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Contents

mycorrhizae through crop and soil management practices
S P Wani, K K Lee 1

Research findings 8

New approaches 10

New publications 11

News from members ....

Recent references ....

Centre for Mycorrhizal Culture Collection (CMCC) ....

About Mycorrhiza Network and CMCC

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Exploiting vesicular–arbuscular mycorrhizae through crop and soil management practices

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S P Wani, K K Lee
International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India

...cular mycorrhizal (VAM) fungi are ubiquitous in natural ecosystems. These fungi form mutualistic symbiosis with most agricultural crops, and enhance plant growth. However, the question generally asked is—Do VAM fungi have a role in managed ecosystems? And if so, can this mutualistic association be exploited for economic or environmental benefits? Exploiting VAM fungi for practical agriculture is not common, mainly because researchers usually consider inoculation as the best option for increasing the population of beneficial microorganisms in the rhizosphere. For example, much VAM research has aimed at developing new mycorrhizal strains, and new inoculation techniques to replace or reinforce the indigenous VAM population. However, rhizosphere is complex, and establishing the introduced organisms in the desired numbers is generally difficult except in specific situations even for those organisms that can be introduced in large numbers in the rhizosphere, e.g., *Rhizobium*, *Azotobacter*, and *Azospirillum* (Wani, Lee 1992a; Wani, Rupela, Lee 1994). In spite of considerable research on the large-scale production of VAM fungi, inoculation on a field scale is not yet possible. Currently, commercial uses of VAM fungi are limited to special situations where natural populations have been destroyed, e.g., in sterilized growth media in greenhouses, and in the rehabilitation of strip mines (Menge 1983; Chang 1994). Though it is possible to manipulate indigenous populations of VAM fungi by means of appropriate crop and soil management practices, little systematic work has been done in this area. This report examines the effect of such management practices as fallowing, tillage, cropping pattern, fertilizers, and pesticides on mycorrhizal association with crop plants after identifying management practices to exploit mycorrhizal associations and thereby increase crop production.

Management practices

Fallowing

Fallowing, in which land is left uncropped for one or more seasons, is a common practice in many agricul-

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tural systems. In some cases, weeds are allowed to grow during fallowing, which are grazed by livestock. In many dryland agricultural systems, either the land is kept weed-free to conserve moisture and nutrients or the climate is such that no plants grow unless supported by irrigation. In many tropical countries, after the rainy-season crop is harvested, no other crop can be grown because of the low water-storing capacity of the soils. The soil temperatures are also high, reaching up to 46–48 °C during the dry summer period. At the ICRISAT Asia Center, India, it has been observed that keeping the Alfisols fallow for 6–8 months after harvesting the rainy-season crop reduced the number of VAM spores in the soil. In an experiment to study different cropping systems, it was found that VAM spores decreased from 31 to 24/gm soil after harvesting castor and before sowing the next crop in June (Resource Management Program, ICRISAT 1992). Such a decrease in VAM spores may affect the colonization of the next crop by VAM fungi. Fallowing leads to a decline in the inoculum in soil and in VAM colonization of the succeeding crop by VAM fungi (Black, Tinker 1979). In Australia, the long-fallow disorder in Vertisols has been traced to the decline in VAM inoculum due to fallowing (Thompson 1987). This problem affects a range of species which show stunted growth because of a deficiency of phosphorus or zinc, depending on the extent to which the plants are dependent on mycorrhiza.

Table 1. Number of VAM spores in soil samples from the plots under different cropping systems during 1991–1993.

