Chapter 22
Use of Arbuscular Mycorrhizal Fungi for Reforestation of Degraded Tropical Forests

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22.1 Introduction

Tropical forests are important for their diverse bioresources as well as the significance of the carbon pool. Tropical forests are disappearing at the rate of 13.5 million hectares (ha) each year, largely due to logging, burning and clearing for agricultural land, and shifting cultivation (Kobayashi 2004). Timber harvesting has resulted in the transformation of more than five million ha of tropical forest annually into over-logged, poorly managed, and degraded forests. Degraded tropical forests require wide-scale rehabilitation and it is not easy to rehabilitate degraded tropical forests because a major obstacle in the rehabilitation of tropical forests is slow tree growth and high mortality of seedlings in the nursery. It is also necessary to understand the physical, chemical, and biological factors of forest soils, in order to remediate degraded tropical forests. Among these properties, biological properties are least well known. Arbuscular mycorrhizal (AM) fungi affect the maintenance of vegetation in various ecosystems and may play an important role in tropical forests. Most tropical tree species form arbuscular mycorrhizas.

The diversity of AM fungi and the breadth of their associations with plant species in natural environments are crucial to understanding the ecological role of AM fungi in plant coexistence. AM fungal community structures differ significantly between host species and have been reported to increase the growth and survival rate of some tropical tree seedlings (Wubet et al. 2009). Phosphorus (P) limits the productivity of trees in many forests and plantations especially in

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highly weathered, acidic, or calcareous profiles in the world. Most trees form mycorrhizal associations which are prevalent in the organic and mineral soil horizons. Mycorrhizal tree roots have a greater capacity to take up phosphate (Pi) from the soil solution than non-mycorrhizal roots (Plassard and Dell 2010). Rehabilitation of degraded tropical forests following inoculation of AM fungi has potential to restore important ecosystem functions. The purpose of this chapter is to review the effect of inoculation of AM fungi on growth of native tree species from tropical forests.

22.2 Degraded Tropical Forest and Reforestation

The total world's forests cover nearly 3.9 billion ha or nearly 30 % of the world's land area (FAO 2001; Fenning and Gershenzon 2002). The number of tropical forests has been declining owing to illegal logging, fire, conversion into agricultural lands, rubber tree and palm oil plantation, and use of the forest plantation estate as pulp trees. Degraded forests are considered to be low-value resources because they are characterized by the vegetation such as ferns, sedges, and scrub. However, it is not easy to rehabilitate this ecosystem in a short term, because it is necessary to select and produce high-quality tree seedling species that have high survival rates during the rehabilitation process.

Tropical forests contribute considerably in sustaining global biodiversity (Laurence 1999). They are homes to indigenous people, pharmacopeias of natural products, and providers of vital ecosystem services, such as flood amelioration and soil conservation. At regional and global scales, tropical forests also have a major influence on climate and carbon storage. Tropical forestlands have been disappearing at the rate of 13.5 million ha each year. Furthermore, timber harvesting has resulted in the transformation of more than five million ha of tropical forest annually into logged-over, poorly managed, and degraded forests.

One of the most serious world problems affecting tropical rain forest is desertification. This is a complex and dynamic process which is claiming several 100 million ha annually. Tropical forests are particularly affected, resulting in a rapid reduction in area. Human activities can cause or accelerate desertification and the loss of most plant species as well as their associated symbioses. The reduction and degradation caused by anthropological activities affect not only the sustainable production of timber but also the global environment. Accurate scientific information will enable managers to devise silvicultural systems to enhance soil properties and forest resources important for sustainable production and for minimizing deleterious impacts of harvesting and short-rotation plantation. Degraded tropical forested lands require wide-scale rehabilitation and it is necessary to improve the biological diversity of tropical forestlands and to enhance the commercial value of timber.

The rapid production of forest planting stock seedlings of high quality in nurseries is important for replenishing degraded tropical forestlands. Moreover, many soils of tropical forests are nutrient poor (Hattenschwiler et al. 2011). Soil nutrient availability is one of the limiting factors for the early growth of transplanted seedlings in degraded tropical forestlands. Degraded tropical forestlands are recognized as low-value forest resources without successful natural regeneration that are dominated by grasslands including fern, sedges, or scrub. Nowadays, reforestation programs have to prepare millions of seedling stocks annually. The use of vigorous seedlings in reforestation programs is important. However, seedling stocks of tropical forest species are usually weak, often N and P deficient, and have high mortality rates after transplanting in the field. Phosphorus was the most limiting nutrient for plant growth of four woody legume species (Moreira et al. 2010). Ultimately, rehabilitation can increase the area of forest as well as contribute to conservation of the remaining primary forests and environmental quality.

22.3 Ecology of Arbuscular Mycorrhizal Fungi in Tropical Forests

Tropical rain forest soils often have high P adsorption because of their strong affinity to P to form iron and aluminum oxides and hydroxides, whereas in neutral and alkaline soils, P is adsorbed on the surface of Ca and Mg carbonates (Holford 1997; Whitmore 1989). Soil P concentration of tropical soil is very low (Table 22.1). In most experiment with tropical rain forest plant species, the influence of AM fungi on P nutrition has been evaluated by measuring the growth response of inoculated and non-inoculated plants cultivated in soils with controlled levels of P (Janos 1980). Moyersoen et al. (1998) reported that AM colonization of the tropical tree *Oubanguia alata* (Scytopetalaceae) was positively correlated with increased P uptake despite low P availability in Korup National Park rain forest, Cameroon.

