THE IMPORTANCE OF MICROORGANISMS IN ORGANIC AGRICULTURE

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Abstract
While conventional agriculture relies on synthetic fertiliser, chemical pesticides or other technological inputs for crop production, organic agriculture aims to make optimal use of the natural capital of the soil and its microbial population through methods such as the selection of indigenous crop varieties, and the production of crops appropriate to soil conditions. A number of different soil microorganisms are involved in these processes. Many show potential biocontrol activities against weeds, crop diseases and pests, while *Rhizobacteria* and mycorrhizal species can play an important role in sustainable fertility management. Microorganisms are currently being used as a replacement for synthetic pesticides and fertilizers for many different crops.

Introduction
A more holistic concept of farming in terms of agro-ecology has begun to challenge the traditional reductionism approach to the study of agriculture. As a result we have become more aware of the importance of microorganisms in such processes as soil formation, plant nutrition, and the suppression of plant pathogens, pests and weeds. Moreover, it has become clear that many farming practices – intensive tillage, pesticide use, fertiliser use and monocropping in particular – are directly or indirectly harmful to soil microbes and therefore to the processes mediated by them. It is concern that since much industrialised agriculture now relies heavily on manufactured inputs rather than using natural resources, the sustainability of agriculture is threatened and a move towards resource conserving agriculture is essential. Farming practices must be designed to optimise soil microbial life as part of a wider strategy aimed at conserving and replenishing natural resources. The practical application of this technology and the role of naturally occurring populations of microorganisms in agroecosystems form the basis of this article.

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Soil microbial biomass is composed of eukaryotic (fungi, yeasts, protozoa and algae), and prokaryotic (eubacteria, actinomycetes and archaea) organisms, whose populations vary from soil to soil (Shannon *et al.*, 2002). Many microorganisms possess urease enzymes which play a role in soil enrichment through the degradation or hydrolysis of organic nitrogen (Hasan, 2000). Soil microbial biomass is dictated by a variety of soil and environmental parameters including soil texture and structure, pH, air/moisture content, and soil temperature (Campbell *et al.*, 1999). One of the prime factors that determine soil microbial status is the type and amount of organic material that enters the soil ecosystem. The vast majority of soil microorganisms are heterotrophic and require organic materials as both carbon and energy sources (Shannon *et al.*, 2002). Management practices in particular, the manipulation of the quality and quantity of organic inputs might, therefore, be predicted to modify soil microbial populations, the soil food web, and the biological processes involved in nutrient transformation (Stockdale *et al.*, 2002).

Microorganisms play a fundamental role in soil creation and stability through the binding of soil aggregates by hyphae and by the secretion of exudates (Andrade *et al.*, 1998). There are many examples of the ways in which soil microbial systems help ecosystem health and stability. In a study examining the influence of the microbial community of a Senegalese Sahel soil on the interactions between root knot nematodes and *Pasteuria. penetrans*, a parasite of plant-parasitic nematodes, the actinomycete was associated with a larger soil microbial population, including mycorrhizal and nematophagous fungi, which together stimulated the attachment of *P. penetrans* to the nematodes to reduce nematode infection (Dupponois & Ba, 1998).

Antagonistic and antibiotic microorganisms
There are many reports that soil organisms might be antagonistic to plant pathogens, pests and weeds. For example, over 100 species of fungi trap and prey on nematodes (Jatala, 1986), and many fungi are hyperparasites of other fungi (Adams, 1990). These activities not only influence the general nutrition, health, and vigour of higher plants (which

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also affects disease susceptibility), but they also determine the competitive behaviour of root-infecting fungi and their microbial antagonists (Curl, 1988). Streptomycetes, filamentous bacteria that are effective and persistent soil saprophytes often associated with plant roots, are well-known producers of antibiotics and extracellular hydrolytic enzymes. Samac *et al.* (2003) reported that they have the potential to contribute significantly to an integrated disease management system that includes alfalfa and other crops such as potato, maize and soybeans due to their ability to colonize plants and decrease damage from a broad range of pathogens.

Mechanisms by which endophytes can act as biocontrol agents include production of antibiotic agents (Lambert *et al.*, 1987), siderophore production, nutrient competition (Kloepper *et al.*, 1980), niche exclusion and induction of systemic acquired host resistance. Bacterial endophytes can thus play a role in pathogen suppression and complementary crop sequences can encourage beneficial allelopathy. *Rhizobacteria*, particularly the so-called plant growth-promoting *rhizobacteria* (PGPR), can directly suppress plant pathogens by the production of antibiotics and hormones, and by competition with pathogens for resources. Some of these bacteria also promote root and shoot growth, nodule formation by *Rhizobium* (when they are known as nodule promoting *rhizobacteria,* NPR), and mycorrhiza establishment (as mycorrhiza helper bacteria, MHB).

Mycorrhizal microorganisms

Mycorrhizal fungi (microbial associations with mycorrhizal fungi and bacteria that live on and near the roots) offer several benefits to the host plant, including faster growth (Thompson *et al.*, 1994), improved nutrition, greater drought resistance (Parke *et al.*, 1983), and protection from pathogens (Cooper and Grandison, 1986). Plant protection arises from the formation of a physical barrier to the invading pathogen, secretion of antagonistic chemicals, competition with the pathogen, increases in the nutrient-uptake ability of plant roots, and by changing the amount and type of plant root exudates (Sullivan, 2001).