Treatment	No. of VAM spores/gm soil	
	1991	1993
Sorghum (S) intercropped with pigeonpea (PP) (4:1 proportion) followed by castor (C) during second year (S/PP-C)	24	36
Sole castor (C) followed by S/PP; (C-S/PP)	20	33
Four rows of groundnut (G) intercropped within one row of pigeonpea (PP) followed by sole castor (C) during second year (G/PP-C)	21	31
Sole castor (C) followed by G/PP (C-G/PP)	25	38
Sole pigeonpea (PP) followed by sole castor during second year (PP-C)	29	34
SE±	2.31	
Mean	24	34
SE±	1.03	

Cropping pattern

Cropping builds up the inoculum of VAM fungi in soil as these fungi are obligate symbionts. Since crop species differ in their ability to form associations with VAM fungi, inclusion of appropriate crops in the cropping pattern can be expected to help raise the population of VAM fungi in soil. Inclusion of such a non-mycorrhizal crop as *kale* or mustard in the rotation reduced the mycorrhizal colonization of the succeeding barley crop to the same extent as fallowing (Black, Tinker 1979; Bagyaraj 1994). Continual mono-cropping frequently leads to declining yields. It has been suggested that reduced mycorrhizal colonization may have a role in such decreasing yields (Fyson, Oaks 1990; Wani, McGill, Tewari 1991). In Alfisols, roots of castor and sorghum were infected to a greater extent by VAM (58–62%), compared to those of groundnut and pigeonpea. Not only the percentage of root colonization by VAM fungi was greater in castor but the number of VAM spores was also higher, compared to groundnut and pigeonpea (Wani, Lee 1992b). During the third year of cropping in this experiment, the number of VAM spores in surface-soil samples (0–30 cm) also increased (34/gm soil) in the samples collected prior to the 1993 sowing, compared to 24 spores/gm soil in the samples collected prior to the 1991 sowing from the same plots (Table 1). In this experiment, all the cropping systems included castor and, as reported earlier, castor roots were heavily infected (62%) by VAM fungi (Wani, Lee 1992). Some plant species, e.g., castor in our studies, may have other properties that make them superior sources of VAM spores. Harinikumar and Bagyaraj (1989) showed that cropping with groundnut resulted in higher VAM colonization, sporulation, and infective propagules in the soil than cropping with cowpea and finger millet. These beneficial effects were carried over to the next season when sunflower was grown. These studies indicate that inclusion of an appropriate crop in crop rotations or intercropping can increase the native population of VAM fungi in soil, which is often the objective of artificial inoculation. However, it must be realized that soil microbial population comprises of many groups including root pathogens, the populations of which may also respond to the previous crop.

In a long-term crop rotation trial conducted at the ICRISAT Asia Center, India, the population of the cyst nematode, *Heterodera cajani*, under pigeonpea-based cropping system was twice to four times than in the cropping systems without pigeonpea (S B Sharma, personal communication). This point needs to be considered carefully while selecting the crops in a cropping system. It is important to know the common pathogens and their host-ranges. Some crop species may exert allelopathic effects that reduce the yield of the succeeding crop. It must be emphasized here that there is a need to take a systems approach while dealing with cropping patterns and to consider all possible effects, both positive and negative, of a particular crop while manipulating the populations of VAM fungi through crop rotations. The wide host-range of VAM fungi, compared to that of most pathogens, enables rotations to be devised that maintain VAM fungi at high levels for mycorrhiza-dependent crops but pathogens at low levels for susceptible crops.

Tillage

Tillage operations disturb the soil and change its physical, chemical, and biological properties, thereby affecting the growth and distribution of roots. Excessive secondary tillage and traffic increased soil bulk density, and decreased VAM colonization in common bean (Mulligan, Smucker, Safir 1985).

