Chapter 12
Mycorrhizae Adsorb and Bioaccumulate Heavy and Radioactive Metals

Hassan Zare-Maivan

12.1 Introduction

Mycorrhizae are mutual symbiosis (associations) between plant roots and a wide group of soil-inhabiting, filamentous fungi. Both partners exchange essential nutrients required for their growth and survival (Sapp 2004). The fungal partner acquires nitrogen, phosphorus, and other nutrients from the soil environment and exchanges them with the plant partner for photosynthetically derived carbon compounds that are essential for its metabolism. Primary function of mycorrhizal fungi is nutrient exchange, and this provides the basis for broad classification into seven groups: ectomycorrhizae, ericoid mycorrhizae, ectendomycorrhizae, arbuscular mycorrhizae, arbutoid mycorrhizae, monotropoid mycorrhizae, and orchid mycorrhizae.

In temperate and boreal forest ecosystems, trees typically form ectomycorrhizal (ECM) symbioses, whereas the major constituents of the understory and rangeland vegetation form arbuscular (AM) and sometimes ericoid (ERM) or arbutoid (ARM) mycorrhizae. The ECM and AM mycorrhizae will be considered in more detail. These two groups of mycorrhizae occur in a wide variety of plants, particularly those plant species capable of propagating in reclaimed areas, such as abandoned mines and contaminated fields. Ectomycorrhizal (ECM) and arbuscular mycorrhiza (AM) are the mutual symbiosis between some fungi and roots of terrestrial plants. Mycorrhizal fungi have been reported to be direct physical links between soil and plant roots increasing soil nutrient exploitation and transfer of minerals to the roots. As such, mycorrhizae have provided an efficient system to advance the stabilization of heavy metals by plants (phytostabilization). This is achieved through secretion of compounds (e.g., enzymes) by the fungal partner that precipitate into polyphosphate granules in the soil and subsequent adsorption to fungal cell walls and chelating of

H. Zare-Maivan (✉)
Department of Plant Biology, Tarbiat Modares University, Tehran, Iran
e-mail: zare897@yahoo.com; zaremaih@modares.ac.ir

E.M. Goltapeh et al. (eds.), *Fungi as Bioremediators*, Soil Biology 32,
DOI 10.1007/978-3-642-33811-3_12, © Springer-Verlag Berlin Heidelberg 2013

heavy metals inside the fungal cells. Therefore, the use of mycorrhizal plants for land remediation and reclamation has been proposed with results including mycorrhizae influencing metal transfer in plants by increasing plant biomass and plant phosphorus nutrition and reducing metal toxicity to plants by decreasing root to shoot heavy metal translocation and or inside cell stabilization. The effect of mycorrhizae on metal uptake in plants is still controversial, and the issue of heavy metal uptake and bioaccumulation in plants needs further research.

12.2 Soil Habitat

Conditions within soil habitats vary by orders of magnitude over micrometer distances, in response to physical (structure and texture), chemical (pH, O_2, pollutants, soluble substances, and plant residues), and biological (soil biota, community fauna, plant roots, and interactions) variables. Such variability provides ample opportunity for establishing infinite variety of microscale habitats and means of interactions among consumer groups in the mycorrhizosphere. It is perhaps because of this, any soil sample contain representative species from major genera of the known microbiota of terrestrial ecosystems. Among these, mycorrhizal fungi form a distinctive and widespread group of organisms that establish mutual symbiotic relationships with fine roots of plant species. In light of growing urbanization, industrialization, and greater environmental disturbances, much effort is being directed toward friendly interaction of man and the environment. As such, considering the new technological and biotechnological advances in the field of ecology and environmental studies, from a management perspective, the genetic potential to mediate virtually any biogeochemical reaction and the habitat needed to support it exist in most soils which with developing specialized capabilities could be investigated further.

