo/ were also examined. Only records giving a description/identification clearly based on morphological or molecular methods were considered. Data on mycorrhizal colonisation obtained by means of root staining were checked, but not listed. The molecular characterization of fungal spores, when found in the description, was also inserted in the data set.

When drawing up maps to show protected sites hosting AMF (Fig. 1), we also listed 25 biodiversity hot spots areas, as described by Myers et al. (2000). Such hot spot areas are terrestrial habitats rich in endemic species considered to be of high priority for conservation. We consider that Myers's approach (based on plant endemisms and degree of threats arising from habitat loss) is also appropriate for AM fungal conservation because if a plant species is endangered, then all the species intimately in contact with it (e.g. insects or obligately symbiotic microorganisms) may likewise be endangered (Fuerst and Hugenholtz 2000; Myers et al. 2000; Staley 1997).

Protected areas hosting AM fungal species

AMF have been reported to occur in 96 parks or reserves distributed in 32 countries around the globe and covering a multitude of habitats (sand dunes, maquis, shrubland, meadows, savannah, prairie, grassland, desert, tropical alpine habitat, tropical rainforest, palm forest, gallery forest, boreal forest, subantartic forest, mixed deciduous woodland, rainfall areas, saline habitat, thermal habitat). The occurrence of AMF, identified by morphological characterisation or by molecular methods or both, was attested in 79 protected areas worldwide (Fig. 1 and Table 1). The presence of AMF that could be detected only through mycorrhizal colonisation assessment was located in 17 protected areas in North America (Korb et al. 2003; Pritekel et al. 2006; Treu et al. 1996; Zubek et al. 2010), South America (Becerra et al. 2005; Menoyo et al. 2007; Zangaro et al. 2000), Europe (Maremmani et al. 2003; Onipchenko and Zobel 2000; Puppi and Tartaglini 1991), Africa (Hartnett et al. 2004; Michelsen 1993), Asia (Hazarika et al. 2009; Yi et al. 1995) and Oceania (Davies et al., 2003; Johnston and Ryan 2000; McGee et al. 1999), but such areas were not recorded on the map. AMF have also been identified in 30 protected sites within hot spots areas (Fig. 1). In the Mediterranean Basin, which is considered hyperhot for conservation priorities, several sites within six protected areas were analysed for AM fungal presence, leading to the discovery of rare or endemic AM fungal species (Palenzuela et al. 2008). Interestingly, 50 AM fungal species, out of about 232 (May 2011), were described for the first time after their isolation from rhizosphere soils of plants living in protected areas.

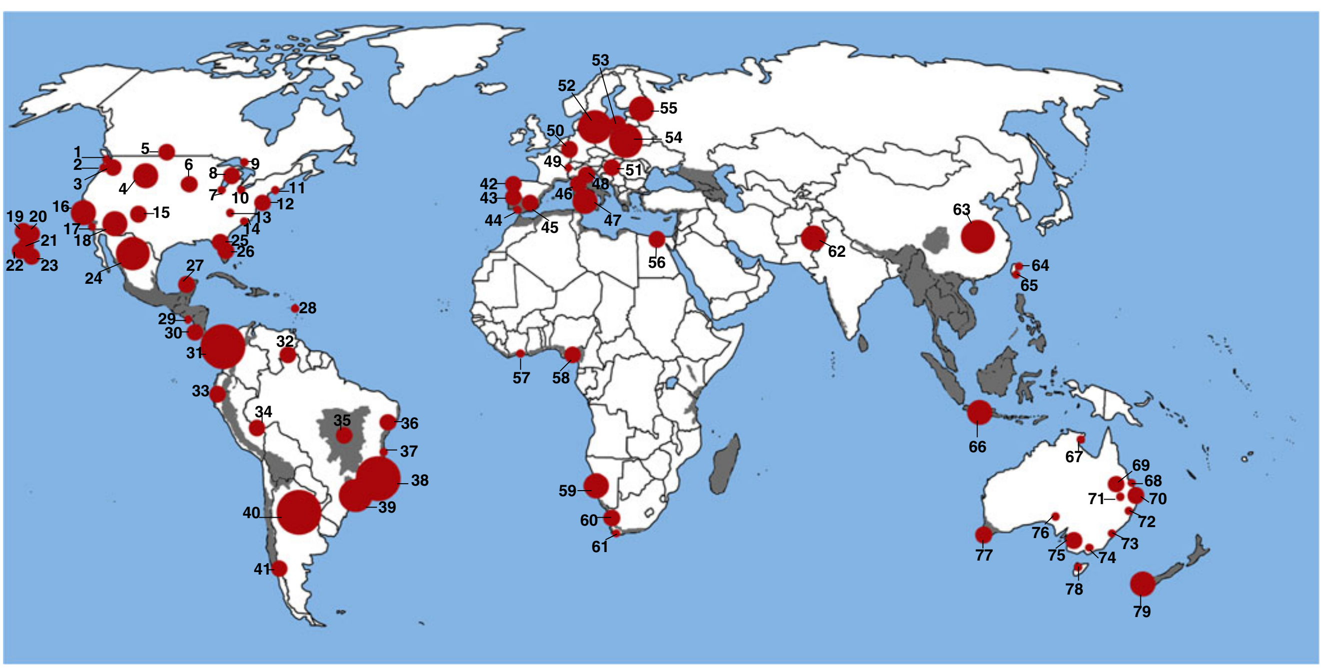

Fig. 1 Worldwide distribution of protected sites hosting AMF. The *numbers* correspond to Parks or Reserves listed in Table 1. *Grey areas* correspond to the 25 hotspots described by Myers et al. (2000). *Dots* on the map correspond to Parks or Reserves; *dot size* refers to the number of AM fungal species occurring in each site (*smallest* to *largest dots* represent 1, 2–10, 11–20, 21–30 and >30 AM fungal species, respectively)

Table 1 Occurrence of AMF in National Parks, nature reserves and protected areas worldwide