Early studies focused primarily on mycorrhizas of the temperate forests, but attention turned toward mycorrhizas of the tropical rain forests (Torti et al. 1997). In contrast to the temperate zone, where mycorrhizal associations of trees tend to be formed by ectomycorrhizal fungi, the majority of tropical tree species surveyed thus far are formed by AM fungi (Janos 1980). Notable exceptions of tropical trees forming ectomycorrhizas occur in the families Myrtaceae, Caesalpiniaceae, Euphorbiaceae, Fagaceae, and Dipterocarpaceae (Munyanziza et al. 1997). The highest number of species and spores of AM fungi was observed during the dry season, with a marked decrease during the rainy season in a tropical rain forest in Veracruz, Mexico (Guadarrama and Alvarez-Sanchez 1999). Moyersoen et al. (2001) reported that AM colonization was about 40 % in tree species in heath forests and mixed Dipterocarpaceae forest in Brunei. Tawaraya et al. (2003) showed that 17 of 22 tree species in a tropical peat swamp forest in Kalimantan, Indonesia, had mycorrhizas formed by AM fungi. Of the 142 species of trees and

Table 22.1 Arbuscular mycorrhizal colonization, mycorrhizal dependency (MD) of different tree species grown in tropical forests, and soil phosphorus concentration

Family	Species	Growth period (d)	Fungal species	Colonization (%)	MD (%)	Soil P (mg P/kg)	References
Anacardiaceae	*Lithraea molleoides*	90	*Glomus etunicatum*	27	97	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Anacardiaceae	*Anacardium occidentale*	90	*Glomus aggregatum*	71	23	6.6 (Bray-1)	Bá et al. (2000)
Anacardiaceae	*Schinus terebinthifolius*	120	Gigaspora margarita, Glomus etunicatum	20	92	2 (Olsen)	Siqueira et al. (1998)
Anacardiaceae	*Sclerocarya birrea*	90	*Glomus aggregatum*	75	17	6.6 (Bray-1)	Bá et al. (2000)
					57		
Apocynaceae	*Aspidosperma parvifolium*	180	*Glomus etunicatum*	–	68	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Apocynaceae	*Dyera polyphylla*	202	*Glomus clarum*	39	61	4.8	Turjaman et al. (2006)
Apocynaceae	*Dyera polyphylla*	202	*Glomus decipiens*	22	62	4.8	Turjaman et al. (2006)
Apocynaceae	*Stemmadenia donnell-smithii*	180	Mixture* 1	10	55	N.D.	Guadarrama et al. (2004)
					62		
Araucariaceae	*Araucaria angustifolia*	686	*Glomus clarum*	81	71	39	Zandavalli et al. (2004)
Bignoniaceae	*Jacaranda mimosaefolia*	120	*Gigaspora margarita, Glomus etunicatum*	77	95	2 (Olsen)	Siqueira et al. (1998)
Bignoniaceae	*Stenolobium stans*	120	*Gigaspora margarita, Glomus etunicatum*	72	85	2 (Olsen)	Siqueira et al. (1998)
Bignoniaceae	*Tabebuia serratifolia*	129	*Glomus etunicatum*	72	89	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)

Bignoniaceae	*Tabebuia impetiginosa*	84	*Glomus etunicatum*	41	58	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
					82		
Boraginaceae	*Cordia trichotoma*	90	*Glomus etunicatum*	–	98	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Caesalpiniaceae	*Caesalpinia ferrea*	97	*Glomus etunicatum*	30	76	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Caesalpiniaceae	*Copaifera langsdorffii*	262	*Glomus etunicatum*	–	50	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Caesalpiniaceae	*Senna macranthera*	120	*Glomus etunicatum*	20	87	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Caesalpiniaceae	*Senna spectabilis*	90	*Glomus etunicatum*	63	95	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Caesalpiniaceae	*Dicorynia guianensis*	350	Indigenous	62	52	N.D.	Bereau et al. (2000)
Caesalpiniaceae	*Dicorynia guianensis*	281	Indigenous	60–95	71	21	de Grandcourt et al. (2004)
Caesalpiniaceae	*Eperua falcata*	281	Indigenous	45–75	22	21	de Grandcourt et al. (2004)
Caesalpinoideae	*Bauhinia sp.*	120	*Gigaspora margarita*, *Glomus etunicatum*	9	6	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Caesalpinia ferrea*	120	*Gigaspora margarita*, *Glomus etunicatum*	30	75	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Caesalpinia peltophoroides*	120	*Gigaspora margarita*, *Glomus etunicatum*	33	48	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Cassia grandis*	120	*Gigaspora margarita*, *Glomus etunicatum*	63	71	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Copaifera langsdorffii*	120	*Gigaspora margarita*, *Glomus etunicatum*	–	−4	2 (Olsen)	Siqueira et al. (1998)