12.3 Ectomycorrhizae

Associations between ECM fungi and the roots of woody plants are characterized by three structural components: the mantle, the Hartig net, and the extraradical mycelium (Smith and Read 1997). The mantle is a sheath of fungal tissue that covers the highly active tips of the lateral roots of the plant and forms the boundary between the root and the soil environment. Its compact, but also variable, morphological nature provides a buffering capacity that helps to prevent root cell dehydration or penetration by pathogenic organisms (Brundrett 1991). Fungal hyphae extend from the outer mantle form a web of extraradical mycelia which grow into the rhizosphere. These mycelia extend into micropore areas and absorb nutrients that may otherwise be inaccessible, usually biochemically to roots (Perez-Moreno and Read 2000). Some ECM fungi also form rhizomorphs, which are thick linear aggregates of hyphae that are specialized for long-distance translocation of nutrients and water (Agerer 2001). Lipids, phenolic compounds, proteins, and polyphosphates may accumulate in the hyphae of the outer mantle, which may also bind heavy metals and thereby prevent their uptake into roots (Peterson et al. 2004). The inner mantle consists of repeatedly branched hyphae, suggesting a role in nutrient exchange such as enabling absorption of simple sugars, such as glucose and fructose from the root, and conversion to fungal sugars such as trehalose, mannitol, or glycogen (Peterson et al. 2004). Hartig net is a highly branched hyphal structure growing between epidermal and cortical cells of the root and is the probable site for exchange of nutrients between symbionts (Peterson et al. 2004). Subtle variations in morphological attributes viewed using light microscopy are often used to distinguish between ECM fungal taxa; development and differentiation of extraradical mycelia has been used to define features relevant to the ecological classification of ECMs (Agerer 1987–2002, 2001). ECM fungi are usually classified among Ascomycetes and Basidiomycetes, unlike AM fungi which are established primarily by Glomeromycetes. ECM plant species represent only about 8,000 species (mostly in the families Pinaceae, Betulaceae, Fagaceae, Dipterocarpaceae, Salicaceae, and Myrtaceae which form extended forest ecosystems and woody habitats). These species are of global importance because of their disproportionate occupancy and domination of terrestrial ecosystems in boreal, temperate, and subtropical forests (Smith and Read 1997). It has been estimated that 5,000–6,000 species of fungi (of the classes Basidiomycetes, Ascomycetes, and few Zygomycetes) form ECM symbioses (Molina et al. 1992; Horton and Bruns 2001), but these numbers are expected to rise as more regions are progressively explored in detail (Cairney 2000). ECM fungal communities exhibit high species richness and diversity, even within small areas with little heterogeneity in plant communities, soil properties, climate, and disturbance patterns (Bruns 1995; Robertson et al. 2006).

12.4 Arbuscular Mycorrhizae Fungi

Arbuscular mycorrhizae (AM) fungi, unlike ECMs fungi, do not induce distinctive changes in the root morphology of partner plant. AMs are generally established in fine lateral roots of plants that are composed of a vascular cylinder, few rows of cortical cells, and an epidermal layer. AM fungi do not form mantles or Hartig nets, but rather penetrate through the epidermal layer of thin roots or from root hairs and develop intracellular hyphal branch-like coils, called arbuscules, that are specialized for nutrient exchange and function as the site of bidirectional nutrient exchange. The intracellular fungal symbiont is separated from the plant cytoplasm by a plant-derived membrane, which invigilates to follow fungal growth and coil formation. Usually, within 2 weeks of arbuscule formation and subsequent growth and development of fungal hyphae in the cortex of the root, thick-walled inter- or intracellular vesicles are formed that act as endophytic storage compartments for fungal partner. Arbuscules are often formed progressively within a short distance behind the penetrating hyphal tip. AM presence in the roots of plants requires dissecting and sectioning of roots, proper tissue staining, and microscopic examination. However, AM fungi are primarily identified on the basis of morphological features of their spores and sporocarps and chlamydospores. These propagules are produced outside the root on the extended fungal mycelium and act as dormant propagules for mycorrhizal establishment under proper environmental conditions. Besides, protein profiling, isozyme polymorphism, and DNA analysis have also been applied to identify AM fungi.

12.5 Evolution and Diversity

Mycorrhizal symbioses have been an important force in evolution (Pirozynski and Malloch 1975; Sapp 2004). Based on reconstructions of evolutionary lineages phylogenies from fungal DNA and the fossil record, it is currently accepted that the first mycorrhizal associations were pivotal in allowing plants to colonize the terrestrial environment about 600 million years ago, and they form the evolutionary basis of present plant communities (Pirozynski and Malloch 1975). ECM fungal diversity appears to have arisen about 200 million years ago, corresponding to changes in climate that allowed for colonization of the land with trees and increased organic matter content of some ancient soils (Cairney 2000). Although phylogenetic analyses reveal that ECM fungi have originated from several independent lineages and that symbiosis with plants has been convergent derived (and perhaps lost) many times over millions of years (Hibbett et al. 2000). Greater diversity and high species richness and abundance in many ecosystems may represent ecological adaptation of mycorrhizae to local environmental heterogeneity and are thought to provide forests with a range of strategies to maintain efficient functioning under an array of environmental conditions (Cairney 1999). In general, soil microbial communities appear to comprise groups of organisms that fulfill broadly similar ecosystem functions, and their diversity represents the potential value and spectrum of capabilities that are possessed by organisms present in a given ecosystem and play a functional role in ecosystem processes (Allen et al. 2003). Knowledge of the individual roles of mycorrhizal fungal species, or of their distribution either in relation to each other or to the physical and chemical environments of the soil, is limited (Rosling et al. 2003) and insufficient for determination of community needs and responses by building up from the species level. Further research will reveal the functional heterogeneity and role as well as effect of fungal community diversity on the functioning of the ecosystems as a whole. These findings will allow environmental managers to adopt a more clearly defined plan of action to remedy a disturbed or polluted ecosystem, to restore and rehabilitate abandoned habitats and to sustain pollution stressed plant communities.