	Parks and reserves	AMF species or rDNA phylotypes	Habitat	References
NORTH AMERICA				
1	Olympic National Park (USA)	*Glomus fasciculatum*	Sand dunes	Gerdemann and Trappe (1974)
2	Fort Stevens State Park (USA)	*Glomus hoi*	Sand dunes	Berch and Trappe (1985)
3	Mount Rainer National Park (USA)	*Acaulospora laevis*, *Glomus convolutum*	Rainforest	Gerdemann and Trappe (1974)
4	Yellowstone National Park (USA)	rDNA phylotypes: *Acaulospora morrowiae* (Acau-6), *Glomus aureum* (Glom A-11), *Glomus diaphanum* (Glom A-13), *Glomus intraradices* (Glom A-1), *Paraglomus laccatum* (Para-1), *Paraglomus occultum* (Para-2, Para-3), *Scutellospora pellucida* (Giga-4), Acau-7, ARCH-2, **ARCH-5 (new genus?)**, **Glom A7a**, Glom A7b, Glom A7c, Glom A-20, **Glom A-24**, **Glom A-26**, **Glom A-27**	Thermal habitat	Appoloni et al. (2008)
5	Grassland National Park (Canada)	rDNA phylotypes: *Glomus mosseae (Glomus* sp1*), Glomus hoi (Glomus* sp4*), Glomus viscosum (Glomus* sp8*), Glomus* sp2, *Glomus* sp3, *Glomus* sp5, *Glomus* sp6, *Glomus* sp 7, *Glomus* sp9	Grassland	Yang et al. (2010)
6	Konza Prairie Natural Area (USA)	***Glomus mortonii*** and 2 rDNA phylotypes: *Glomus intraradices*, *Glomus* sp.	Prairie	Bentivenga and Hetrick (1991); Jumpponen and Johnson (2005)
7	Kohler-Andre State Park (USA)	***Glomus lamellosum***	Sand dunes	Dalpè et al. (1992)
8	Sleeping Bear Dunes National Park (USA)	*Glomus microaggregatum*, ***Glomus pansihalos***	Sand dunes	Berch and Koske (1986); Koske and Walker (1986)
9	Wasaga Beach Provincial Park (Canada)	*Glomus lamellosum*	Sand dunes	Dalpè et al. (1992)
10	Iroquois State Wildlife Area (USA)	***Acaulospora colliculosa***	Prairie	Kaonongbua et al. (2010)
11	Saugatuck Dunes State Park (USA)	*Glomus microaggregatum*	Sand dunes	Koske et al. (1986)
12	Seashore State Park (USA)	***Glomus globiferum, Glomus microaggregatum, Glomus trimurales, Racocetra fulgida, Racocetra verrucosa, Racocetra weresubiae, Scutellospora dipapillosa, Scutellospora pellucida***	Sand dunes	Koske and Walker (1986); Koske and Halvorson (1989); Koske and Walker (1985); Koske et al. (1986)
13	Daniel Boone National Forest (USA)	***Glomus botryoides***	Mixed hardwood forest	Rothwell and Victor (1984)
14	Huntington State Park (USA)	*Diversispora spurca*	Sand dunes	Kennedy et al. (1999)
15	Virginia Park (USA)	2 rDNA phylotypes: *Glomus intraradices, Glomus* sp.	Grassland	Hawkes et al. (2006)
16	Channel Island National Park (USA)	*Entrophospora infrequens*, *Glomus aggregatum, Glomus etunicatum*, *Glomus intraradices*, *Glomus microaggregatum, Glomus monosporum, Glomus pansihalos,* ***Glomus trimurales***, *Glomus* 601, ***Scutellospora arenicola***, *Scutellospora calospora*, *Scutellospora pellucida*, *Scutellospora* 581	Sand dunes	Koske and Walker (1986); Koske and Halvorson (1989); Koske et al. (1986)
17	Organ Pipe National Monument (USA)	***Glomus eburneum***	Desert	Kennedy et al. (1999)
18	Sonoran Desert National Monument (USA)	*Archaeospora trappei, Entrophospora infrequens, Diversispora spurca, Glomus eburneum, Glomus etunicatum, Glomus intraradices, Glomus macrocarpum, Glomus microaggregatum, Glomus mosseae, Paraglomus occultum, Glomus* AZ112*, Glomus* AZ122*, Glomus* AZ123	Desert	Stutz et al. (2000)
19	Salt Pond Beach Park (USA)	*Diversispora spurca*, *Glomus intraradices*, *Glomus microaggregatum*, *Scutellospora hawaiiensis, Glomus* 807, *Glomus* 90, *Scutellospora* 836	Sand dunes	Koske and Gemma (1996)
20	Kapa'a State Park (USA)	*Acaulospora* 869, *Diversispora spurca, Glomus intraradices, Scutellospora hawaiiensis,Glomus* 807, *Scutellospora* 836	Sand dunes	Koske and Gemma (1996)
21	Polihale State Park (USA)	*Glomus microaggregatum,* ***Glomus nanolumen***, *Glomus sinuosum,* ***Scutellospora hawaiiensis***, *Scutellospora* 836	Sand dunes	Koske and Gemma (1989, 1995, 1996)
22	Hapuna Beach State Park (USA)	*Glomus microaggregatum,* ***Scutellospora hawaiiensis***	Sand dunes	Koske and Gemma (1995)
23	Haleakala National Park (USA)	*Acaulospora* 8156, *Acaulospora* 8159, *Entrophospora infrequens*, *Glomus* 8155, *Glomus* 8156, *Scutellospora* 8156, *Scutellospora* 8170	Tropical alpine	Koske and Gemma (2002)

Table 1 (continued)