(continued)

Table 22.1 (continued)

Family	Species	Growth period (d)	Fungal species	Colonization (%)	MD (%)	Soil P (mg P/kg)	References
Caesalpinoideae	*Peltophorum dubium*	120	*Gigaspora margarita*, *Glomus etunicatum*	18	61	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Schizolobium parahyba*	120	*Gigaspora margarita*, *Glomus etunicatum*	8	−25	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Senna macranthera*	120	*Gigaspora margarita*, *Glomus etunicatum*	81	84	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Senna multijuga*	120	*Gigaspora margarita*, *Glomus etunicatum*	–	38	2 (Olsen)	Siqueira et al. (1998)
Caesalpinoideae	*Senna spectabilis*	120	*Gigaspora margarita*, *Glomus etunicatum*	17	85	2 (Olsen)	Siqueira et al. (1998)
					52		
Casuarinaceae	*Casuarina equisetifolia*	144	*Glomus geosporum*	45	55	0.34 (Olsen)	Muthukumar and Udaiyan (2010)
Cecropiaceae	*Cecropia pachystachya*	98	*Glomus etunicatum*	62	100	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Clusiaceae	*Clusia minor*	420	*Scutellospora fulgida*	100	99	3.05	Cáceres and Cuenca (2006)
Clusiaceae	*Clusia minor*	420	*Scutellospora fulgida*	75	−42	39	Cáceres and Cuenca (2006)
Clusiaceae	*Clusia multiflora*	180	*Scutellospora fulgida*	98	71	3.05	Cáceres and Cuenca (2006)
Clusiaceae	*Clusia multiflora*	180	*Scutellospora fulgida*	92	−21	39	Cáceres and Cuenca (2006)
					27		
Euphorbiaceae	*Croton floribundus*	101	*Glomus etunicatum*	48	92	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)

Euphorbiaceae	*Macaranga denticulata*	120	Indigenous	70	42	4.10 (Bray II)	Youpensuk et al. (2004)
					67		
Fabaceae	*Dalbergia sissoo*	111	*G. albida*, *G. intraradices*, *A. scrobiculata*	70	61	14.9 (Olsen)	Bisht et al. (2009)
Fabaceae	*Dalbergia sissoo*	111	*G. albida*, *G. intraradices*, *A. scrobiculata*	30	59	6.3 (Olsen)	Bisht et al. (2009)
Fabaceae	*Dialium guineensis*	90	*Glomus aggregatum*	50	45	6.6 (Bray-1)	Bá et al. (2000)
Fabaceae	*Leucaena diversifolia*	45	*G. aggregatum*	73	73	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Leucaena leucocephala*	45	*G. aggregatum*	76	79	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Leucaena leucocephala*	56	Mixture	98	77	4.22 (Bray II)	Saif (1987)
Fabaceae	*Leucaena retusa*	45	*G. aggregatum*	56	35	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Leucaena trichodes*	45	*G. aggregatum*	58	70	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Sesbania pubescens*	120	*G. aggregatum*	83	−69	4.8 (Olsen)	Duponnois et al. (2001)
Fabaceae	*Sesbania formosa*	45	*G. aggregatum*	75	24	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Sesbania grandiflora*	120	*G. aggregatum*	90	−4	4.8 (Olsen)	Duponnois et al. (2001)
Fabaceae	*Sesbania grandiflora*	45	*G. aggregatum*	80	35	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Sesbanica nubica*	120	*G. aggregatum*	97	−32	4.8 (Olsen)	Duponnois et al. (2001)
Fabaceae	*Sesbania pachycarpa*	45	*G. aggregatum*	54	17	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Sesbania paludosa*	120	*G. aggregatum*	79	59	4.8 (Olsen)	Duponnois et al. (2001)

(continued)

Table 22.1 (continued)

Family	Species	Growth period (d)	Fungal species	Colonization (%)	MD (%)	Soil P (mg P/kg)	References
Fabaceae	*Sesbania sesban*	45	*G. aggregatum*	70	14	0.02 mg/L	Manjunath and Habte (1991)
Fabaceae	*Tamarindus indica*	90	*Glomus aggregatum*	88	53	6.6 (Bray-1)	Bá et al. (2000)
					35		
Faboideae	*Platycyamus regnellii*	120	*Gigaspora margarita, Glomus etunicatum*	–	20	2 (Olsen)	Siqueira et al. (1998)
Faboideae	*Tipuana tipu*	120	*Gigaspora margarita, Glomus etunicatum*	75	74	2 (Olsen)	Siqueira et al. (1998)
					47		
Guttiferae	*Calophyllum hosei*	270	*Glomus aggregatum*	18	60	0.17	Turjaman et al. (2008)
Guttiferae	*Calophyllum hosei*	270	*Glomus clarum*	19	57	0.17	Turjaman et al. (2008)
Guttiferae	*Ploiarium alternifolium*	270	*Glomus aggregatum*	32	51	0.17	Turjaman et al. (2008)
Guttiferae	*Ploiarium alternifolium*	270	*Glomus clarum*	27	56	0.17	Turjaman et al. (2008)
					56		
Malvaceae	*Adansonia digitata*	90	*Glomus aggregatum*	63	8	6.6 (Bray-1)	Bá et al. (2000)
Melastomaceae	*Tibouchina granulosa*	144	*Glomus etunicatum*	20	100	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Meliaceae	*Azadirachta indica*	120	*Glomus geosporum*	25	8	N.D.	Muthukumar et al. (2001)
Meliaceae	*Azadirachta indica*	120	*Glomus intraradices*	28	20	N.D.	Muthukumar et al. (2001)
Meliaceae	*Azadirachta indica*	120	*G. geosporum, G. intraradices*	44	26	N.D.	Muthukumar et al. (2001)