At the ICRISAT Asia Center, in a long-term experiment, effect of soil management practices on soil properties, soil processes, and crop productivity is being studied since 1987. In this experiment, three tillage treatments (tillage-depth of 0, 10, and 20 cm) along with three amendment treatments [no amendment (bare), 15t/ha farmyard manure, and 5t/ha paddy straw mulch each year] are tested on an annual cereal crop. All tillage operations are conducted only prior to sowing; no tillage operations are conducted in a standing crop growth. In addition, treatments involving such perennial crops as *Cenchrus ciliaris*, *Stylosanthes hamata*, and pigeonpea are also studied. Paddy straw and farmyard manure are applied to the surface after tillage operations. The mean number of VAM spores in soil samples collected at the flowering stage during 1991–1993 showed a marginal increase from 13 spores/gm soil in the zero tillage-no amendment treatment to 16 spores/gm soil in the deep tillage (20 cm)-no amendment treatment (Figure 1). The deep tillage-no amendment treatment significantly increased mycorrhizal colonization of roots (58%) during 1991–1993 as compared to 44% in the zero tillage-no amendment (Figure 2). Similar effects in terms of increased mycorrhizal colonization due to deep tillage were also observed in the plots mulched with paddy straw. However, no effect of tillage was observed in the plots amended with farmyard manure as seen in Figure 2. Such favourable effects of tillage on the number of VAM spores and percentage of root colonization may be due to the breaking of hyphae, because of tillage, and mixing up of soil layers. In Queensland, different tillage treatments showed only modest differences in VAM colonization. In the

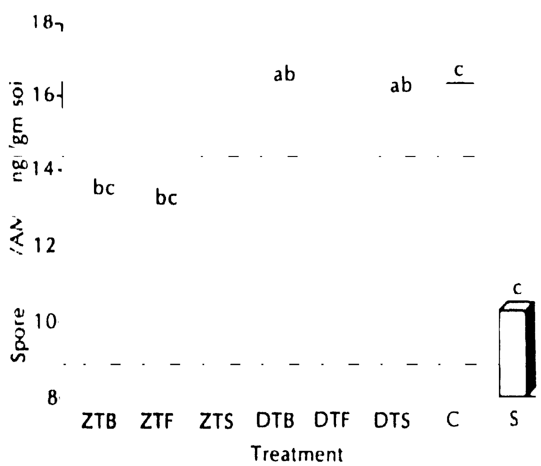

Figure 1. Number of mycorrhizal spores (mean of three years) in Alfisol as influenced by tillage and organic matter amendment practices.
ICRISAT Asia Center, Patancheru, India
(Bars with different letters differ significantly ($p \leq 0.05$))
ZTB-Zero tillage bare (no amendments), ZTF-Zero tillage + farmyard manure, ZTS-Zero tillage + paddy straw mulch, DTB-Deep tillage bare (no amendments), DTF-Deep tillage + farmyard manure, DTS-Deep tillage + paddy straw mulch, *C-Cenchrus ciliaris, S-Stylosanthes hamata*

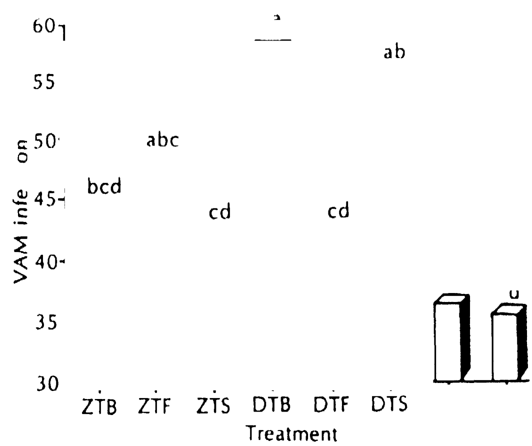

Figure 2. Mycorrhizal infection (mean of three years) of cereal crops (maize during 1991 and 1992 and sorghum in 1993) grown in Alfisol as influenced by tillage and organic matter amendment practices.
ICRISAT Asia Center, Patancheru, India
(Bars with different letters differ significantly ($p \leq 0.05$))
ZTB-Zero tillage bare (no amendments), ZTF-Zero tillage + farmyard manure, ZTS-Zero tillage + paddy straw mulch, DTB-Deep tillage bare (no amendments), DTF-Deep tillage + farmyard manure, DTS-Deep tillage + paddy straw mulch, *C-Cenchrus ciliaris, S-Stylosanthes hamata*

zero tillage treatment, VAM colonization was greater at 5–10 cm depth than at 0–5 or 10–15 cm depth. Increasing the frequency of tillage tended to decrease colonization percentage at 5–10 cm and increase it at 0–5 and 10–15 cm depths (Peck, Thompson, Haak 1992).