Parks and reserves	AMF species or rDNA phylotypes	Habitat	References
24 Mapimì Biosphere Reserve (Mexico)	*Acaulospora delicata, Acaulospora denticulata, Acaulospora morrowiae, Acaulospora sporocarpia, Acaulospora sp.2, Acaulospora sp3, Acaulospora sp.4, Acaulospora sp5 Acaulospora sp.6, Acaulospora sp.7, Entrophospora infrequens, Gigaspora decipiens, Glomus cerebriforme, Glomus claroideum, Glomus constrictum, Glomus etunicatum, Glomus geosporum, Glomus microaggregatum, Glomus mosseae, Glomus sp.1, Glomus sp.2*, *Glomus sp. 3, Glomus sp.41, Glomus sp.5*	Desert	Pezzani et al. (2006)
25 Fort Clinch State Park (USA)	*Acaulospora morrowiae, Acaulospora scrobiculata, Glomus aggregatum, Glomus deserticola, Glomus globiferum, Racocetra weresubiae*	Primary foredunes	Sylvia (1986)
26 Anastasia State Park (USA)	*Acaulospora scrobiculata, Acaulospora morrowiae, Glomus aggregatum, Glomus deserticola, Glomus globiferum, Racocetra weresubiae*	Primary foredunes	Sylvia (1986)
27 El Eden Ecological Reserve (Mexico)	*Acaulospora denticulata, Acaulospora spinosa, Gigaspora gigantea, Glomus constrictum, Glomus macrocarpum, Glomus mosseae, Glomus rubiforme, Scutellospora calospora, Racocetra persica*	Mature forest	Allen et al. (2005)
28 Guadeloupe National Park (Guadeloupe, France)	*Glomus constrictum*	Tropical forest	Trappe (1977)
29 Guanacaste Conservation Reserve (Costa Rica)	*Paraglomus occultum*	Tropical forest	Morton and Redecker (2001)
30 La Selva Field Station (Costa Rica)	***Acaulospora foveata, Acaulospora tuberculata***	Tropical rainforest	Janos and Trappe (1982)
31 Barro Colorado Nature Monument (Panama)	***Acaulospora foveata, Acaulospora tubercolata,*** 31 rDNA types: 4 *Acaulospora* sp. (**Acau8**, **Acau9**, **Acau10**, **Acau12**), *Glomus intraradices* (Glo8, Glo10), *Glomus mosseae* (Glo1B), *Glomus sinuosum* (Glo3b), 20 *Glomus* sp. (Glo2, **Glo3a**, **Glo9**, Glo14a, **Glo 14b**, Glo17, Glo18, Glo20, Glo21,**Glo30**, **Glo31**, **Glo32**, **Glo33**, **Glo34**, **Glo35**, **Glo36**, **Glo37**, **Glo38**, **Glo39**, **Glo45**), 4 *Scutellospora* sp. (Scut1, Scut2, **Scut3**, **Scut4**)	Tropical rainforest	Janos and Trappe (1982); Husband et al. (2002a, b)
SOUTH AMERICA			
32 Canaima National Park - La Gran Sabana (Venezuela)	***Scutellospora crenulata, Scutellospora spinosissima, Scutellospora striata***, *Acaulospora* sp., *Glomus* sp., *Scutellospora* sp.	Sclerophyllous shrubland, meadows, savannah	Walker et al. (1998), Cuenca and Herrera-Peraza (2008), Herrera-Peraza et al. (2001)
33 Riserva Biologica San Francisco and Podocarpus National Park (Ecuador)	7 rDNA phylotypes: *Acaulospora laevis, Acaulospora spinosa, G. geosporum/G. caledonium, G. intraradices/G. clarum, Glomus* sp., *Gigaspora gigantea/Gigaspora margarita, Scutellospora* sp.	Tropical mountain rainforest	Haug et al. (2004)
34 Manu National Park (Peru)	*Glomus aggregatum, Glomus coreimioides, Glomus geosporum, Glomus macrocarpum, Glomus microcarpum*	Tropical rainforest	Janos et al. (1995)
35 Brasilia National Park (Brazil)	*Entrophospora colombiana, Gigaspora margarita, Paraglomus occultum, Acaulospora* sp., *Gigaspora* sp., *Entrophospora* sp., *Glomus* sp., *Scutellospora* sp.	Savannah	Martins et al. (1999)
36 Vale do Catimbau National Park (Brazil)	***Racocetra intraornata, Scutellospora colliculosa***	Semi-arid biome	Goto et al. (2009, 2010)
37 Serra do Cipò National Park (Brazil)	*Ambispora brasiliensis*	Savannah	Goto et al. (2008)
38 State Park of Campo de Jordao (Brazil)	*Acaulospora bireticulata, Acaulospora colombiana, Acaulospora foveata, Acaulospora kentinensis, Acaulospora koskei, Acaulospora laevis, Acaulospora mellea, Acaulospora morrowiae, Acaulospora scrobiculata, Acaulospora spinosa, Acaulospora rehmii, Acaulospora* sp. 1, *Acaulospora* sp. 2, *Acaulospora* sp. 3, *Ambispora leptoticha, Ambispora jimgerdemanni, Archaeospora trappei, Gigaspora decipiens, Gigaspora margarita, Gigaspora* sp. 1, *Glomus aggregatum*, *Glomus clarum, Glomus diaphanum, Glomus etunicatum, Glomus fasciculatum, Glomus geosporum, Glomus macrocarpum, Glomus microcarpum, Glomus* sp. 1, *Glomus pansihalos, Glomus rubiforme, Scutellospora calospora, Scutellospora gilmorei, Scutellospora pellucida, Scutellospora cerradensis, Scutellospora heterogama, Scutellospora nigra, Scutellospora* sp. 1, *Scutellospora* sp. 2, *Scutellospora* sp. .3	Subropical forest	Moreira-Souza et al. (2003); Moreira et al. (2007)
39 State Park of Alto Ribeira (Brazil)	*Acaulospora bireticulata, Acaulospora colombiana, Acaulospora foveata, Acaulospora kentinensis, Acaulospora laevis, Acaulospora mellea, Acaulospora morrowiae, Acaulospora scrobiculata, Acaulospora spinosa, Acaulospora* sp. 1, *Acaulospora* sp. 2, *Acaulospora* sp. 3, *Ambispora*	Subtropical forest	Moreira et al. (2007)