Meliaceae	*Cedrela fissilis*	96	*Glomus etunicatum*	70	95	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Meliaceae	*Cedrela fissilis*	120	*Gigaspora margarita*, *Glomus etunicatum*	34	41	2 (Olsen)	Siqueira et al. (1998)
					38		
Mimosoideae	*Albizia lebbeck*	120	*Gigaspora margarita*, *Glomus etunicatum*	55	62	2 (Olsen)	Siqueira et al. (1998)
Mimosoideae	*Anadenanthera falcata*	120	*Gigaspora margarita*, *Glomus etunicatum*	11	81	2 (Olsen)	Siqueira et al. (1998)
Mimosoideae	*Leucaena leucocephala*	136	*Glomus etunicatum*	17	92	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Mimosoideae	*Parkia biglobosa*	90	*Glomus aggregatum*	68	32	6.6 (Bray-1)	Bá et al. (2000)
					67		
Myrsinaceae	*Myrsine umbellata*	111	*Glomus etunicatum*	52	98	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Myrtaceae	*Syzygium jambolanum*	120	*Gigaspora margarita*, *Glomus etunicatum*	50	91	2 (Olsen)	Siqueira et al. (1998)
Rhamnaceae	*Hovenia dulcis*	120	*Gigaspora margarita*, *Glomus etunicatum*	47	63	2 (Olsen)	Siqueira et al. (1998)
Rhamnaceae	*Zizyphus mauritiana*	90	*Glomus aggregatum*	98	78	6.6 (Bray-1)	Bá et al. (2000)
					71		
Rubiaceae	*Coffea arabica*	150	*Glomus clarum*	12	−15	3 (Olsen)	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Glomus clarum*	20	61	13	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Glomus clarum*	22	46	27	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Glomus clarum*	26	19	42	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Acaulospora mellea*	26	−31	3	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Acaulospora mellea*	50	55	13	Vaast et al. (1996)

(continued)

Table 22.1 (continued)

Family	Species	Growth period (d)	Fungal species	Colonization (%)	MD (%)	Soil P (mg P/kg)	References
Rubiaceae	*Coffea arabica*	150	*Acaulospora mellea*	32	16	27	Vaast et al. (1996)
Rubiaceae	*Coffea arabica*	150	*Acaulospora mellea*	22	−18	42	Vaast et al. (1996)
					17		
Sapindaceae	*Sapindus saponaria*	116	*Glomus etunicatum*	24	36	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Sapindaceae	*Aphania senegalensis*	90	*Glomus aggregatum*	40	21	6.6 (Bray-1)	Bá et al. (2000)
Sapindaceae	*Sapindus saponaria*	120	*Gigaspora margarita, Glomus etunicatum*	41	66	2 (Olsen)	Siqueira et al. (1998)
					41		
Thymelaeaceae	*Aquilaria filaria*	202	*Glomus clarum*	93	53	4.8	Turjaman et al. (2006)
Thymelaeaceae	*Aquilaria filaria*	202	*Glomus decipiens*	87	48	4.8	Turjaman et al. (2006)
					51		
Tiliaceae	*Heliocarpus appendiculatus*	180	Mixture*1	83	−47	N.D.	Guadarrama et al. (2004)
Tiliaceae	*Luehea grandiflora*	120	*Gigaspora margarita, Glomus etunicatum*	60	93	2 (Olsen)	Siqueira et al. (1998)
					23		
Ulmaceae	*Luehea grandiflora*	93	*Glomus etunicatum*	21	98	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Ulmaceae	*Trema micrantha*	70	*Glomus etunicatum*	32	98	1 (Mehlich I)	Siqueira and Saggin-Junior (2001)
Ulmaceae	*Trema micrantha*	120	*Gigaspora margarita, Glomus etunicatum*	64	92	2 (Olsen)	Siqueira et al. (1998)

					96		
Zygophyllaceae	*Balanites aegyptiaca*	90	*Glomus aggregatum*	52	0	6.6 (Bray-1)	Bá et al. (2000)
Average (all species)					50		

Average of MD of each family was also shown
Mixture*1: Sclerocystis, Acaulospora and Gigaspora

liana surveyed in Guyana, 137 were exclusively formed by AM fungi (McGuire et al. 2008). A light microscopy investigation showed arbuscular mycorrhizas in 112 tree species from 53 families on mineral as well as organic soils in Ecuador (Kottke et al. 2004). In a related study, a segment of fungal 18S rDNA was sequenced from the mycorrhizas of *Cedrela montana*, *Heliocarpus americanus*, *Juglans neotropica*, and *Tabebuia chrysantha* in reforestation plots from degraded pastures in Ecuador and observed distinct species-rich AM communities (Haug et al. 2010). Dual ectomycorrhizal and AM colonization was observed in 4 of 14 ectomycorrhizal tree species belonging to Caesalpiniaceae and Uapacaceae from rain forest in Cameroon (Moyersoen and Fitter 1999). In total, 193 glomeromycotan sequences were analyzed, 130 of them previously unpublished.

