EFFECTS OF FUNGICIDES ON MYCORRHIZAL FUNGI AND ROOT COLONIZATION

Introduction:

When wishing to encourage root colonization by natural or applied mycorrhizal fungi inoculants, it is important to consider what effect any planned fungicide treatments may have on this goal. Mycorrhizal fungi can be quite sensitive to certain fungicides, but by no means all of them. Moreover, sensitivity can be influenced by the method of application of the fungicide. Some fungicides may actually stimulate mycorrhizal fungi, while others may be detrimental.

PHC has reviewed the available literature in this field and has compiled the following lists of fungicides for which published data exists regarding their effect on mycorrhizal fungi. The detailed data tables and references are provided later in this document. Furthermore, based on field tests, PHC has composed some general rules regarding fungicide use in this context. These rules are presented here:

General Rules Regarding Use of Fungicides with Mycorrhizal Fungi Inoculants:

1. Typically, **foliar application of *non-systemic* fungicides** (applied at label rates) has very little impact on mycorrhizal fungi, which reside on the roots. Even though some fungicide material may reach the soil, the amount reaching the actual root zone is usually too low to have any significant, long-term effect on mycorrhizal fungi.

2. **Soil drench applications of *non-systemic* fungicides** (applied at label rates) can be detrimental to mycorrhizal fungi particularly if applied before root colonization takes place. This method places the greatest fungicidal load at the root zone and is therefore the method most likely to cause harm to mycorrhizal fungi. Because of this, it is important to avoid using soil drench fungicides too close to inoculation time. Once spores have thoroughly colonized the roots, mycorrhizal fungi tend to be less sensitive to detrimental, ***non-systemic*** fungicides applied by soil drench because:

    a. fungicide levels will be high in the soil, but tend to be considerably lower inside root tissue.
    b. high levels of fungicides in soil can kill off fungal tissue in the soil, but not fungal tissue embedded inside the root.
    c. when fungicide levels in soil diminish from leaching or gradual degradation, fungal tissue inside the root will grow a new absorbing network out into the soil to restore the mycorrhizal effect.

3. Foliar or soil applications of **systemic fungicides** can lead to accumulation of fungicide in the root tissue having a negative impact on mycorrhizal fungi. In general, roots of treated plants are not susceptible to colonization by mycorrhizal fungi for up to 3 weeks after systemic fungicide treatment.

4. In general, **fungicidal seed treatment** effects on mycorrhizal colonization are minor and inconsistent across species. Even though some fungicides have been shown to have deleterious effects when applied as a soil drench, it appears that the low rates needed for seed treatment dissipate sufficiently to allow for root colonization during early growth.

Summary of Fungicide Use with Mycorrhizal Fungi:

1. **Foliar *non-systemic*** fungicides typically can be used at any time.

2. Avoid using **soil drench** fungicides too close to the time of inoculation, that is, two weeks before inoculation (longer if systemic) and four weeks after inoculation.

3. **Seed treatment** fungicides are generally safe due to the low rates used and rapid dissipation in the soil and roots.

4. **No fungicides eradicate either target fungi or mycorrhizae;** they only decrease development for a short time after application. The duration of this effect depends on the length of time for which the chemical persists in the environment.

Please continue overleaf to data tables and references.

REVIEW OF PUBLISHED DATA ON SPECIFIC FUNGICIDAL EFFECTS ON MYCORRHIZAL FUNGI AND ROOT COLONIZATION:

PHC has compiled, from published data, the following lists of fungicidal effects on mycorrhizal fungi.

1. In this data summary, seed treatments are considered separately from all other applications, and effects on vesicular-arbuscular mycorrhizae (VAM) and ectomycorrhizae are also listed separately.

2. The data is tabulated alphabetically by fungicidal a.i.

3. The reported effects are classified as either positive (P), no effect (O) or negative (N) and in each case a number signifying the reference is provided as a superscript to the letter. The complete list of references is provided at the foot of each Table.