Table 1 (continued)

Parks and reserves	AMF species or rDNA phylotypes	Habitat	References
	jimgerdemanni, Gigaspora decipiens, Gigaspora margarita, Glomus diaphanum, Glomus etunicatum, Glomus macrocarpum, Glomus microcarpum, Glomus sp. 1, *Glomus* sp. 2, *Scutellospora heterogama, Scutellospora pellucida, Scutellospora* sp. 1		
40 El Palmar National Park (Argentina)	*Acaulospora bireticulata, Acaulospora delicata, Acaulospora denticulata, Acaulospora dilatata, Acaulospora elegans,* ***Acaulospora entreriana****, Acaulospora excavata, Acaulospora foveata, Acaulospora lacunosa, Acaulospora laevis, Acaulospora mellea, Acaulospora nicolsonii, Acaulospora rehmii, Acaulospora scrobiculata, Acaulospora spinosa, Acaulospora tuberculata, Acaulospoea sp1., Acaulospora sp2., Archaeospora trappei, Entrophospora infrequens, Gigaspora candida, Gigaspora gigantea, Gigaspora margarita, Gigaspora sp1., Gigaspora sp2., Glomus aggregatum, Glomus ambisporum, Glomus claroideum, Glomus clarum, Glomus constrictum, Glomus coronatum, Glomus diaphanum, Glomus dimorphicum, Glomus etunicatum, Racocetra coralloidea, Racocetra fulgida, Scutellospora biornata, Scutellospora calospora,, Scutellospora dipapillosa, Scutellospora gilmorei, Scutellospora heterogama, Scutellospora sp.1, Pacispora sp.1, Paraglomus laccatum*	Subtropical scrubland, marsh, palm forest, grassland, gallery forest	Velazquez et al. (2008, 2010)
41 Nahuel Huapi National Park (Argentina)	2 rDNA phylotypes: *Glomus* group A (*Arachnitis uniflora* symbiont, *Arachnitis uniflora* symbiont 1, 2, 3)	Subantartic forest	Bidartondo et al. (2002)
EUROPE			
42 Natural Reserve of Sao Jacinto (Portugal)	*Glomus constrictum, Glomus globiferum, Racocetra persica,* 7 rDNA phylotypes: *Glomus constrictum*, *Glomus fasciculatum, Glomus intraradices, Glomus hoi,* 1 *Scutellospora* sp., 5 *Glomus* sp., 1 *Diversispora* sp.	Sand dunes	Rodriguez-Echeverrìa and Freitas (2006)
43 Arrabìda Natural Park (Portugal)	*Acaulospora* sp., *Glomus geosporum, Glomus mosseae, Scutellospora calospora*	Maquis	Carvalho et al. (2003)
44 Sierra de Baza National Park (Spain)	*Ambispora gerdemanii, Glomus constrictum, Glomus coronatum, Glomus etunicatum, Glomus mosseae,* ***Otospora bareai****, Pacispora scintillans*	Dolomitic shrubland	Palenzuela et al. (2008)
45 Sierra Nevada National Park (Spain)	***Entrophospora nevadensis***		Palenzuela et al. (2008)
46 Selva Pisana Biosphere Reserve (Italy)	*Glomus coronatum, Glomus fasciculatum, Racocetra fulgida, Racocetra persica, Scutellospora calospora,*	Sand dunes	Giovannetti and Nicolson (1983); Giovannetti (1985); Turrini et al. (2008)
47 Tuscan Island Biosphere Reserve (Italy)	*Entrophospora sp., Glomus coronatum, Glomus etunicatum, Glomus geosporum, Glomus mosseae, Glomus rubiforme, Glomus viscosum, Glomus sp., Pacispora sp., Scutellospora dipurpurescens, Scutellospora sp.,*	Maquis	Turrini et al. (2010)
48 Secovlje salterns landscape Park (Slovenia)	6 rDNA phylotypes: *Glomus caledonium/Glomus geosporum, Glomus intraradices, 3 Glomus sp., 1 Diversispora sp.*	Saline habitat	Sonjak et al. (2009)
49 Swiss National Park (Swizerland)	***Acaulospora alpina***	Alpine grasslands	Oehl et al. (2006)
50 Nature Reserve Kaisersthul (Germany)	***Glomus badium, Glomus caesaris, Glomus spinuliferum***	Grassgrown vineyard, grassland	Oehl et al. (2002, 2003b, 2005)
51 Kiskunsag National Park (Hungary)	9 rDNA phylotypes: *Glomus intraradices,* 7 *Glomus* sp., *Racocetra gregaria*	Mixed deciduous woodland	Kovács et al. (2007)
52 Slowinski National Park (Poland)	*Acaulospora dilatata,* **Acaulospora koskei**, *Acaulospora lacunosa, Acaulospora paulinae, Acaulospora polonica, Acaulospora rugosa, Archaeospora trappei, Glomus aggregatum,* ***Glomus arenarium***, ***Glomus irregulare***, Glomus constrictum, Glomus corymbiforme, Glomus deserticola, Glomus etunicatum, Glomus fasciculatum, Glomus macrocarpum, Glomus pustulatum, Glomus 107, Glomus 111, Glomus sp., Paraglomus laccatum, Racocetra persica, Scutellospora armeniaca, Scutellospora dipurpurescens, Scutellospora pellucida	Sand dunes	Blaszkowski (1992, 1994a,b, 1995); Blaszkowski et al. (2001, 2008); Tadych and Blaszkowski (2000)
53 Kampinos National Park (Poland)	*Acaulospora lacunosa, Acaulospora paulinae, Glomus constrictum, Glomus deserticola,* ***Glomus fuegianum****, Glomus fasciculatum, Glomus geosporum, Glomus heterosporum, Pacispora scintillans, Scutellospora dipurpurescens*	inland dunes	Blaszkowski et al. 1998
54 Tatra National Park (Poland)	*Acaulospora bireticulata, Acaulospora capsicula, Acaulospora gedanensis, Acaulospora koskei, Acaulospora mellea, Acaulospora paulinae, Acaulospora scrobiculata, Ambispora gerdemannii, Archaeospora trappei, Entrophospora baltica, Glomus aggregatum, Glomus caledonium, Glomus*	alpine woodland, meadows	Zubek et al. 2008, 2009