Spores of AM fungi have been isolated from soils of tropical forests and their population and richness were affected by environmental conditions. Spore density and richness based on soil cores were higher in the dry season than in the rainy season in a tropical sclerophyllous shrubland in the Venezuelan Guayana (Cuenca and Lovera 2010). Spore numbers of AM fungi were higher in young secondary forest and pastures and lower in pristine forest in the Amazon region (Sturmer et al. 2009), and AM fungal diversity was high in dry tropical Afromontane forests of Ethiopia (Wubet et al. 2009). AM fungal spores in soil decreased from an early plant succession to mature tropical forest in a Brazilian study (Zangaro et al. 2008). AM fungal types that were dominant in the newly germinated seedlings were almost entirely replaced by previously rare types in the surviving seedlings the following years (Husband et al. 2002a). As the seedlings matured in a tropical forest in the Republic of Panama, the fungal diversity decreased and there was a significant shift (Husband et al. 2002b). Based on spore morphology, 29 species of AM fungi were found in the rhizosphere of *Macaranga denticulata* (Youpensuk et al. 2004).

22.4 Inoculation of Tropical Tree Species with AM Fungi

AM fungi have been reported to increase growth of some tropical trees (Table 22.1). AM fungi increased seedling growth of 23 of 28 species from a lowland tropical rain forest in Costa Rica under nursery conditions (Janos 1980). AM colonization of the tropical tree *Oubanguia alata* (Scytopetalaceae) was positively correlated with increased P uptake despite low P availability in a study in Cameroon (Moyersoen et al. 1998). AM fungi improved growth of the Brazilian pine *Araucaria angustifolia* (Araucariaceae) (Zandavalli et al. 2004). There are also reports of improved growth of non-timber forest product tree species following AM fungal inoculation in tropical forests. For example, Muthukumar et al. (2001) reported that inoculation of *Azadirachta indica* (Meliaceae) with AM fungi improved seedling growth. Furthermore, the inoculation of AM fungi with phosphate-solubilizing and nitrogen-fixing bacteria increased the growth of *A. indica*. Conversely, *A. excelsa* inoculated with AM fungi (without fertilizer) grew more slowly than did the uninoculated plants (Huat et al. 2002). Kashyap et al. (2004) showed that inoculation of *Morus alba* (Moraceae) with both AM fungi and *Azotobacter* increased the survival percentage of saplings.

Clusia minor and *Clusia multiflora* inoculated with *Scutellospora fulgida* in acidic soil had greater shoot and root biomass, leaf area, and height in comparison to the biomass of P-fertilized plants and non-mycorrhizal plants (Cáceres and Cuenca 2006). Inoculation with the AM fungus *Glomus geosporum* improved the growth, nutrient acquisition, and seedling quality of *Casuarina equisetifolia* seedlings under nursery conditions (Muthukumar and Udaiyan 2010). Seedlings of *Araucaria angustifolia* inoculated with *Glomus clarum* had higher shoot biomass; leaf concentrations of P, K, Na, and Cu; and lower concentrations of Ca, Mg, Fe, Mn, and B than controls (Zandavalli et al. 2004). Inoculation with soil-containing AM fungi increased shoot growth nutrient contents when P was limiting but N was applied (Youpensuk et al. 2004). Inoculation with AM fungi *Glomus clarum* and *Gigaspora decipiens* increased shoot N and P uptake of non-timber forest product species *Dyera polyphylla* and *Aquilaria filaria* under greenhouse conditions, indicating that AM fungi can reduce the application of chemical fertilizer (Turjaman et al. 2006). Other studies have used mycorrhizal roots from individual tree species or from a mixture of the four trap species with resulting improvement in growth of 6-month-old *Cedrela montana* and *Heliocarpus americanus* (Urgiles et al. 2009). This latter technique is much easier to handle and has lower costs than spore production for tropical countries with limited facilities for storage of inoculum.

AM fungi increased the growth of *Acacia nilotica* and *Leucaena leucocephala* (Leguminosae) 12 weeks after transplantation under greenhouse conditions (Michelsen and Rosendahl 1990), and similar observations were made for three multipurpose fruit-tree species: *Parkia biglobosa*, *Tamarindus indica*, and *Ziziphus mauritiana* 2 months after inoculation (Guissou et al. 1998). The AM fungus *Glomus aggregatum* stimulated plant growth of 17 leguminous plants (Duponnois et al. 2001), and *Glomus macrocarpum* increased the growth of two species: *Sesbania aegyptiaca* and *S. grandiflora* (Giri et al. 2004). Some studies have successfully used mixed inocula of AM fungi including two (Bá et al. 2000), three (Adjoud et al. 1996), and nine species (Rajan et al. 2000).