TABLE 1: Reported Effects of <u>Seed Treatment</u> Fungicides on Vesicular Arbuscular Mycorrhizae and Root Colonization:

FUNGICIDE A.I.	EFFECT	COMMENTS
Azoxystrobin [strobilurin]	**O**[X]	In corn, soybeans and wheat
Carbendazim [benzimidizole]	N[3]	In peanuts
Captan [phthalimide]	**O**[1]	In zucchini and corn captan reduced root colonization [albeit inconsistently] but did not do so at all in tomato.
Emisan [MEMC mercuric]	N[3]	In peanuts
Fludioxonil [phenylpyrrole]	**P**[2]/**P**[4]	In soybeans
Fludioxonil + Mefenoxam	N[2]/**P**[4]	In soybeans
Copper oxychloride	**P**[3]	In peanuts
Mancozeb [dithiocarbamate]	N[3]	In peanuts
Mefenoxam [acylalanine]	**O**[1]/N[2]/**0**[4]	N in soybeans only.
Metalaxyl [acylalanine]	**O**[X]	In corn, soybeans and wheat
Tebuconazole [triazole] + Metalaxyl	**O**[1]	In corn, tomato, zucchini and muskmelon
Thiram [dithiocarbamate]	**O**[1]/N[3]	O in corn and muskmelon, N in peanuts
Ziram [dithiocarbamate]	N[3]	In peanuts

TABLE 1: Commentary:

From this table it is clear that most of the modern, widely used seed treatment fungicides are safe for VAM fungi, having zero or even positive effects on mycorrhizal colonization.

The exceptions, those reported as having negative effects, tend to be older fungicides, most of which are not in common use for seed treatments today, having been replaced by the more modern fungicides. Mancozeb, thiram and ziram are all dithiocarbamates so, as a group, these appear to be deleterious to mycorrhizal fungi, at least when tested in peanuts but thiram was not deleterious in corn or muskmelon. Emisan (a mercuric treatment) and carbendazim [a benzimidazole] were both negative for mycorrhizal fungi but again, have only been tested in peanuts. Copper, however appeared to provide a stimulus to mycorrhizae in peanuts. Captan (a phthalimide) reduced root colonization inconsistently in corn and zucchini but not in tomato.

Neutral or positive effects have generally been recorded for azoxystrobin [strobilurin], fludioxonil [phenylpyrrole], mefenoxam and metalaxyl [acylalanines], tebuconazole [triazole]and thiram (in corn) and these materials are in very common use in seed treatments in major crops today. Negative mycorrhizal responses to mefenoxam in soybeans have been reported but not in other crops. This is consistent with some mixed reports for metalaxyl on mycorrhizal fungi so some crop, or mycorrhizal species, effects may be in play here.

TABLE 1: Reference Listing:

1. Rhoda L. Burrows & Ismael Ahmed. 2007. Fungicide seed treatments minimally affect Arbuscular-Mycorrhizal Fungi (AMF) colonization of selected Vegetable crops. J Biol Sci 7 (2): 417-420.
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3. Sugavanam V *et al*. 1994. Effect of fungicides on Vesicular-Arbuscular Mycorrhizal infection and nodulation in Groundnut (*Arachis hypogeal L.*). Agriculture, ecosystems & environment 48 (3): 285-293.
4. Adrianna Murillo-Williams & Palle Pedersen. Effect of fungicide seed treatments on mycorrhizal colonization of soybean (*Glycine max L.*). Dept of Agronomy, Iowa State University.
   Poster from: Soybean Extension and Research Program, Department of Agronomy, Iowa State University (www.soybeanmanagement.info).
   http://extension.agron.iastate.edu/soybean/documents/Adriana.pdf

X. Plant Health Care Inc. – Unpublished Internal Studies.

Please continue overleaf to Tables 2 and 3.

TABLE 2: Reported Effects of Fungicides on Vesicular Arbuscular Mycorrhizae and Root Colonization [applied other than as seed treatments]:

FUNGICIDE A.I.	EFFECT	COMMENTS
Azoxystrobin [strobilurin]	0[5]/0[6]/0[7]/0[22]	N[22] as soil drench
Benomyl [benzimidazole]	N[8]/0[10]/N[11]/N[14]/N[16]/0[18] /N[21]/N[23]/N[24]	N[8]as soil drench/ N [10]at high dose/P[24] on cotton
Captafol [phthalimide]	P[24]	
Captan [phthalimide]	N[6]/N[7]/N[8]/0[16]/0[18]/N[21]/P[24]	N[8] as soil drench/N[24] on onion & maize
Carbamate [carbamate]	0[7]/N[16]/0[21]	N[7] at high rate
Carbendazim [benzimidazole]	0[7]/0[16]/N[19]/0[21]/0[24]	N[7] at high rate/N[24] on wheat
Carbendazim + Iprodione [dicarboxamide]	0[20]	
Carboxin [carboxamide]	N[7]/N[21]/N[24]	
Chloroneb [aromatic hydrocarbon]	0[7]/0[6]/0[21]	N[6,7] at high rate in both studies
Chloronitropropane [chloronitrile]	N[17]/N[24]	Ref within 17, not trial
Chloropicrin [aromatic hydrocarbon]	N[24]	
Chlorothalonil [chloronitrile]	0[6]/0[7]/N[14]/N[15]/N[16]/0[21]/P[24]	N[7] at high rate/N[15]as soil drench
Copper Oxychloride Sulfate	N[7]/N[21]	
Cyproconazole + propiconazole [triazoles]	N[7]/0[18]/N[19]/N[21]	
Dichlorfluanid [sulfamide]	0[18]/N[24]	
Dicloran [aromatic hydrocarbon]	N[17]/N[24]	Ref within 17, not trial
Difolatan [carboxamide]	0[7]/0[21]	N[7] at high rate
Ethirimol [hydroxy pyrimidine]	0[19]	
Fenaminosulf [unclassified]	0[21]	
Fenarimol [pyrimidine]	0[6]/0[7]	
Fenhexamid [hydroxyanilide]	O[25]	
Fenpropimorph [morpholine]	N[25]/0[23]	N[23] @100x rec. dose
Fludioxonil [phenylpyrrole]	0[X2]	

TABLE 2: continued

FUNGICIDE A.I.	EFFECT	COMMENTS
Folpet [phthalimide]	N[6]/N[7]/N[21]	
Fosetyl-aluminum [phosphonate]	0[6]/N[7]/ O[16]/P[18]/N[21]/0[24]	
Iprodione [dicarboxamide]	0[6]/0[7]/N[11]/0[21]	N[7] at high rate
Kresoxim-methyl [triazole]	0[22]	N[22] as soil drench
Mancozeb [dithiocarbamate]	0[6]/N[7]/P[13]/0[18]/0[21]	0[13] and N[13] at mid and high dose
Maneb [dithiocarbamate]	O[21]/P[24]	
Metalaxyl [acylalinine]	0[6]/0[7]/0[10]/0[16]/P[17]/N[21]/P[24]	N[7] at high rate/ P[17]soil treatment/N [24] on leek
Oxime benzoate [unclassified]	O[21]	
Paclobutrazol [triazole]	0[12]	
PCNB [aromatic hydrocarbon]	0[6]/N[7]/N[16]/N[21]	0[6]At low dose
Prochloraz [imidazole]	N[19]/N[24]	
Propiconazole [triazole]	N[6]/N[7]/N[19]/N[21]/N[23]/N[24]	
Prothiocarb [carbamate]	P[24]	
Pyrazophos [phosphoro-thiolate]	P[9]	
Pyroxychlor [pyridine]	P[24]	
Quintozene [aromatic hydrocarbon]	N[24]	
Sulfur compounds	0[7]/O[21]	
Tebuconazole [triazole]	0[5]	
Terrazole [thiadiazole]	N[7]/N[21]/P[24]	
Thiabendazole [benzimidazole]	0[7]/0[21]	N[7] at high rate
Thiazole [carboxamide]	N[6]/N[7]	
Thiophanate methyl [thiophanate]	0[6]/0[7]/0[18]/N[21]/O[21]	
Thiophanate-methyl + Etridiozole [thiophanate + thiazole]	N[7]	
Thiram [carbamate]	0[6]/0[7]/0[18]/0[21]/N[24]	
Triadimefon [triazole]	N[6]/N[7]/P[9]/N[16]/0[18]/N[21]/N[24]	
Triadimenol [triazole]	N[7]	
Tridemorph [morpholine]	P[19]	
Triforine [piperazine]	0[7]/O[21]	N at[7] high rate

TABLE 2: Commentary:

The Table above can best be summarized by listing the fungicide classes that have provided a neutral or positive result compared with those with negative reports. These divisions can be further divided into those with multiple or single results. Such a summary follows:

TABLE 2: Breakdown of Reports by Fungicide Classes and Number of Reports:

	No. of compounds in given class with:				
	Multiple Reports			Single Reports	
Fungicide Classes	Neutral/ Positive	Even	Negative	Neutral/ Positive	Negative
acylalanines	1				
aromatic hydrocarbons	1		2		2
benzimidazoles	2		1		
carbamates/dithiocarbamates	4			1	
carboxamides/ dicarboxamides	2		2	1	
chloronitriles	1		1		
copper compounds			1		
fenaminosulf				1	
hydroxyanilides				1	
imidazoles			1		
morpholines		1		1	
oxine benzoate				1	
phenylpyrroles				1	
phosphonates	1				
phosphoro-thiolates				1	
phthalimides			2	1	
piperazines	1				
pyrimidines / OH-pyrimidines	1			1	
pyridines				1	
strobilurins	1				
sulfamides		1			
sulfur compounds	1				
thiadiazoles			1		
thiazoles			1		1
thiophanates	1				
triazoles			2	3	1

This breakdown enables some broad generalizations to be made as follows:

- the preponderance of evidence presented above indicate that the following classes are likely safe for use where mycorrhizal colonization and survival is an important criterion; acylalanines, benzimidazoles, carbamates/dithiocarbamates, fenaminosulf, hydroxyanilides, morpholines, oxine benzoate, phenylpyrroles, phosphonates, phosphoro-thiolates, piperazines, pyrimidines and hydroxy-pyrimidines, pyridines, strobilurins, sulfur compounds and thiophanates. It is noteworthy that dithiocarbamates were more deleterious in the seed treatment analysis above. Most of that data was however from peanuts only and perhaps either peanuts, or the mycorrhizal strains used in those tests are particularly susceptible to dithiocarbamates.

- the preponderance of evidence presented above indicate that the following classes may be detrimental to mycorrhizal colonization and survival; aromatic hydrocarbons, copper compounds, imidazoles, phthalimides, thiadiazoles and thiazoles

- for the following classes the data is split between positive and neutral versus detrimental effects; carboxamides/ dicarboxamides, chloronitriles and sulfamides

- a final class, the triazoles is a large and important class that requires some further examination in respect of the different application methods. Within this class tebuconazole, which is an important seed treatment fungicide was reported as having no negative effects on mycorrhizae whether applied by seed treatment (Table 1) or, as seen in Table 2, when sprayed on the crop. Propiconazole however, as seen in Table 2, has proven almost uniformly detrimental to mycorrhiza. Incidentally this triazole is not in common use a seed treatment. Of other triazoles, paclobutrazol and kresoxim-methyl (except when applied as a soil-drench) appeared to be neutral to mycorrhizae but triadimenol had one negative report. The several reports on triadimefon were mixed. Overall the triazoles appear mixed in their effects on mycorrhizae but as with other materials they do appear to be safe at the lower rates used for seed treatment.

TABLE 2: Reference Listing:

5. Martina S. Girvan *et al*. 2004. Responses of active bacterial and fungal communities in soils under winter wheat to different fertilizer and pesticide regimes. Applied and Environmental Microbiology 70 (5): 2692-2701.
6. Mycorrhizal Applications Inc. Effects of Turf & Ornamental Fungicides on Mycorrhizal Fungi. http://www.mycorrhizae.com/index.php?cid=396&
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11. Pomology Lab, Kyoto University. Vesicular-Arbuscular mycorrhizae. http://bio.kpu.ac.jp/pomlab/Vaminf.html

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13. Saleh M. Saleh Al-Garni. 2006. Influence of Malathion and Mancozeb on Mycorrhizal colonization and growth of *Zea mays* and *Vicia faba*. World Journal of Ag Sci 2 (3): 303-310.
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15. M. Habte, T. Aziz, J.E. Yuen. 2006. Residual toxicity of soil-applied chlorothalonil on mycorrhizal symbiosis in *Leucaena leucocephala.* Plant and Soil 140 (2): 263-268.
16. A. Clesen. Becker Underwood Inc. Rhizanova™ Power point presentation http://www.arthurclesen.com/resources/Rhizanova.ppt
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20. Patton Fertilizers 2005. Mycorrhizal fungi in Turf. http://www.paton.com.au/Research/Turf/Organic/mychorizal%20fungi.pdf
21. F.T. Davies Jr. 2000. How Mycorrhizal fungi can benefit nursery propagation and production systems. Department of Horticultural Science. Texas A&M. Online at: http://www.ipps.org/SouthernNA/pdf/2008papers/Davies-Fred.pdf or in print at: Davies, FT. Benefits and Opportunities with Mycorrhizal Fungi in Nursery Propagation and Production Systems. Combined Proceedings International Plant Propagators' Society 50: 482-489.
22. P.M. Diedhiou, E.C. Oerke, H.W. Dehne. 2004. Effects of strobilurin fungicides azoxystrobin and kresoxim-methyl on arbuscular mycorrhiza. Zeitschrift fur Pflanzenkrankheiten und Pflanzenaschutz 111 (6). http://www.cababstractsplus.org/abstracts/Abstract.aspx?AcNo=20053018326
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X2. Plant Health Care inc. – Unpublished Internal Studies.