12.6 Soil and Rhizosphere

Soils are living, open, dynamic systems in which constant integrating and disintegrating (i.e., maintaining and releasing) of inorganic and organic substrates and plant residues occur. Soils contain structured and heterogeneous matrices, generally store nutrients and energy, and support high microbial diversity and biomass (Nannipieri et al. 2003). To thrive, soil microorganisms must mobilize energy and nutrients stored in soil. Soil structure provides a complex and variable set of microbial microhabitats ranging from energy-rich to barren, or aerobic to anaerobic, over minuscule distances. Soils are composed of sand, silt, and clay particles that are held together by organic matter (i.e., humus), precipitated inorganic materials, microorganisms, and the products of chemical reactions and interactions by plant roots and other substances. Soil particles adsorb important biological molecules (e.g., DNA, enzymes, etc.), and many soil reactions are catalyzed at the surfaces of soil minerals such as clays, Mn oxides, and Fe oxides (Nannipieri et al. 2003). Water occupies the aggregate pore spaces and forms a meniscus around a central pocket of air, which provides an aerobic and aqueous habitat suitable for supporting microbial communities. Water-logged soils usually create anaerobic microsites which retard gas exchange and limit the distribution of aerobic organisms such as mycorrhizal fungi. When mycorrhizae are present in the soil, even under suboptimal conditions, the rhizosphere is more metabolically active. Fungal metabolic activities produce organic acids that percolate with rainwater down through the soil profile and contribute to accelerated weathering of mineral of the soil, and this provides an opportunity for mycorrhizal propagules to adsorb and/or to interact with metal ions under proper matrix potential of the soil. Although less than 5 % of the soil volume is occupied by microorganisms, including mycorrhizal fungi, increased biological activity takes place in these sites, and this is where the majority of soil reactions are mediated (Diaz 2004). The availability and nutrient content of organic matter are key factors influencing microbial biomass and community composition. Other major factors controlling the distribution and abundance of soil microbial communities include (1) chemical properties of the soil environment (e.g., pH, O_2 supply and capacity for gas exchange and availability of water and nutrients such as N, P, and Fe), (2) physical properties of the soil affecting dispersal (e.g., soil structure and texture), and (3) biotic properties and recycling (i.e., turnover) capacity of soil. If heavy metals and other contaminants that alter soil chemical and physical properties limit resources and/or disturb the ongoing biological processes and are introduced into soils in established ecosystems, the functional capacities of mycorrhizal fungi have proven to be effective in ecological risk management of such ecosystems. These capacities are as follows: (1) altering of the morphology and physiology of plant roots as for the permeability of root membranes, (2) changing root exudation patterns as well as the types of C substrates exuded (Linderman 1988), (3) generating extra volume on colonized roots via mantle in ECMs and extraradical mycelia for increased absorption surface and microbial colonization platform, and (4) generating competitive advantage between interacting microbial species in the immediate microscale distance.

12.7 Phytoremediation

Phytoremediation is the use of plants to extract, sequester, and detoxify pollutants from contaminated ecosystems. It was once regarded as an effective, nonintrusive, inexpensive, and socially accepted technology to remediate polluted soils. Plants that are growing in mine sites are usually tolerant to heavy metals. Plants that survive on metalliferous soils can be grouped into one of three categories: (1) excluders, where metal concentrations in the shoots are maintained up to a critical value at a low level across a wide range of metal concentrations in soil (Baker and Brooks 1989); (2) accumulators, where metals are concentrated in aboveground plant parts from low to high soil concentrations (Baker and Brooks 1989); and (3) indicators, where internal concentrations in the plant reflect external levels such as soil concentrations (McGrath and Zhao 2003). However, heavy metal tolerance in all these plants is heavily dependent on various biological, chemical, and physiological adaptations in contaminated sites. Mycorrhizal formation in plants may contribute by providing a metal excluder barrier and improving nutritional status (Turnau et al. 1993; Wissenhorn et al. 1995). Severe metal pollution does have an evolutionary impact on the plant mycorrhizal interaction. Evolutionary adaptation of these AM-colonized plants to the polluted conditions can be accepted based on numerous lines of evidence, including genetic variation in tolerance, habitability of tolerance, higher fitness of tolerant individuals on polluted sites, and higher fitness of non-tolerant individuals on unpolluted sites. Therefore, the AM-colonized plant grown on mine sites has its own survival strategy such as chelating heavy metals by forming organic complexes by creating a symbiotic relationship with mycorrhizal fungi. It is a fact that mycorrhizal fungi are associated with a majority of the plants in the industrially polluted sites and support plant survival in acidic soils polluted with industrial effluent containing heavy metals. However, the interrelationship between indigenous fungi and heavy metal accumulation in plants and also in mycorrhizosphere soil is not known.