Mycorrhizal dependency was calculated to compare the degree of plant growth change associated with AM colonization of 76 species, 25 families (Table 22.1). The average mycorrhizal dependency value of all the plants was 50 % (−69 Min. and 100 Max.). Mycorrhizal dependency was also different among families. It was higher in Ulmaceae and Bignoniaceae. Guissou et al. (1998) reported that mycorrhizal dependency of *Parkia biglobosa* and *Tamarindus indica* was similar, reaching no more than 36 %, while *Ziziphus mauritiana* showed higher mycorrhizal dependency values, reaching up to 78 %. A similar effectiveness of AM fungi for different plant species was also reported by Adjoud et al. (1996). Mycorrhizal dependency is frequently related to the morphological properties of the root of different plant species, and also root systems with only a few, short root hairs are indicative of a high mycorrhizal dependency of the plant species concerned (Baylis

1970). Responses of 12 native woody species to the inoculation of AM fungi were related to root morphological plasticity of the plant (Zangaro et al. 2007).

The survival rate of seedling stocks in the field is vital to reforestation. In one study, the survival rates of AM-inoculated cuttings of *Ploiarium alternifolium* and *Calophyllum hosei* were 100 % after 6 months (Turjaman et al. 2008). These values were higher than the survival rates of two tropical tree species from Panama inoculated with AM fungi, which were *Ochroma pyramidale* (97 %) and *Luehea seemannii* (52 %), respectively (Kiers et al. 2000). Inoculation with AM fungi can reduce the cost of seedling production for reforesting vast areas of disturbed tropical forests. Despite extensive studies of inoculation of tree species under controlled conditions, there are few reports about the effect of AM fungal inoculation on growth of tropical tree species under field conditions. Recently, Graham et al. (2013) showed that inoculation of *Glomus clarum* and *Gigaspora decipiens* increased N and P content of *Dyera polyphylla* under tropical peat swamp forest in Central Kalimantan, Indonesia.

22.5 Conclusion

Colonization of roots by AM fungi can improve growth of many tree species that occur in tropical forests. Survival rate of seedlings is a key measure of success in reforestation and afforestation. Survival rates of inoculated seedlings can be higher than those of non-inoculated seedlings. Inoculation with AM fungi at the nursery stage is a useful technique to include in large-scale reforestation programs. However, mycorrhizal dependency differs among plant species and with species of AM fungi. Therefore, selection of appropriate combination of plant species and fungal species is also important for reforestation programs.

References

Adjoud D, Plenchette C, Hallihargas R, Lapeyrie F (1996) Response of 11 eucalyptus species to inoculation with three arbuscular mycorrhizal fungi. Mycorrhiza 6:129–135

Bá AM, Plenchette C, Danthu P, Duponnois R, Guissou T (2000) Functional compatibility of two arbuscular mycorrhizae with thirteen fruit trees in Senegal. Agrofor Syst 50:95–105

Baylis GTS (1970) Root hairs and phycomycetous mycorrhizas in phosphorus-deficient soil. Plant and Soil 33:713–716

Bereau M, Barigah TS, Louisanna E, Garbaye J (2000) Effects of endomycorrhizal development and light regimes on the growth of Dicorynia guianensis Amshoff seedlings. Ann For Sci 57:725–733

Bisht R, Chaturvedi S, Srivastava R, Sharma AK, Johri BN (2009) Effect of arbuscular mycorrhizal fungi, Pseudomonas fluorescens and Rhizobium leguminosarum on the growth and nutrient status of Dalbergia sissoo Roxb. Trop Ecol 50:231–242

Cáceres A, Cuenca G (2006) Contrasting response of seedlings of two tropical species Clusia minor and Clusia multiflora to mycorrhizal inoculation in two soils with different pH. Trees 20:593–600

Cuenca G, Lovera M (2010) Seasonal variation and distribution at different soil depths of arbuscular mycorrhizal fungi spores in a tropical sclerophyllous shrubland. Botany 88:54–64

de Grandcourt A, Epron D, Montpied P, Louisanna E, Bereau M, Garbaye J, Guehl JM (2004) Contrasting responses to mycorrhizal inoculation and phosphorus availability in seedlings of two tropical rainforest tree species. New Phytol 161:865–875

Duponnois R, Plenchette C, Ba AM (2001) Growth stimulation of seventeen fallow leguminous plants inoculated with Glomus aggregatum in Senegal. Eur J Soil Biol 37:181–186

FAO (2001) The global forest resources assessment 2000. http://www.fao.org/docrep/meeting/003/X9835e/X9835e00.htm#P469_24024

Fenning TM, Gershenzon J (2002) Where will the wood come from? Plantation forests and the role of biotechnology. Trends Biotechnol 1–6

Giri B, Kapoor R, Agarwal L, Mukerji KG (2004) Preinoculation with arbuscular mycorrhizae helps Acacia auriculiformis grow in degraded Indian wasteland soil. Commun Soil Sci Plant Anal 35:193–204