In Canada, studies on the effects of soil disturbance due to the tillage on VAM and phosphorus nutrition showed that disturbing the soils that had not been tilled for a long time reduced VAM colonization and the uptake of phosphorus, and zinc by the mycorrhizal host plants—maize and wheat, but not by the non-mycorrhizal spinach and rapeseed. The effects of disturbance appeared to be due to the death of VAM hyphae in soil (Evans, Miller 1990). It seems that optimum tillage does not affect mycorrhizal colonization in general and in studies conducted at the ICRISAT Asia Center, India, tillage increased mycorrhizal colonization of crops. However, there are reports of adverse effects of tillage on VAM colonization. In the tropics, where subsistence farming is a rule rather than an exception, and farmers cannot afford to adopt zero tillage, more detailed studies are required to find out the appropriate frequency and intensity of tillage that would benefit VAM fungi.

Fertilizers

In general, beneficial effects of VAM fungi on plant growth have been observed under sub-optimal nutrient status of the soils. Maximum root colonization and sporulation occur in soils of low fertility (Hayman 1970). Application of phosphorus can reduce colonization by VAM fungi. However, adding phosphatic fertilizers to soils that are very low in phosphate can increase colonization of the root systems possibly through a direct effect on the VAM fungi (Bolan, Robson, Barrow 1984). However, yield increases were observed in barley grown on soil with 40 ppm available phosphorus ($NaHCO_3$-extractable) following inoculation with VAM fungi (Clark, Mosse 1981). Increased root infection by *Glomus manitrotis* was observed in Cassava, after increased application of phosphorus up to 200 kg P/ha (Sieverding, Howeler 1985). Internal concentration of phosphorus in roots rather than its external concentration in soil, controls root colonization by VAM fungi (Menge et al. 1978; Wani, McGill, Tewari 1991). The level of phosphatic fertilizer at which VAM symbiosis becomes ineffective depends on the content of phosphorus in soil that is available to the plant and to the VAM fungi, the host plant, the species of VAM fungi, and other biotic and abiotic factors.

Nitrogen is the most limiting nutrient in crop production and to overcome this, nitrogenous fertilizers are widely used. In a Vertisol containing 7 mg (NH_4+NO_3)-N/kg soil, application of nitrogen up to 160 kg/ha decreased the VAM colonization of sorghum roots. In sorghum, the root colonization was maximum (76%) in zero-N treatment, followed by that in 10 and 20 kg N/ha equivalent. Higher doses (above 20 kg N/ha) decreased root colonization significantly (30–50%) (Wani S P, unpublished data). Similar results with high rates of nitrogen fertilizers inhibiting VAM fungi have been reported earlier (Hayman 1982). However, Thompson (1986) observed a positive relationship between nitrogen concentration in wheat and maize, and root colonization by *Glomus* spp. Many of these experiments were conducted in pots, using extremely high rates of fertilizers. More information from field experiments is needed to understand the effect of nitrogen and phosphorus levels, and their interaction on VAM colonization.

In the long-term trial conducted at the ICRISAT Sahelian Center, Sadore, Niger, application of 30 kg N, 13 kg P, and 25 kg K/ha to sandy soils increased the population of VAM spores to 7.3/gm soil during early growth stage of pearl millet as compared to 4.3 spores/gm soil that received no fertilizers (Lee, Wani 1991). Fertilizer application may also affect the composition of species such that less efficient mycorrhizal species become dominant (Johnson 1993). Eight years of fertilizer application altered the composition of mycorrhizal species, compared to that in soils that received no fertilizers. Subsequent bioassays showed that mycorrhizal fungi from the control plots increased the growth of test plants compared to these from the plots to which fertilizers that had received regular application of fertilizers.