12.8 AM Fungal Spores as Bioindicators and Biomonitors of Contaminating Heavy Metals

Recent studies have shown that ecosystems are constantly contaminated through wet and dry deposition of atmospheric pollutants such as gases, heavy metals, and radioactive isotopes. Studies with pollutants applied singly in controlled fumigation or mixed with soil provide the basis for much of our present understanding of the effects of gases, toxic metals, and contaminants on plants. Additional studies have shown that effects of any particular pollutant on plants may not necessarily be similar to those when it is applied simultaneously or in combination with other pollutants (Runeckles 1984). Increased mining activities as well as disposal of increasing quantities of waste containing heavy metals and use of fossil fuels introduce considerable amounts of contaminating pollutants to ecosystems (Ritchie and Thingvold 1985; Baes and McLaughlin 1987). Although adverse effects of toxic metals on pollen germination, seedling growth, and revegetation schemes are known nowadays, many plants are capable of ameliorating such contaminations to a certain extent (Marx and Artman 1979; Seaward and Richardson 1990; Wissenhorn et al. 1994, 1995). Further research has shown that symbiotic relationships of plants, such as mycorrhizae, play a significant part in stabilization and biodegradation of toxic metal compounds and amelioration of contaminated ecosystems (Tam and Griffith 1993; Tam 1995; Baghvardani 1997; Baghvardani and Zare-maivan 1998). Tam (1995) investigated heavy metal tolerance by ectomycorrhizal fungi and metal amelioration by *Pisolithus tinctorius* in vitro. Baghvardani and Zare-maivan (1998) showed that as many as 18 heavy and radioactive metals were adsorbed by mycorrhizal fungi in two separated field investigations on the Hyrcanian broadleaf forests of Iran. Natural occurrence of some radioactive and heavy metals in parts of Hyrcanian forests, south of Caspian Sea, prompted the idea of this research with the following objectives: (1) to determine differences in capability of adsorbing radioactive and heavy metals by AM fungal species isolated from naturally contaminated forest soil and (2) to determine effects fungal community composition might have on metal adsorbing capability.

In recent decades, interest to having healthy environment has increased. Phytoremediation of contaminated sites, abandoned mining areas, and waste disposal landfills is taking place widely in many parts of the world. Similarly, application of biomonitoring techniques is expanding in many aquatic and terrestrial ecosystems. Access to new, accurate, fast, and reliable techniques, such as that of Mc Kenny and Donald (1987), has always been appealing to scientists and environmental managers. For example, indicator species have been one of approaches taken by many researchers and environmental decision makers for environment impact assessments of contaminated or disturbed ecosystems. Mycorrhizal fungi have been used extensively in mine reclamation and landfill reforestation. These fungi have been indicated as biotracers, bioaccumulators, and biodegraders of toxic compounds. For example, adsorption of radioactive isotopes and heavy metals has been demonstrated in Caspian (Hyrcanian) deciduous forests of Iran (Baghvardani 1997; Baghvardani and Zare-maivan 1998). These researchers investigated capability of AM spores adsorption in areas of high background radiation near Ramsar, a city located on the southern coast of the Caspian Sea and on northern slopes of the Alborz mountain ranges, Iran, and well known for its higher background radiation which is usually five times higher than the 20 mSv year^{-1} that is permitted for radiation workers. Tam (1995) indicated the capability of ectomycorrhizal fungus *Pisolithus tinctorius* for amelioration of heavy metal contaminated sites (Vare 1990; Tam 1995) and involves extrahyphal mucilaginous substances (Denny and Wilkins 1987a, b; Tam 1995) or chelators (Bradley et al. 1982). Brown and Wilkins (1985) investigated the bioavailability and uptake of heavy metals by AM fungi in areas polluted *via* atmospheric depositions from a smelter or from a waste sludge. In this study, however, adsorption capability of various species of AM fungi exposed to naturally occurring chronic heavy metal contamination and background radiation was investigated. Many researchers have indicated that heavy metal uptake in mycorrhizal fungal species is achieved by polyphosphate linkage of copper and zinc (Vare 1990; Tam 1995) and involves extrahyphal mucilaginous substances (Denny and Wilkins 1987a, b; Tam 1995) or chelators (Bradley et al. 1982; Brown and Wilkins 1985). Findings of this research, however, indicated that spore surface and ornamentation contributed to metal adsorption capability of AM fungal spores. *G. multicaule*, for instance, with its larger and highly ornamented spores, demonstrated the highest adsorption readings of many cations. Therefore, adsorbing range of heavy and radioactive metals may be species specific and within a certain range of tolerance. There are many ways that one can measure and track pollutants of greater concentration in the environment; however, AM spores can be used as bioindicators of traces of contaminating metals and as biomonitors for fluctuations in the concentration of metals throughout the year, particularly in environments with definite arid and wet or warm and cold seasons. Further research regarding the mechanisms of amelioration of contaminating metals and adaptation to chronic background radioactive radiation is necessary.