Graham LL, Turjaman M, Page SE (2013) *Shorea balangeran* and *Dyera polyphylla* (syn. *Dyera lowii*) as tropical peat swamp forest restoration transplant species: effects of mycorrhizae and level of disturbance. Wetl Ecol Manag 21(5):307–321

Guadarrama P, Alvarez-Sanchez FJ (1999) Abundance of arbuscular mycorrhizal fungi spores in different environments in a tropical rain forest, Veracruz, Mexico. Mycorrhiza 8:267–270

Guadarrama P, Alvarez-Sanchez FJ, Briones O (2004) Seedling growth of two pioneer tree species in competition: the role of arbuscular mycorrhizae. Euphytica 138:113–121

Guissou T, Ba AM, Ouadba JM, Guinko S, Duponnois R (1998) Responses of Parkia biglobosa (Jacq.) Benth, *Tamarindus indica* L. and *Zizyphus mauritiana* Lam. to arbuscular mycorrhizal fungi in a phosphorus-deficient sandy soil. Biol Fertil Soils 26:194–198

Hattenschwiler S, Coq S, Barantal S, Handa IT (2011) Leaf traits and decomposition in tropical rainforests: revisiting some commonly held views and towards a new hypothesis. New Phytol 189:950–965

Haug I, Wubet T, Weiss M, Aguirre N, Weber M, Gunter S, Kottke I (2010) Species-rich but distinct arbuscular mycorrhizal communities in reforestation plots on degraded pastures and in neighboring pristine tropical mountain rain forest. Trop Ecol 51:125–148

Holford ICR (1997) Soil phosphorus: its measurement, and its uptake by plants. Aust J Soil Res 35:227–239

Huat OK, Awang K, Hashim A, Majid NM (2002) Effects of fertilizers and vesicular-arbuscular mycorrhizas on the growth and photosynthesis of *Azadirachta excelsa* (Jack) Jacobs seedlings. For Ecol Manag 158:51–58

Husband R, Herre EA, Turner SL, Gallery R, Young JPW (2002a) Molecular diversity of arbuscular mycorrhizal fungi and patterns of host association over time and space in a tropical forest. Mol Ecol 11:2669–2678

Husband R, Herre EA, Young JPW (2002b) Temporal variation in the arbuscular mycorrhizal communities colonising seedlings in a tropical forest. FEMS Microbiol Ecol 42:131–136

Janos DP (1980) Vesicular-arbuscular mycorrhizae affect lowland tropical rain forest plant growth. Ecology 61:151–162

Kashyap S, Sharma S, Vasudevan P (2004) Role of bioinoculants in development of salt-resistant saplings of *Morus alba* (var. sujanpuri) in vivo. Sci Hortic 100:291–307

Kiers ET, Lovelock CE, Krueger EL, Herre EA (2000) Differential effects of tropical arbuscular mycorrhizal fungal inocula on root colonization and tree seedling growth: implications for tropical forest diversity. Ecol Lett 3:106–113

Kobayashi S (2004) Landscape rehabilitation of degraded tropical forest ecosystems. Case study of the CIFOR/Japan project in Indonesia and Peru. For Ecol Manage 201:13–22

Kottke I, Beck A, Oberwinkler F, Homeier J, Neill D (2004) Arbuscular endomycorrhizas are dominant in the organic soil of a neotropical montane cloud forest. J Trop Ecol 20:125–129

Laurance WF (1999) Reflection on the tropical deforestation crisis. Biol Conserv 91:109–117

Manjunath A, Habte M (1991) Root morphological characteristics of host species having distinct mycorrhizal dependency. Can J Bot 69:671–676

McGuire KL, Henkel TW, de la Cerda IG, Villa G, Edmund F, Andrew C (2008) Dual mycorrhizal colonization of forest-dominating tropical trees and the mycorrhizal status of non-dominant tree and liana species. Mycorrhiza 18:217–222

Michelsen A, Rosendahl S (1990) The effect of VA mycorrhizal fungi, phosphorus and drought stress on the growth of Acacia nilotica and Leucaena leucocephala seedlings. Plant and Soil 124:7–13

Moreira FMD, de Carvalho TS, Siqueira JO (2010) Effect of fertilizers, lime, and inoculation with rhizobia and mycorrhizal fungi on the growth of four leguminous tree species in a low-fertility soil. Biol Fertil Soils 46:771–779

Moyersoen B, Fitter AH (1999) Presence of arbuscular mycorrhizas in typically ectomycorrhizal host species from Cameroon and New Zealand. Mycorrhiza 8:247–253

Moyersoen B, Alexander IJ, Fitter AH (1998) Phosphorus nutrition of ectomycorrhizal and arbuscular mycorrhizal tree seedlings from a lowland tropical rain forest in Korup National Park, Cameroon. J Trop Ecol 14:47–61

Moyersoen B, Becker P, Alexander IJ (2001) Are ectomycorrhizas more abundant than arbuscular mycorrhizas in tropical heath forests? New Phytol 150:591–599