Organic amendments

Organic manures increase the biological activity in soils and also the activity of specific groups, e.g., *Azotobacter* and *Azospirillum*, involved in soil fertility (Wani, Lee 1992a). However, work on effect of organic amendments on activity of VAM fungi in soil is limited. At the ICRISAT Asia Center at an Alfisol site, mulching with paddy straw or farmyard manure in minimum-tilled and deep-tilled plots had no effect on VAM spores in soil (Figure 2). At the ICRISAT Sahelian Center, Sadore, Niger, in sandy soils, mulching with pearl millet straw (2–4 t/ha) after harvesting the crop increased the number o spores of VAM fungi by 2.4 times than in plots tha were not mulched (11.7 versus 4.3/gm soil) durin early stage of millet growth (Lee, Wani 1991) Harinikumar and Bagyaraj (1989) reported signi cantly higher number of spores of VAM fungi i soil, and greater colonization of roots, during t second and the third season due to application 7.5 t/ha of farmyard manure.

Kruckelman (1975) reported inconsistent fects of farmyard manure on root colonization, a the effects were influenced by soil type. In a greenhouse experiment at the ICRISAT Asia Center, in a Vertisol application of 0.5 and 1% (W/W) farmyard manure had no effect on the colonization of pigeonpea roots. Under field conditions also, application of farmyard manure had no effect on the colonization of roots of sorghum, chickpea, pigeonpea, sunflower, safflower, pearl millet, and green gram.

At the Rothamsted Experimental Station in UK, the number of spores of VAM fungi was maximum in a non-manurial plot in silty clay loam, whereas in a loamy sand the number was much lower (Kruckelmann 1975). Such effects of farmyard manure on VAM activity may be due to the indirect effects, as biological activity is generally increased due to carbon source applied and some of these microbes may enhance or decrease the VAM activity. These indirect effects can be attributed to such improved soil conditions as water-holding capacity, aggregate formation, and nutrient composition. However, direct effects may also be involved. For instance, *G. mossae* and *G. caledonium* hyphae grew saprophytically on organic matter (Warner 1984). Organic farming relies heavily on the use of natural resources, and biological processes and crop rotations are integrated in the system. In such systems, functioning of soil organisms becomes a major determinant of nutrient cycling and plant growth (Fraser *et al.* 1988; Wani, McGill, Robertson 1991) in contrast to conventional agriculture, which bypasses many of the beneficial activities of soil micro-organisms (Lopez-Real 1985). Wheat grown on an organic farm was two to three times more mycorrhizal than that grown on a conventional farm. Continual use of soluble phosphatic fertilizers had negative effects on the colonization rate, maintained higher levels of soluble P in the soil, and decreased the levels of mycorrhizal inoculum (Ryan, Chilvers, Dumaresq 1994).

Pesticides

Generally, such broad-spectrum biocidal fumigants as methyl bromide are very toxic to VAM fungi under ideal conditions. Johnson and Pfleger (1992) indicated two classes of fungicides that are toxic to VAM fungi, namely, the substituted aromatic hydrocarbons comprising botran, chlorothalonil, lanstan, and quintozene or PCNB, and the benzimidazoles comprising benomyl, carbendazim, and thiophanate.

In a recent review, the effects of fungicides on VAM fungi have been given in detail (Vyas, Singh 1992). In general, stunted growth following fumigation was due to the reduced population of VAM fungi in soil (Clark 1978; Kleinschmidt, Gerdemann 1972) and inoculation of fumigated soil with mycorrhizal fungi increased plant growth (Clark 1978).