In recent decades, a great attention has been paid to the problem of radioactive and heavy waste disposals. Trace and heavy metal depositions in sediments and metal accumulation in forest soils suggest that forests have been exposed increasingly to greater concentrations of atmospheric pollutants (Baes and McLaughlin 1987). It has been shown that severe contamination by pollutants such as heavy metals can result in pollen malfunctioning and seedling mortality and thus in several decades cause delays in revegetation schemes (Ritchie and Thingvold 1985). Similarly, it has been known for long that exposure to radioactive waste or radiation, such as that from Chernobyl and Fukushima, Japan, power plant accident, contaminates environment and affects genetic material of impacted species. This, in turn, influences plant species composition and process of succession in impacted ecosystems. In contrast, many fungal species exhibit tolerance to radioactive and heavy metals in concentrations that normally can be toxic to higher plants (Tam 1995). Similarly, mycorrhizal fungi have also been shown to accumulate a greater concentration of heavy metals. For example, Bargagli and Baldi (1984) demonstrated that mycorrhizal fungi could accumulate up to 63 times the concentration of mercury in soil from a mercury mining area. Chemical analysis of shortleaf pine tree cores from east Tennessee, USA (Baes and McLaughlin 1987), and of *Ziziphus* trees from Hormozgan Province, Iran (Korury et al. 1999), have shown trace metal accumulation in tree rings with local and regional increase in combustion of fossil fuels. Crowded roadsides, reclaimed areas, and landfills exhibit greater concentration of heavy metals, particularly lead, copper, zinc, and nickel (Seaward and Richardson 1990). Revegetation of such areas usually requires planting of mycorrhizal plant species. Such a phytoremediation practice has become common in many parts of the world; however, there are dense deciduous forest ecosystems, for example, Caspian forest near Ramsar in Northern Iran, whereby radioactive and heavy metals occur naturally (Baghvardani and Zare-maivan 1998). Previous studies by Akbarloo (1994), Nourbakhsh (1994), and

Nourbakhsh and Zare-maivan (1995) demonstrated the widespread occurrence of mycorrhizae in plant communities south of Caspian Sea. These authors indicated that there was a succession pattern of vegetation from seaside toward upper mountains.

Salt-tolerant aquatic weeds dominated sandy coastal areas followed by grasses, shrubs, and trees as distance from the coast and altitude from sea level increased. Accordingly, there was a mycorrhizal succession pattern, with no mycorrhizae on aquatic weeds, endomycorrhizae on grasses and few shrub species and ectomycorrhizae on tree species. Occurrence of mycorrhizal propagules has been reported in contaminated sites by many researchers (Marx and Artman 1979; Wissenhorn et al. 1994, 1995). Previous research indicated that ectomycorrhizal fungi were capable of establishing symbiotic relationship with various Eucalypt, pine, beech, and oak tree species (Marx and Artman 1979; Zare-maivan 1983; Chan and Griffith 1991; Tam and Griffith 1993). Also, research has shown that polyphosphate granules may be responsible for detoxification of radioactive and heavy metals at high concentrations; for example, Vare (1990) demonstrated that aluminum polyphosphate granules were located in the ectomycorrhizal fungus, *Suillus variegatus*. Tam (1995) also demonstrated through polyphosphate linkage of copper and zinc and by energy dispersive X-ray spectroscopy that heavy metal amelioration mechanism in the metal-tolerant fungal species, *Pisolithus tinctorius*, involved extrahyphal slime. Amelioration of heavy metals by mycorrhizal fungi improves plant species ability to establish in new environments. This might explain, to some extent, why so many plant species are mycorrhizal. In this context, while the possibility that forest trees may be important indicators of trends in atmospheric deposition of pollutants (Baes and McLaughlin 1987; Korury et al. 1999) offers a potentially useful tool for regressing historical trends and characterizing of metal depositions in an area, there is far less knowledge regarding the role of mycorrhizal fungi for metal accumulation in natural ecosystems. Natural occurrence of unexpected concentrations of radioactive and heavy metals and dense and diverse vegetation in parts of Hyrcanian (Caspian) forest prompted the idea of present investigation. The purpose of this study was first to determine the accumulation (adsorption) spectrum of radioactive and heavy metals by mycorrhizal fungal structures in nature and second to examine the trend in succession of metal adsorption along the succession gradient of plant communities.