Munyanziza E, Kehri HK, Bagyaraj DJ (1997) Agricultural intensification, soil biodiversity and agro-ecosystem function in the tropics: the role of mycorrhiza in crops and trees. Appl Soil Ecol 6:77–85

Muthukumar T, Udaiyan K (2010) Growth response and nutrient utilization of Casuarina equisetifolia seedlings inoculated with bioinoculants under tropical nursery conditions. New For 40:101–118

Muthukumar T, Udaiyan K, Rajeshkannan V (2001) Response of neem (Azadirachta indica A. Juss) to indigenous arbuscular mycorrhizal fungi, phosphate-solubilizing and asymbiotic nitrogen-fixing bacteria under tropical nursery conditions. Biol Fertil Soils 34:417–426

Plassard C, Dell B (2010) Phosphorus nutrition of mycorrhizal trees. Tree Physiol 30:1129–1139

Rajan SK, Reddy BJD, Bagyaraj DJ (2000) Screening of arbuscular mycorrhizal fungi for their symbiotic efficiency with Tectana grandis. For Ecol Manage 126:91–95

Saif SR (1987) Growth-responses of tropical forage plant-species to vesicular-arbuscular mycorrhizae. I. Growth, mineral uptake and mycorrhizal dependency. Plant and Soil 97:25–35

Siqueira JO, Saggin-Junior OJ (2001) Dependency on arbuscular mycorrhizal fungi and responsiveness of some Brazilian native woody species. Mycorrhiza 11:245–255

Siqueira JO, Saggin-Junior OJ, Flores-Aylas WW, Guimaraes PTG (1998) Arbuscular mycorrhizal inoculation and superphosphate application influence plant development and yield of coffee in Brazil. Mycorrhiza 7:293–300

Sturmer SL, Leal PL, Siqueira JO (2009) Occurrence and diversity of arbuscular mycorrhizal fungi in trap cultures from soils under different land use systems in the Amazon, Brazil. Braz J Microbiol 40:111–121

Tawaraya K, Takaya Y, Turjaman M, Tuah SJ, Limin SH, Tamai Y, Cha JY, Wagatsuma T, Osaki M (2003) Arbuscular mycorrhizal colonization of tree species grown in peat swamp forests of Central Kalimantan, Indonesia. For Ecol Manage 182:381–386

Torti SD, Coley PD, Janos DP (1997) Vesicular-arbuscular mycorrhizae in two tropical monodominant trees. J Trop Ecol 13:623–629

Turjaman M, Tamai Y, Santoso E, Osaki M, Tawaraya K (2006) Arbuscular mycorrhizal fungi increased early growth of two nontimber forest product species Dyera polyphylla and Aquilaria filaria under greenhouse conditions. Mycorrhiza 16:459–464

Turjaman M, Tamai Y, Sitepu IR, Santoso E, Osaki M, Tawaraya K (2008) Improvement of early growth of two tropical peat-swamp forest tree species *Ploiarium alternifolium* and

Calophyllum hosei by two arbuscular mycorrhizal fungi under greenhouse conditions. New For 36:1–12

Urgiles N, Lojan P, Aguirre N, Blaschke H, Gunter S, Stimm B, Kottke I (2009) Application of mycorrhizal roots improves growth of tropical tree seedlings in the nursery: a step towards reforestation with native species in the Andes of Ecuador. New For 38:229–239

Vaast P, Zasoski RJ, Bledsoe CS (1996) Effects of vesicular-arbuscular mycorrhizal inoculation at different soil P availabilities on growth and nutrient uptake of in vitro propagated coffee (Coffee arabica L) plant. Mycorrhiza 6:493–497

Whitmore TC (1989) Southeast Asian tropical forests. In: Leith H, Werger MJA (eds) Biogeographical and ecological studies. Ecosystems of the world 14B: tropical rain forest ecosystems. Elsevier, Amsterdam, pp 195–218

Wubet T, Kottke I, Teketay D, Oberwinkler F (2009) Arbuscular mycorrhizal fungal community structures differ between co-occurring tree species of dry Afromontane tropical forest, and their seedlings exhibit potential to trap isolates suited for reforestation. Mycol Prog 8:317–328

Youpensuk S, Lumyong S, Dell B, Rerkasem B (2004) Arbuscular mycorrhizal fungi in the rhizosphere of Macaranga denticulata Muell. Arg., and their effect on the host plant. Agrofor Syst 60:239–246

Zandavalli RB, Dillenburg LR, de Souza PVD (2004) Growth responses of *Araucaria angustifolia* (Araucariaceae) to inoculation with the mycorrhizal fungus *Glomus clarum*. Appl Soil Ecol 25:245–255

Zangaro W, Nishidate FR, Vandresen J, Andrade G, Nogueira MA (2007) Root mycorrhizal colonization and plant responsiveness are related to root plasticity, soil fertility and successional status of native woody species in southern Brazil. J Trop Ecol 23:53–62

Zangaro W, de Assis RL, Rostirola LV, Souza P, Goncalves MC, Andrade G, Nogueira MA (2008) Changes in arbuscular mycorrhizal associations and fine root traits in sites under different plant successional phases in southern Brazil. Mycorrhiza 19:37–45