Table 1 (continued)

Parks and reserves	AMF species or rDNA phylotypes	Habitat	References
	claroideum, Glomus constrictum, Glomus deserticola, Glomus fasciculatum, Glomus geosporum, Glomus macrocarpum, Glomus tenue, Glomus trimurales, Pacispora scintillans, Scutellospora dipurpurescens		
55 Soomaa National Park (Estonia)	11 rDNA phylotypes: *Acaulospora koskei* (MO-A2), 1 *Acaulospora sp.* (MO-A1), *Glomus hoi* (MO-G7), *Glomus mosseae* (MO-G11), 5 *Glomus sp.* (MO-G2, MO-G5, MO-G6, MO-G1, MO-G9), *2 Scutellospora sp.* (MO-S1, MO-S2)	boreal forest	Öpik et al. 2003
AFRICA			
56 El-Omayed Biosphere Reserve (Egypt)	*Glomus* sp., *Gigaspora* sp., *Scutellospora* sp.	Sand dunes, saline depressions	Agwa and Al-Sodany (2003)
57 Mopri Forest Reserve (Cote d'Ivoire)	***Acaulospora excavata***	Tropical forest	Ingleby et al. (1994)
58 Korup National Park (Cameroon)	2 rDNA phylotypes: A2 (*Afrothismia korupensis* mycobiont α, *Afrothismia korupensis* mycobiont β, A3 (*Afrothismia hydra* mycobiont α, *Afrothismia hydra* mycobiont β)	Tropical rainforest	Franke et al. (2006)
59 Namib Naukluft Park (Namibia)	*Acaulospora morrowiae, Archaeospora trappei, Diversispora spurca, Glomus etunicatum, Glomus intraradices, Glomus microaggregatum, Glomus mosseae, Paraglomus occultum, Glomus* AZ112, *Glomus* AZ123, *Glomus* NB118, *Glomus* TX106	Desert	Stutz et al. (2000)
60 Richtersveld National Park (South Africa)	*Acaulospora denticulata, Glomus aggregatum, Glomus claroideum*	Rainfall area	Uhlmann et al. (2004)
61 Reserve Rooiels (South Africa)	***Glomus africanum***		Blaszkowski et al. (2010)
ASIA			
62 Lal Suhanra Biosphere Reserve (Pakistan)	*Ambispora leptoticha, Glomus aggregatum, Glomus claroideum, Glomus constrictum, Glomus deserticola, Glomus fasciculatum, Glomus geosporum, Glomus mosseae, Glomus reticulatum, Glomus sinuosum, Glomus sp Mg17, Glomus sp. LS26, Glomus sp. LS31, Gigaspora albida, Gigaspora gigantea, Gigaspora sp Mg11,*	Desert	Chaudhry et al. (2009)
63 World Heritage of Huangshan (China)	*Acaulospora denticulata, Acaulospora laevis, Acaulospora mellea, Acaulospora scrobiculata, Acaulospora spinosa, Acaulospora tuberculata, Diversispora spurca, Entrophospora infrequens, Glomus aggregatum, Glomus claroideum, Glomus clarum, Glomus constrictum, Glomus etunicatum, Glomus geosporum, Glomus macrocarpum, Glomus microaggregatum, Glomus monosporum, Glomus rubiforme, Glomus verruculosum, Glomus sp.1, Glomus sp.2, Glomus sp. 3, Glomus sp. 4, Scutellospora verrucosa, Scutellospora sp. 1*	Subtropical forest	Yang et al. (2011)
64 Yang-Ming Shan National Park (Taiwan)	***Glomus liquidambaris***		Wu and Chen (1987)
65 Ken-tin National Park (Taiwan)	***Acaulospora kentinensis***		Wu et al. (1985)
66 Gede-Pangrango National Park (Indonesia)	*Entrophospora infrequens*, ***Scutellospora projecturata***, 9 *Glomus* sp., 4 *Acaulospora* sp., 3 *Sclerocystis* sp., 2 *Scutellospora* sp.	Tropical forest	Kramandibrata et al. (2000)
OCEANIA			
67 Kakadu National Park (Australia)	*Ambispora gerdemannii*	*Eucaliptus* woodland	Morton and Redecker (2001)
68 Ku-ring-gai National Park (Australia)	*Glomus pellucidum*		McGee and Trappe (2002)
69 Styx River State Forest (Australia)	***Glomus canum, Glomus pubescens***	Rainforest	McGee and Trappe (2002)
70 Royal National Park (Australia)	*Glomus australe*, ***Glomus cuneatum***, *Glomus fuegianum, Glomus tenerum*	Rainforest	McGee and Trappe (2002)
71 Barrington Tops National Park (Australia)	*Glomus fulvum*	Wet forest	McGee and Trappe (2002)
72 Blue Mountains National Park (Australia)	*Glomus australe*	Wet forest	McGee and Trappe (2002)
73 Coolumbooka Nature Reserve (Australia)	*Glomus caledonium*	Forest	McGee and Trappe (2002)

Table 1 (continued)