Vegetation and mycorrhizae succession have been investigated in Kheiroud Kenar region (Assadi 1984; Nourbakhsh and Zare-maivan 1995) which is in general agreement with succession pattern of vegetation in South Caspian Sea forest realm. Succession pattern of mycorrhizae in this ecosystem follows general trend observed elsewhere with similar climatic and edaphic conditions (Barbour et al. 1999). Presence of barium and chloride in soil and mycorrhizal propagules, respectively, indicated the intrusion of marine water into sandy coastal areas; however, presence of eight radioactive and heavy metals on mycorrhizal plants in coastal area demonstrated the capability of mycorrhizal propagules as potential bioaccumulators and, therefore, as bioindicators of contaminating pollutants. This finding is supported further by the fact that similar trends are seen in other plant communities along the succession gradient.

Except for the coastal sand in station 1 which exhibited only barium, soil in all other stations contained three to five elements. This might be attributed to presence of clay particles in soil; because, it is widely accepted that cations have a greater tendency to be adsorbed to clay particles. Since mycorrhizal propagules throughout the succession gradient have greater number of elements on them than that in soil, presumably, it seems that presence of mycorrhizae might have contributed to the ability of plant species to tolerate radioactive and heavy metals more extensively. Availability of sufficient nutrients and chronic exposure to radioactive and heavy metals may have been responsible for this adaptation. Adaptive response in humans can be induced by chronic exposure to natural background radiation as opposed to acute exposure to higher levels of radiation in the laboratory. Our knowledge of prevalence of adaptive response phenomenon in the Hyrcanian (Caspian) forest ecosystems is minimal and needs further research. There are many radioactive and heavy metals in the mycorrhizosphere on all sites. Many of these elements are known to be toxic and have adverse effects on plant growth and regeneration; for example, presence of aluminum in forest soil and on mycorrhizal propagules indicates its potential adverse effects on forest trees. Aluminum reduces root growth and limits availability of essential plant nutrients such as phosphorus and calcium. Favoring role of mycorrhizae for facilitated absorption of nutrients in phosphorus poor soils and in reclaimed mining areas has been indicated frequently in the literature (Marx and Artman 1979; Zare-maivan 1983; Marshner and Dell 1994). Therefore, planting mycorrhizal plant species for phytoremediation of aluminum and other metal contaminated sites becomes a formidable possibility. Presence of radioactive metals on ectomycorrhizal roots of Hyrcanian forest trees has been indicated in the past (Baghvardani and Zare-maivan 1998). Previous research has demonstrated that ectomycorrhizal fungi improve metal tolerance of their host plant by primarily accumulating metals in the extra-matrical hyphae and extrahyphal slime (Brown and Wilkins 1985; Denny and Wilkins 1987a, b; Tam 1995). Prevalence of mycorrhizae has been indicated in Hyrcanian forest plant communities recently (Nourbakhsh and Zare-maivan 1995; Baghvardani and Zare-maivan 1998). Findings of this research showed that many herbaceous and shrubby plants were AM and all other tree species were ectomycorrhizal. Considering the fact that occurrence of high levels of natural background radiation has been reported by Baghvardani and Zare-maivan (2000) for Ramsar, a city located about 60 km west of Kherood Kenar Forest Research Station (KKFR) station, this research implicates KKFR as well. However, scale of this study does not permit one to draw a comprehensive conclusion before further research is undertaken. Widespread occurrence of contaminating metals on mycorrhizal plants and in greater frequencies than that in soil throughout the succession gradient suggest the possibility of application of mycorrhizal propagules for identifying (and quantifying) radioactive and heavy metals. Therefore, a reliable and accurate technique is at hand to biomonitor traces of contaminating elements and to show trends in contaminant depositions. However, there are substantial gaps in our understanding of the linkages between metal inputs to ecosystems and their uptake by trees or by their mycorrhizal symbionts. Similarly, the possible role of mycorrhizal fungi in the metal tolerance of higher plants and mechanism of detoxification and biodegradation of toxic elements and tolerance limits by mycorrhizal fungi is poorly understood. But natural occurrence of such elements and high background radiation in parts of Caspian (Hyrcanian) forest in Iran provides a very opportunistic situation for further and more detailed studies.

12.9 Future Perspective

Evolutionary biology and ecology of plant species has broaden our knowledge of origin and adaptive capability of plants and symbiosis in plant ecosystems in the past. Using mycorrhizal plants in phytoremediation practices in contaminated sites has been an effective restoration tool in many parts of the world. As such, taking advantage of mycorrhizal fungal spores or mycelial structures for tracing residual and chronic distribution of contaminating elements would provide an efficient and less costly way of decision making for environmental managers. For those interested in the world geological and ecosystem development, perhaps mycorrhizal propagules and their functioning under different magnetic fields of the earth throughout the geologic time could prove a useful research tool.