Please continue overleaf to Table 3.

TABLE 3: Reported Effects of Fungicides on Ectomycorrhizal Fungi and Root Colonization:

FUNGICIDE A.I.	EFFECT	COMMENTS
Azoxystrobin [strobilurin]	0[1]	
Benodamil [analide]	N[1]/N[11]	
Benomyl [benzamidizole]	0[2]/P[4]/N[5]/0[8]/P[11]	N[2] above 100 µg/g
Captan [phthalimide]	0[1]/0[2]/P[4]/P[5]/0[8]/P[11]	N[1] at high rate/N[2] above 100 µg/g
Carbamate [carbamate]	0[8]	
Carbendazim [benzamidizole]	0[8]	
Chloroneb [aromatic hydrocarbon]	N[1]	
Chlorothalonil [chloronitrile]	0[1]/ N[3]/N[8]/N[9]	N[1] at high rate
Difolatan [carboxamide]	0[8]	
Etridiazole [thiazole]	N[1]	
Fenaminosulf [unclassified]	N[1]	
Folpet [phthalimide]	0[8]/N[1]	
Fosetyl-Aluminum [phosphonate]	0[1]/0[8]	
Fuberidizole [benzamidizole]	0[8]	
Hymexazol [isoxazole]	N[2]	
Iprodione [dicarboxamide]	0[10]	0[10] as seed treatment
Mancozeb [dithiocarbamate]	N[1]/ N[8]	
Maneb [dithiocarbamate]	N[1]/P[9]	
Metalaxyl [acylalanine]	0[1]/0[8]	
Paclobutrazol [triazole]	0[7]	
PCNB [aromatic hydrocarbon]	N[1]/ N[8]/0[11]	
Propamocarb [carbamate]	0[2]	
Propiconazole [triazole]	N[3]/N[9]	
Thiazole [carboxamide]	0[1]	N[1] at high rate
Thiophanate methyl [thiophanate]	0[8]	
Thiophanate-methyl + Etridiozole [thiophanate + thiazole]	N[1]/N[8]	
Thiram [carbamate]	N[1]/0[2]/0[8]	N[2] above 100µg/g
Triadimefon [triazole]	N[1]/ N[4]/N[6]/N[8]	

TABLE 3: continued		
FUNGICIDE A.I.	**EFFECT**	**COMMENTS**
Zinc oxide [unclassified]	N[1]	
Zineb [dithiocarbamate]	0[1]/ N[8]	N[1] at high rate
Ziram [dithiocarbamate]	N[1]	

TABLE 3: Commentary:

A review of the data presented above enables the following broad generalizations to be made:

- the preponderance of evidence presented above indicate that the following classes are likely safe for use where ectomycorrhizal root colonization and survival is an important criterion; acylalanines, benzimidazoles, carbamates, carboxamides/dicarboxamides, phosphonates, phthalimides, strobilurins, and thiophanates.

- the preponderance of evidence presented above indicate that the following classes may be detrimental to mycorrhizal colonization and survival; analides, aromatic hydrocarbons, chloronitriles, fenaminosulf, isoxazoles, phthalimides, thiazoles and zinc oxide.

- for the following classes the data is split between positive and neutral versus detrimental effects; dithiocarbamates and triazoles. Of the triazoles it is noteworthy that paclobutrazol was reported as neutral to ectomycorrhizae whilst propiconazole and triadmefon were reported as negative. This is the same result as for the VAM fungi.

TABLE 3: Reference Listing:

1. Mycorrhizal Applications Inc. Effects of Turf & Ornamental Fungicides on Mycorrhizal Fungi. http://www.mycorrhizae.com/index.php?cid=396&
2. G. Diaz, C. Carrillo, M. Honrubia. 2003. Differential responses of ectomycorrhizal fungi to pesticides in pure culture. Cryptogamie Mycologie 24(3): 199-211.
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August, 2009.