	Parks and reserves	AMF species or rDNA phylotypes	Habitat	References
74	Lind National Park (Australia)	*Glomus fulvum*	Warm temperate rainforest	McGee and Trappe (2002)
75	Loftia National Park (Australia)	*Glomus caledonium, Glomus macrocarpum*	Forest	Tandy (1975)
76	Belair National Park (Australia)	*Glomus macrocarpum*	Forest	Tandy (1975)
77	Boranup National Park (Australia)	*Glomus caledonium, Glomus fulvum*	Forest	McGee and Trappe (2002)
78	Mount Field National Park (Australia)	*Glomus caledonium*	Rainforest	McGee and Trappe (2002)
79	Tautuku Reserve (New Zeland)	*Acaulospora laevis, Glomus caledonium, Glomus convolutum, Glomus coreimioides, Glomus fasciculatum, Glomus geosporum, Glomus macrocarpum, Glomus monosporum, Glomus mosseae,* ***Glomus pallidum****, Glomus rubiforme,* ***Scutellospora aurigloba***	Sand dunes	Hall (1977)

AMF species or DNA phylotypes, whose first description or detection was performed on spores or roots collected in protected areas, parks or reserves, are indicated in bold type

AM fungal diversity in protected areas worldwide

Morphological methods, which are most frequently used for the detection of AMF in protected areas, have led to the identification of local isolates belonging to 124 species. Molecular methods have been used only in the last two decades, leading to the detection of sequences of either formally described AMF or AMF found only in plant roots. The highest numbers of AMF described by morphological methods have been recorded in South America, in an Argentinian park (El Palmar National Park) and in two different State Parks of Brazil (State Park of Campo de Jordao and State Park of Alto Ribeira), located inside Brazil's Atlantic Forest (a hotspot protection area), with 44, 40 and 24 species, respectively (Moreira et al. 2007; Moreira-Souza et al. 2003; Velazquez et al. 2008, 2010; Fig. 1). Among the studies on AM fungal diversity performed using molecular methods, the highest number of AM fungal sequence phylotypes was detected in the tropical rainforest of Barro Colorado Nature Monument (within the Mesoamerica hotspot). In this rainforest, only three phylotypes corresponded to the sequences of the described species (*G. mosseae*, *G. sinuosum*, *G. intraradices*), whilst at least 20 phylotypes were new to science (Husband et al. 2002a, b).

Our survey showed a general predominance of Glomeraceae (Table 2), although a high number of Acaulosporaceae and Gigasporaceae were found in tropical or subtropical forests in Brazil and Argentina (Moreira-Souza et al. 2003; Moreira et al. 2007; Velazquez et al. 2008, 2010; Fig. 2). It is worth noting that Acaulosporaceae and Gigasporaceae are well documented in protected areas, representing 75.7% and 63.8%, respectively, of all the species described so far, whilst Glomeraceae represents only 46.3% (Table 2). The least widespread family is Pacisporaceae (14.3%, Table 2). *Acaulospora* species are reported mainly from South America, in particular in the El Palmar National Park in Argentina, where a new *Acaulospora* species (*Acaulospora entreriana*) was described (Velazquez et al. 2008). Additionally, they have been frequently retrieved from three protected areas in Poland (Table 1). *Scutellospora* species have been located above all in sand dune systems in the USA and in Europe, whilst in South America they have been recovered from forests or savannas (Table 1).

Common and rare AMF in protected areas

Fourteen AM fungal species have been detected to be common to more than four continents (Table 3) and in more than four protected sites. Ecotypes of *Glomus aggregatum* and *G. intraradices* have been retrieved in the highest number among AMF from protected areas (11 sites),

Table 2 Number of species in each Glomeromycota family in protected areas worldwide

Family	Total known species	Total species in protected areas worldwide	No. of species per family retrieved in protected areas from each continent					
			Africa	Asia	Europa	North America	Oceania	South America
Acaulosporaceae	37	28 (75.7%)[a]	3 (8.1%)[b]	7 (18.9%)	12 (32.4%)	11 (29.7%)	2 (5.4%)	20 (54%)
Ambisporaceae	9	4 (44.4%)	0 (0%)	1 (11.1%)	1 (11.1%)	0 (0%)	0 (0%)	3 (33.3%)
Archaeosporaceae	2	1 (50%)	1 (50%)	0 (0%)	1 (50%)	1 (50%)	0 (0%)	1 (50%)
Diversisporaceae	10	5 (50%)	1 (10%)	1 (10%)	2 (20%)	3 (30%)	0 (0%)	0 (0%)
Entrophosporaceae	3	3 (100%)	0 (0%)	1 (33.3%)	2 (66.6%)	1 (33.3%)	0 (0%)	1 (33.3%)
Gigasporaceae	47	30 (63.8%)	0 (0%)	4 (8.5%)	7 (14.9%)	11 (23.4%)	1 (2.1%)	18 (38.3%)
Glomeraceae	108	50 (46.3%)	6 (5.5%)	14 (13.0%)	24 (22.2%)	24 (22.2%)	18 (16.7%)	15 (13.9%)
Glomus Group B	6	3 (50%)	2 (33.3%)	2 (33.3%)	2 (33.3%)	3 (50%)	0 (0%)	2 (33.3%)
Pacisporaceae	7	1 (14.3%)	0 (0%)	0 (0%)	1 (14.3%)	0 (0%)	0 (0%)	0 (0%)
Paraglomeraceae	3	2 (66.6%)	1 (33.3%)	0 (0%)	1 (33.3%)	2 (66.6%)	0 (0%)	2 (66.6%)
Total	232	127 (54.7%)	14 (6.0%)	30 (12.9%)	53 (22.8%)	56 (24.1%)	21 (9.1%)	62 (26.7%)

[a] Per cent of the total known species of each family occurring in protected areas worldwide