References

Agerer R (ed) (1987–2002) Colour atlas of ectomycorrhizae. Einhorn-Verlag Eduard Dietenberger, Schwäbisch Gmünd

Agerer R (2001) Exploration types of ectomycorrhizae: a proposal to classify ectomycorrhizal mycelial systems according to their patterns of differentiation and putative ecological importance. Mycorrhiza 11:107–114

Akbarloo S (1994) Mycorrhizal distribution in Kheiroud Kenar Forest Research Station. MSc thesis, Tarbiat Modarres University, Tehran (In Persian)

Allen MF, Swenson W, Querejeta JI, Egerton-Warburton LM, Treseder KK (2003) Ecology of mycorrhizae: a conceptual framework for complex interactions among plants and fungi. Annu Rev Phytopathol 41:271–303

Assadi M (1984) Plant sociology of Kheiroud Kenar. MSc thesis, Tehran University, Iran (In Persian)

Baes CF III, McLaughlin SB (1987) Trace metal uptake and accumulation in trees as affected by environmental pollution. In: Hutchinson TC, Meems KM (eds) Effects of atmospheric pollutants on forests, wetlands and agricultural ecosystems, vol G16, NATO ASI series. Springer, Berlin, pp 307–319

Baghvardani M (1997) Determining adsorption of radioactive and heavy metals by mycorrhizal fungi in Ramsar Forests. MSc thesis, Tarbiat Modares University, Tehran (in Farsi with English Abstract)

Baghvardani M, Zare-maivan H (1998) Determining adsorption of radioactive and heavy metals by mycorrhizal fungi. In: 13th Iranian plant pathology congress (abstract)

Baghvardani M, Zare-maivan H (2000) Determining adsorption capacity of radioactive and heavy metals by mycorrhizal fungi. Iran J Plant Pathol 36:1–5

Baker AJM, Brooks RR (1989) Terrestrial higher plants which hyperaccumulate metallic elements: a review of their distribution, ecology and phytochemistry. Biorecovery 1:81–126

Barbour M, Burk JH, Pitts DW, Gilliam FS, Schwartz MW (1999) Terrestrial plant ecology. Addison-Wesley Longman, New York, 678 p

Bargagli R, Baldi F (1984) Mercury and methyl mercury in higher fungi and their relation with sulfur in a Cinnabar mining area. Chemosphere 13:1059

Bradley R, Burt AJ, Read DJ (1982) The biology of mycorrhiza in the Ericaceae. VIII. The role of mycorrhizal infection in heavy metal resistance. New Phytol 91:197–209

Brown MT, Wilkins DA (1985) Zinc tolerance of mycorrhizal Betula. New Phytol 99:101–106

Brundrett M (1991) Mycorrhizas in natural ecosystems. In: Begon M, Fitter AH, MacFayden A (eds) Advances in ecological research, vol 21. Academic, Harcourt Brace Jovanovich, New York, pp 171–313

Bruns TD (1995) Thoughts on the processes that maintain local species diversity of ectomycorrhizal fungi. Plant Soil 170:63–73

Cairney JWG (1999) Intraspecific physiological variation: implications for understanding functional diversity in ectomycorrhizal fungi. Mycorrhiza 9:125–135

Cairney JWG (2000) Evolution of mycorrhiza systems. Naturwissenschaften 87:467–475

Chan WK, Griffith DA (1991) The induction of mycorrhizas in Eucalyptus microcorys and E. torrelliana grown in Hong Kong. Forest Ecol Manag 43:15–24

Denny HJ, Wilkins DA (1987a) Zinc tolerance in Betula spp. II. Microanalytical studies of zinc uptake into root tissues. New Phytol 106:525–534

Denny HJ, Wilkins DA (1987b) Zinc tolerance in Betula spp. IV. The mechanism of ectomycorrhizal amelioration of zinc toxicity. New Phytol 106:546–553

Diaz E (2004) Bacterial degradation of aromatic pollutants: a paradigm of metabolic versatility. Int Microbiol 7:173–180

Hibbett DS, Gilbert L-B, Donoghue MJ (2000) Evolutionary instability of ectomycorrhizal symbioses in basidiomycetes. Nature 407:506–508

Horton TR, Bruns TD (2001) The molecular revolution in ectomycorrhizal ecology: peeking into the black box. Mol Ecol 10:1855–1871

Korury SAA, Teimuri M, Khoshnevis M, Salehi P, Salahi A, Matinzadeh M (1999) Determining heavy metal accumulation in *Ziziphus spina-christi using Peroxidase analysis*. Iranian Forest and Rangeland Institute Report. Ministry of Jihad-Agriculture, Tehran (In Farsi)