Vyas and Singh (1992) concluded that, in general, systemic fungicides adversely affected VAM fungi and such effects were specific to particular combinations of the host and the VAM species. It was also suggested that it is possible to select prescribed dosages of fungicides for developing integrated disease management strategies. Mode of fungicide application also governs the severity of the fungicides' effect on VAM infection. It was observed that application of fungicides as seed treatment had no effect on mycorrhizal infection whereas fungicides applied as soil drenches inhibited mycorrhizal infection (Vyas, Singh 1992).

Generally, insecticides and nematicides at recommended rates do not inhibit VAM fungi. The nematicides may even increase colonization by VAM fungi through control of fungivorous nematodes. Likewise, herbicides generally do not directly inhibit VAM fungi (Ryan, Chilvers, Dumaresq 1994) although they may reduce the inoculum of VAM fungi by eliminating potential hosts. Another possibility of VAM/herbicide interactions is that VAM fungi may improve uptake of residual herbicides. Mycorrhizal soybeans suffered more damage than non-mycorrhizal soybeans in soil with low concentrations of residual atrazine (Busse, Ellis 1987).

Discussion

The VAM fungi have been associated with increased plant growth, enhanced accumulation of plant nutrients (mainly phosphorus, zinc, copper, and sulphur) through greater soil exploration by mycorrhizal hyphae (Abbott, Robson 1984; Wani, Lee 1992a), physiological effects other than by enhancement of nutrient uptake (Allen, Moore, Christensen 1980), and reduction in the severity of diseases caused by soil pathogens (Dehne 1982). For developing environment-friendly sustainable agriculture, such beneficial micro-organisms as *rhizobia, rhizobacteria,* and VAM fungi will have to be exploited to the greatest extent possible. However, researchers usually concentrate on inoculations with specific micro-organisms to increase/replace the indigenous populations. Evidence suggests that such an approach is successful only in specific situations, and that crop and soil management options could possibly be exploited for harnessing the benefits from VAM fungi.

Maintaining a plant cover on soil for as long as possible during a year not only helps in reducing soil erosion but also in maintaining the population of VAM fungi in soil. Mono-cropping and use of chemical fertilizers result in declining yields whereas crop rotations involving legumes help in maintaining soil fertility as well as mycorrhizal population. Selection of appropriate crops/cultivars, which encourage sporulation of VAM fungi and thus their inoculum in soil is essential; along with such crop and soil management practices as the minimal use of chemical fertilizers, greater reliance on organic sources of nutrients, appropriate tillage practices, judicious use of pesticides, and integrated disease management practices, would go a long way in increasing the contribution of VAM fungi to increase crop production. However, little systematic work has been done on soil and crop management practices which will enhance the benefits from VAM. The present literature suggest varying view on effects of tillage, use of fertilizers and organic amendments and it is difficult to identify appropriate crop and soil management practices for harnessing VAM benefits for increasing crop production. More systematic work is needed on crop and soil management practices that encourage VAM fungi. Further, study of the ecology of VAM fungi under field conditions must be undertaken to understand the mechanisms through which cultural practices benefit VAM association. There is a need to move away from the option of inoculations with VAM fungi towards systems approach to identify the management practices that can increase the indigenous population of VAM fungi in soil. Such an approach will confer more long-term benefits as it can be usefully adopted by farmers.

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References

Abbott L K, Robson A D. 1984. The effect of mycorrhizae on plant growth, 113–130. In: *VA Mycorrhiza*. C L Powell, D J Bagyaraj (eds). CRC Press, Boca Raton, Florida, USA

Allen M F, Moore T S (Jr), Christensen M. 1980. Phytohormone changes in *Bouteloua gracilis* infected by vesicular-arbuscular mycorrhizae I. Cytokinin increases in the host plant. *Canadian Journal of Botany* 58: 371–374

Bagyaraj D J. 1994. Effect of soil management practices on mycorrhizae. Paper presented during the one-day meeting on *Soil Management and Beneficial Soil Biota in SAT Agroecosystems* held at ICRISAT Asia Center, Patancheru, 21 October 1994.