[b] Per cent of the total known species of each family occurring in protected areas of each continent

probably because these species have a wide host range and a generalist habit. Seventy-four AM fungal species have been repoted in only one continent and 58 species in only one protected area (Table 4 and Electronic supplementary materials Table 5). Ecotypes of rare AMF within protected areas, such as *Glomus viscosum* (Table 4), can easily be found both in natural and in arable sites, whilst others have been retrieved only from particular habitats. For example, a newly described AM fungal species, *Otospora bareai*, discovered in the rhizosphere of two endangered endemic plants in the Sierra de Baza National Park (Granada, Spain) and not found elsewhere (Palenzuela et al. 2008), may represent an endemic fungus, important for the survival of its host plants. *Acaulospora alpina* can also be considered endemic since it has been detected only in the grassland of high mountains at 1,900–2,600 m a.s.l. (Oehl et al. 2006) and in alpine meadows in Central Europe. Another three AM fungal species may be considered endemic: *Ambispora brasiliensis*, recovered only from the rhizosphere of native plant species of the Brazilian Cerrado Biome in Serra do Cipò (Goto et al. 2008), and *Scutellospora hawaiiensis* and *Glomus nanolumen*, retrieved only from Hawai'i, USA (Koske and Gemma 1995, 1996). In Haleakala National Park, Maui, Hawai'i (USA), the threatened plant silver-sword (*Argyroxiphium sandwicense* subsp. *macrocephalum*) and the endemic plant *Dubautia menziesii* were found

Fig. 2 Glomeromycota families occurring in different continents based on the total number of AM fungal species found in each continent

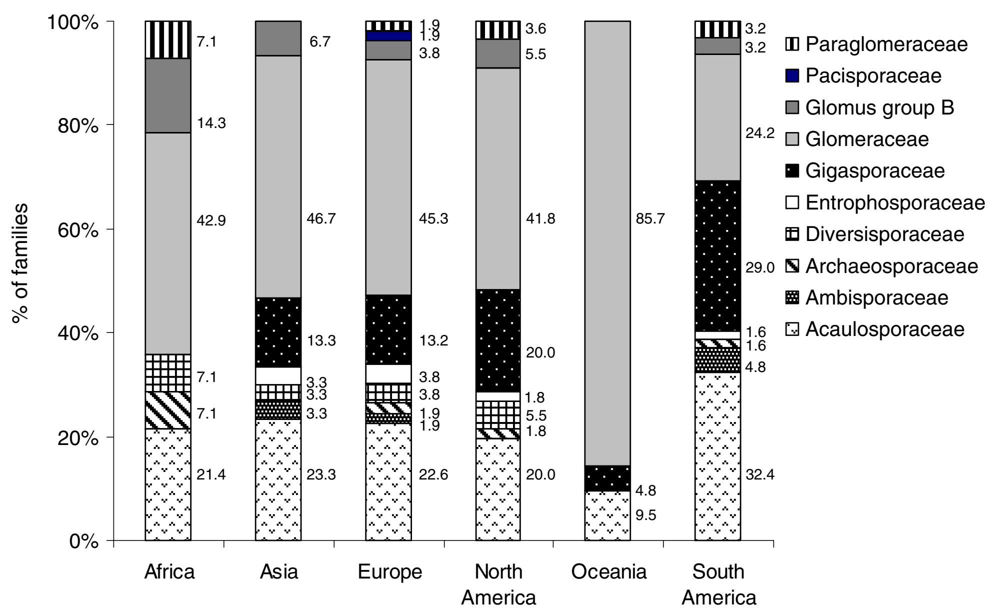

Table 3 Most common Glomeromycota species reported from protected areas around the world

Species occurring in at least 4 continents	No. of protected areas hosting the species	Continents
Acaulospora denticulata	4	North America, South America, Africa, Asia
Acaulospora laevis	8	North America, South America, Asia, Oceania
Acaulospora scrobiculata	7	Europe, North America, South America, Asia
Archaeospora trappei	4	Europe, North America, South America, Africa
Glomus aggregatum	11	Europe, North America, South America, Africa, Asia
Glomus claroideum	5	Europe, North America, South America, Asia
Glomus constrictum	10	Europe, North America, South America, Asia
Glomus etunicatum	8	Europe, North America, South America, Africa, Asia
Glomus fasciculatum	9	Europe, North America, South America, Asia, Oceania
Glomus geosporum	8	Europe, South America, Asia, Oceania
Glomus intraradices	11	Europe, North America, South America, Africa
Glomus macrocarpum	10	Europe, North America, South America, Asia, Oceania
Glomus mosseae	9	Europe, North America, Africa, Asia, Oceania
Glomus rubiforme	5	Europe, North America, South America, Asia, Oceania

associated with various unidentified species belonging to the genera *Acaulospora*, *Glomus* and *Scutellospora* (Koske and Gemma 2002). Three *Scutellospora* species, i.e. *Scutellospora crenulata*, *Scutellospora spinosissima* and *Scutellospora striata* have been isolated only from La Gran Sabana (Venezuela), a region with a high degree of plant endemism (Rull 1991).

Priorities for AMF conservation in natural ecosystems

AMF are considered evolutionarily successful living fossils, which have survived over a period ranging from 460 to possibly 980 Mya (Morton 1990; Simon et al. 1993; Redecker et al. 2000; Blair 2009) and which are considered to have played a fundamental role in land colonisation by plants (Pirozynski and Malloch 1975; Pirozynski 1981). Such fungi may, on account of their biological and ecological features, be generally less susceptible to extinction than other groups of organisms. However, specific ecotypes affiliated to certain taxa (in particular Gigasporaceae) have been shown to be highly sensitive to contemporary ecological forces.

Among AMF fungal species identified so far, some have a global distribution, such as ecotypes of *G. mosseae* (Rosendahl et al. 2009), isolated mainly from arable land and representing a species adapted to disturbed environments and of *G. intraradices* (Öpik et al. 2006), which is considered a non-selective generalist and a disturbance-tolerant fungus (Öpik et al. 2006; Sýkorová et al. 2007; van der Heijden and Scheublin 2007). Our analysis of AM fungal occurrence only in protected sites is not interpretable within the context of the biogeographic distribution of AMF species. However, the description of potential endemic AMF ecotypes suggests that the study of their occurrence and distribution in protected areas worldwide may offer a strategic perspective to increase awareness of the importance of these beneficial symbionts and to preserve their biodiversity in the years to come.