Linderman RG (1988) Mycorrhizal interactions with the rhizosphere microflora: the mycorrhizosphere effect. Phytopathology 78:366–371

Marshner H, Dell B (1994) Nutrient uptake in mycorrhizal symbiosis. Plant Soil 159:89–102

Marx DH, Artman JD (1979) Pisolithus tinctorius ectomycorrhizae improve survival and growth of pine seedlings on acid coal soils in Kentucky and Virginia. Reclam Rev 2:23–31

Mc Kenny MC, Donald DL (1987) Improved method for quantifying endomycorrhizal fungi: spores from soil. Mycologia 79:179–187

McGrath SP, Zhao FJ (2003) Phytoremediation of metals and metalloids from soils. Curr Opin Biotechnol 14:277–282

Molina R, Massiocotte H, Trappe JM (1992) Specificity phenomena in mycorrhizal symbioses: community-ecological consequences and practical implications. In: Allen MF (ed) Mycorrhizal functioning: an integrative plant-fungal process. Chapman and Hall, New York, pp 357–423

Nannipieri P, Ascher J, Ceccherni MT, Landi L, Pietramellara G, Renella G (2003) Microbial diversity and soil functions. Eur J Soil Sci 54:655–670

Nourbakhsh A (1994) Succession of vegetation and mycorrhizae in Kheiroud Kenar Forest. MSc thesis, Tarbiat Modares University, Tehran (In Farsi with English abstract)

Nourbakhsh A, Zare-maivan H (1995) Succession pattern of vegetation and mycorrhizae in Kheiroud Kenar Forest. In: 11th Iranian plant pathology congress (abstract)

Perez-Moreno J, Read DJ (2000) Mobilization and transfer of nutrients from litter to tree seedlings via the vegetative mycelium of ectomycorrhizal plants. New Phytol 145:301–330

Peterson RL, Massiocotte HB, Melville LH (2004) Mycorrhizas: anatomy and cell biology. NRC Research Press, Ottawa

Pirozynski KA, Malloch DW (1975) The origin of land plants: a matter of mycotrophism. Biosystems 6:153–164

Ritchie IM, Thingvold DA (1985) Assessment of atmospheric impacts of large-scale copper-nickel development in northern Minnesota. Water Air Soil Pollut 25:145–160

Robertson SJ, Tackabery LE, Egger KN, Massiocotte HB (2006) Ectomycorrhizal fungal communities of black spruce differ between wetland and upland forests. Can J Forest Res 36:972–985

Rosling A, Landeveert R, Lindhall BD, Larsson KH, Kuyper TW, Taylor AFS, Finlay RD (2003) Vertical distribution of ectomycorrhizal fungal taxa in a podzol soil profile. New Phytol 159:775–783

Runeckles VC (1984) Impact of air pollution combinations on plants. In: Treshaw M (ed) Air pollution and plant life. Wiley, Chichester, p 239

Sapp J (2004) The dynamics of symbiosis: an historical overview. Can J Bot 82:1046–1056

Seaward MRD, Richardson DHS (1990) Atmospheric source of metal pollution and effects on vegetation. In: Shaw AJ (ed) Heavy metal tolerance in plants: evolutionary aspects. CRC, Boca Raton, FL, pp 75–92

Smith SE, Read DJ (1997) Mycorrhizal symbiosis, 2nd edn. Academic, London

Tam PCF (1995) Heavy metal tolerance by ectomycorrhizal fungi and metal amelioration by Pisolithus tinctorius. Mycorrhiza 5:181–187

Tam PCF, Griffith DA (1993) Mycorrhizal associations in Hong Kong Fagaceae. IV. The mobilization of organic and poorly soluble phosphates by ectomycorrhizal fungus Pisolithus tinctorius. Mycorrhiza 2:133–139

Turnau K, Kotke I, Oberwinkler F (1993) Element localization in mycorrhizal roots of *Pteridium aquilinum* (L) Kuhn collected from experimental plots treated with cadmium dust. New Phytol 123:313–324

Vare H (1990) Aluminum polyphosphate in the ectomycorrhizal fungus Suillus variegatus (Fr) O. Kunze as revealed by energy dispersive spectroscopy. New Phytol 116:663–668

Wissenhorn I, Leyval C, Berthelin J (1994) Bioavailability of heavy metals and abundance of arbuscular mycorrhizae in soil polluted by atmospheric deposition from a smelter. Biol Fertil Soils 19:22–28

Wissenhorn L, Leyval C, Belgy G, Berthelin J (1995) Arbuscular mycorrhizal contribution to heavy metal uptake by maize(Zea mays L.) in pot culture with contaminated soil. Mycorrhiza 5:245–251

Zare-maivan H (1983) Root and mycorrhizal distribution of healthy and declining English oaks (Quercus robur L.). MSc thesis, Western Illinois University, Macomb, IL