Black R, Tinker P B. 1979. The development of endomycorrhizal root systems. II. Effect of agronomic factors and soil conditions on the development of vesicular arbuscular mycorrhizal infection in barley and on endophytic spore density. *New Phytologist* 83: 67–78

Bolan N S, Robson A D, Barrow N J. 1984. Increasing phosphorus supply can increase the infection of plant roots by vesicular-arbuscular mycorrhizal fungi. *Soil Biology and Biochemistry* 16: 419–420.

Busse M E, Ellis J R. 1987. VAM effect on atrazine uptake by soy-beans. In: *Mycorrhizae in the Next Decade: Practical Applications and Research Priorities*. Proceedings of the 7th North American Conference on mycorrhiza D M Sylvia, L L Hung, J H Graham (eds). Institute of Food and Agricultural Sciences, University of Florida, Gainesville, Florida, p.242

Chang D C N. 1994. What is the potential for management of vesicular-arbuscular mycorrhizae in horticulture? In: *Management of Mycorrhzae in Agriculture, Horticulture and Forestry* A D Robson, L K Abbott, N Malajczuk (eds). Kluwer Academic Publishers, The Netherlands, 187–190

Clark F B. 1978. Effect of pesticides on vesicular-arbuscular mycorrhizae. Part I. In: *Rothamsted Experimental Station Research Report* for 1978, 236–237

Clarke C, Mosse B. 1981. Plant growth responses to vesicular-arbuscular mycorrhiza. XII. Field inoculation responses of barley at two soil P levels. *New Phytologist* 87: 695–703.

Dehne H W. 1982. Interaction between vesicular-arbuscular mycorrhizal fungi and plant pathogens. *Phytopathology* 72: 1115–1119

Evans D G, Miller M H. 1990. The role of the external mycelial network in the effect of soil disturbance upon vesicular-arbuscular mycorrhizae colonization of maize. *New Phytologist* 114: 65–71

Fraser D G, Doran J W, Sahs W W, Lesoing G W. 1988. Soil microbial populations and activities under conventional and organic management. *Journal of Environment Quality* 17: 585–590

Fyson A, Oaks A. 1990. Growth promotion of maize by legume soils. *Plant and Soil* 122: 259–266

Harinikumar K M, Bagyaraj D J. 1989. Effect of cropping sequences, fertilizers and farmyard manure on vesicular-arbuscular mycorrhizal fungi in different crops over three consecutive seasons. *Biology and Fertility of Soils* 7: 173–175

Hayman D S. 1970. *Endogone* spore numbers in soil and vesicular-arbuscular mycorrhiza in wheat as influenced by season and soil treatment. *Transactions of the British Mycological Society* 54: 53–63

Hayman D S. 1982. Influence of soils and fertility on activity and survival of vesicular-arbuscular mycorrhizal fungi. *Phytopathology* 72: 1119–1125

Johnson N C. 1993. Can fertilization of soil select less mutualistic mycorrhizae? *Ecological Applications* 3: 749–757

Johnson N C, Pfleger F L. 1992. VA-mycorrhizae and cultural stresses. In: *Mycorrhizae in Sustainable Agriculture* G J Bethlenfalvay (ed). Wisconsis, Madison, USA

Kleinschmidt G D, Gerdemann J W. 1972. Stunting of citrus seedlings in fumigated nursery soils related to the absence of endomycorrhizae. *Phytopathology* 62:. 1447–1453

Kruckelmann H W. 1975. Effect of fertilizers, soil, soil tillage, and plant species on the frequency of *Endogone* chlamydospores and mycorrhizal infections in arable soils. In: *Endomycorrhizas* P E Sanders, B Mosse, P B Tinker (eds). Academic Press, London, UK, 511–525

Lee K K, Wani S P. 1991. Possibilities for manipulating mycorrhizal associations in crops. In: *Phosphorus nutrition of grain legumes in the semi-arid tropics* (eds). C Johansen, K K Lee, K L Sahrawat, the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), Patancheru, India, 107–116