Most studies on AMF in protected areas have been performed in America, Europe and Australia, partly because of the large number of laboratories dedicated to the study of such beneficial symbionts and possibly also because these areas of the world host the highest number of protected sites. Unfortunately, very few studies on AM fungal diversity in protected areas of Asia are available to the scientific community, with the exception of two reviews on AMF in Chinese protected areas (Gai et al. 2006; Wang and Shi 2008). Since many invaluable "hot spots", such as the mountains of Central Asia and of Southwest China, the Sundaland, the Wallacea, may host a large number of AMF that are either endemic or still to be discovered, further studies on their occurrence should be performed, aimed at boosting recognition of the importance of preserving these special places and their natural genetic resources. Furthermore, major efforts need to be devoted to the study of AMF biodiversity in tropical countries where not only have many AM fungal species been detected on the basis of spore occurrence but where environmental DNA sequences have also been retrieved which do not correspond to formally described species (Husband et al. 2002a, b; Öpik et al. 2010). Also, research needs to be aimed at understanding the role of AMF in the survival of threatened endemic plant species or in the maintenance of special habitats (Hermann et al. 2010). In this context, some data have recently been made available on three endangered plants inoculated with AMF isolated

Table 4 Glomeromycota species localised only in one continent or in one protected site

Continent	Species occurring in one continent		Species occurring only in one protected site	
	No. of species	Species	No. of species	Species
Africa	1	*Glomus africanum*	1	*Glomus africanum*
Asia	4	*Gigaspora albida, Glomus liquidambaris, Glomus reticulatum, Scutellospora projecturata*	4	*Gigaspora albida, Glomus liquidambaris, Glomus reticulatum, Scutellospora projecturata*
Europa	23	*Acaulospora alpina, Acaulospora capsicula, Acaulospora gedanensis, Acaulospora paulinae, Acaulospora polonica, Acaulospora rugosa, Scutellospora armeniaca, Entrophospora baltica, Entrophospora nevadensis, Glomus arenarium, Glomus badium, Glomus caesaris, Glomus corymbiforme, Glomus heterosporum, Glomus irregulare, Glomus pustulatum, Glomus spinuliferum, Glomus tenue, Glomus viscosum, Otospora bareai, Pacispora scintillans, Scutellospora gregaria, Scutellospora dipurpurescens*	20	*Acaulospora alpina, Acaulospora capsicula, Acaulospora gedanensis, Acaulospora polonica, Acaulospora rugosa, Scutellospora armeniaca, Entrophospora baltica, Entrophospora nevadensis, Glomus arenarium, Glomus badium, Glomus caesaris, Glomus corymbiforme, Glomus heterosporum, Glomus irregulare, Glomus pustulatum, Glomus spinuliferum, Glomus tenue, Glomus viscosum, Otospora bareai, Scutellospora gregaria*
North America	13	*Acaulospora colliculosa, Acaulospora sporocarpia, Scutellospora hawaiiensis, Glomus aureum, Glomus botryoides, Glomus cerebriforme, Glomus eburneum, Glomus lamellosum, Glomus mortonii, Glomus nanolumen, Glomus verruculosum, Racocetra weresubiae, Scutellospora arenicola*	10	*Acaulospora colliculosa, Acaulospora sporocarpia, Glomus aureum, Glomus botryoides, Glomus cerebriforme, Glomus eburneum, Glomus mortonii, Glomus nanolumen, Glomus verruculosum, Scutellospora arenicola*
Oceania	9	*Glomus australe, Glomus canum, Glomus cuneatum, Glomus fulvum, Glomus pallidum, Glomus pellucidum, Glomus pubescens, Glomus tenerum, Scutellospora aurigloba*	7	*Glomus canum, Glomus cuneatum, Glomus pallidum, Glomus pellucidum, Glomus pubescens, Glomus tenerum, Scutellospora aurigloba*
South America	24	*Acaulospora delicata, Acaulospora elegans, Acaulospora entreriana, Acaulospora nicolsonii, Acaulospora remhii, Ambispora brasiliensis, Ambispora jimgerdemanni, Scutellospora gilmorei, Scutellospora spinosissima, Scutellospora striata, Scutellospora cerradensis, Scutellospora colliculosa, Scutellospora heterogama, Scutellospora nigra, Gigaspora candida, Gigaspora decipiens, Gigaspora margarita, Glomus ambisporum, Glomus microcarpum, Acaulospora colombiana, Racocetra intraornata, Scutellospora biornata, Racocetra coralloidea, Scutellospora crenulata*	16	*Acaulospora delicata, Acaulospora elegans, Acaulospora entreriana, Acaulospora nicolsonii, Ambispora brasiliensis, Scutellospora spinosissima, Scutellospora striata, Scutellospora cerradensis, Scutellospora colliculosa, Scutellospora nigra, Gigaspora candida, Glomus ambisporum, Racocetra intraornata, Scutellospora biornata, Racocetra coralloidea, Scutellospora crenulata*
Total	74		58	

from the same protected area, the Tatra Mountains National Park in Poland (Zubek et al. 2008, 2009). Finally, additional attention should be paid to extreme habitats (thermal habitat, high-altitude habitat, high-salinity habitat, desert, wetland, polluted soils) where AM fungal ecotypes capable of tolerating such harsh conditions could be retrieved and preserved for future generations.

Acknowledgements This work was supported by University of Pisa and by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR), SOILSINK project (Fondo Integrato Speciale Ricerca-FISR) "Cambiamenti climatici e sistemi produttivi agricoli e forestali: impatto sulle riserve di carbonio e sulla diversita` microbica del suolo". A.T. was supported by a SOILSINK Project grant.

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