Lopez-Real J M. 1985. Sustainable agriculture: the microbial potential-the microbiologists' challenge. In: *The Role of Micro-organisms in sustainable agriculture* J M Lopez-Real, R D Hedges (eds). Academic Press, Berkhamsted, 1–8

Menge J A. 1983. Utilization of vesicular-arbuscular mycorrhiza fungi in agriculture. *Canadian Journal of Botany* 61: 1015–1024

Menge J A, Steirle D, Bagyaraj D J, Johnson E L V, Leonard R T. 1978. Phosphorus concentrations in plants responsible for inhibition of mycorrhizal infection. *New Phytologist* 80: 575–578

Mulligan M E, Smucker A J M, Safir G F. 1985. Tillage modifications of dry edible bean root colonization by VAM fungi. *Agronomy Journal* 77: 140–144

Peck D M, Thompson J P, Haak M I. 1992. Effects of conservation tillage practices on vesicular-arbuscular mycorrhizae build-up after a long fallow. Abstracts, *International Symposium on Management of Mycorrhizas in Agriculture, Horticulture, and Forestry*, University of Western Australia, Perth, pp.130

Resource Management Program, ICRISAT. 1993. In: *Quarterly Technical Report*, October–December, 1993 34–35

Ryan M H, Chilvers G A, Dumaresq D C. 1994. Colonization of wheat by VA-mycorrhizal fungi was found to be higher on a farm managed in an organic manner than on a conventional neighbour. *Plant and Soil* 160: 33–40

Sieverding E, Howeler R H. 1985. Influence of species of VA-mycorrhizal fungi on cassava yield response to phosphorus fertilization. *Plant and Soil* 88: 213–221

Vyas S C, Singh S. 1992. Role of fungicides in the formation of vesicular-arbuscular mycorrhiza in plants. *Mycorrhiza News* 4 (3): 1–6

Thompson J P. 1986. Soil less culture of vesicular-arbuscular mycorrhizae of cereals: Effects of nutrient concentration and nitrogen source. *Canadian Journal of Botany* 64: 2282–2294

Thompson J P. 1987. Decline of vesicular-arbuscular mycorrhizae in long fallow disorder of field crops and its expression in phosphorus deficiency of sunflower. *Australian Journal of Agricultural Research* 48: 847–867

Wani S P, Lee K K. 1992a. Role of biofertilisers in upland crop production. In: *Fertilizers, Orgnaic Manures, Recyclable Wastes and Biofertilisers*, H L S Tandon (ed)., Fertilizer Development and Consultation Organization, 204–204 A Bhanot Corner, 1–2 Pamposh Enclave, New Delhi, India, 91–112

Wani S P, Lee K K. 1992b. Effect of cropping systems on VAM colonisation of crops and the abundance of VAM spores in soil. *Abstracts, International Symposium on Management of Mycorrhizas in Agriculture, Horticulture, and Forestry*, University of Western Australia, Perth, pp.131

Wani S P, McGill W B, Robertson J A. 1991. Soil N dynamics and N yield of barley grown on Breton loam using N from biological fixation or fertilizer. *Biology and Fertility of Soils* 12: 10–18

Wani S P, McGill W B, Tewari J P. 1991. Mycorrhizal and common root-rot infection, and nutrient accumulation in barley grown on Breton loam using N from biological fixation or fertilizer. *Biology and Fertilizer of Soils* 12: 46–54

Wani S P, Rupela O P, Lee K K. 1994. BNF technology for sustainable agriculture in the semi-arid tropics. 4a: In: *Transactions of the 15th World Congress of Soil Science*, Commission III: Symposia, International Society of Soil Science and Mexican Society of Soil Science, 245–262

Warner A. 1984. Colonization of organic matter by vesicular-arbuscular mycorrhizal fungi. *Transactions of the British Mycological Society* 82: 352–354