Mycorrhizal fungi can be broadly categorised into two groups: vesicular arbuscular mycorrhizas (VAM or AM) and ecto-mycorrhizas (EM), which vary widely in structure and function (Harrier, 2001). The former are microscopic obligate symbionts that can only be cultured with a host plant and constitute the largest proportion of fungal biomass in the soil. VAM produce structures known as arbuscules and vesicles within the root cell that are involved in the nutrient transfer process. This symbiosis confers benefits directly to the host plants through the acquisition of phosphate and other mineral nutrients from the soil by the fungus while the fungus receives a carbon source from the host. In addition, the symbiosis may also enhance the plants resistance to biotic and abiotic stresses. Ectomycorrhizas (EM), regularly produce large above-ground fruiting bodies (the familiar mushroom and toadstool) as well as a hyphal net around the plant root. Vesicles and arbuscules are absent and hyphal penetration of the root is limited. EM fungi are amenable to axenic culture. Potential inoculum can also be produced in the field from mycelium.

It is generally agreed that in agriculture and forestry, the most significant function of both EM and VAM fungi is in optimising phosphate uptake by the plant. Since P uptake by plants occurs at a faster rate than the movement of P in the soil, a P depletion zone can develop at the root surface (Mosse, 1986). Mycorrhizal hyphae can cross this depletion zone and access P (and other minerals) in the bulk soil, thereby making them available to the plant (Mosse, 1986). This is most significant in low P soils, as would be the case in many organic, low input or subsistence farming systems. The addition of P fertiliser to ostensibly low-P soils has the effect of increasing P availability to plants but it suppresses mycorrhiza. It follows that the long term use of fertilisers, as is usually the case in modern agriculture, will have the effect of creating fertiliser dependency since the natural resources represented by soil organisms and the soil itself may be systematically depleted.

Mycorrhizal fungi are also believed to control root pathogens by one or more of: (1) improving nutrient acquisition by host plant; (2) excluding pathogens at root infection sites and within the rhizosphere; (3) inducing anatomical and structural changes in the root thereby creating physical barriers to pathogen entry; (4) producing substances antagonistic to root pathogens; and (5) activation of plant defence mechanisms. The role of mycorrhizal fungi, as well as other microorganisms, in stimulating induced resistance to soil-borne plant pathogens in a range of crops has received much attention over the past 25 years (Azcon-Aguilar & Barea, 1996) and it is worth considering its significance to organic farming. Interactions between plants, mycorrhizal fungi and soil bacteria are not random but appear to occur in an ordered manner between compatible species. The presence in the soil of given mycorrhizal species can influence the persistence and activities of native bacteria and *vice versa* (Andrade *et al.*, 1998).

Combinations of a range of beneficial bacteria and fungi have also been used not only to improve plant growth and health but also to achieve concomitant improvements in soil. In experiments to assess the effectiveness of combined mycorrhizal inoculation and compost application for afforestation with *Olea europaea*, significant improvements in soil structure (increased aggregate stability and decreased bulk density) were reported (Caravaca *et al.*, 2002). The growth of *O.europaea* was significantly enhanced by both composted organic residues and mycorrhizal inoculation treatments. The increase in mycorrhizal *O. europaea* seedling growth was attributed to the positive influence of mycorrhizal fungi on soil aggregate stability. In addition, the positive interaction between composting and VAM inoculation that led to increased growth of tree seedlings was related to the ability of the mycorrhiza to enhance plant nutrient uptake from the compost. The possibilities for exploiting these types of synergism have been investigated in many cases (Srivastava *et al.*, 2002).

Heavy metal pollution of soils (along with severe compaction) is common on metalliferous mine spoils and on modern brown-field sites following industrial activities. Polluted soils such as these are slow to support new vegetation and so remain prone to further damage from erosion. One of the ways in which plants benefit from ecto-

Table 1. Application of VAM inoculum in agriculture, horticulture and forestry.

Crop	VAM Fungus	Outcome	Source
Banana	*Acaulospora* sp	Improved growth & nutritional status	Yano-Melo *et al* 1999
Mulberry	*Glomus* sp	Reduced P requirements, Improved growth	Setua *et al* 1999
Douglas fir	*Laccaria bicolor*	60% increase in wood volume	Selosse *et al* 2000
Cyclamen	*Glomus* sp	Increased survival in nursery	Vosatka *et al* 1999
Acacia	*Terminalia* sp	Improved growth & survival	Munro *et al* 1999
Douglas fir	*Melanogaster* sp *Rhizopogon* sp	Improved growth	Pera 1999
Black spruce	*Paxillus* sp	Protection against *Cylindrocladium* root rot	Morin *et al* 1999

mycorrhizal infection in nature is through an increased tolerance to heavy metals in the soil. Mycorrhizal fungi confer protection to the plant against uptake of heavy metals by adsorption on hyphae and through various forms of fungal metabolism (Gadd, 1983).

Organic agriculture and microorganisms

Soil management practices that change the soil carbon content also influence the size and structure of the soil biomass. Application of organic amendments and/or cover crops increases carbon availability to microorganisms. Schjonning *et al.* (2002) found that, after more than 40 years, microbial biomass C was higher in organic than in conventionally managed dairy farm soils. Carbon released from crop residues contributes to increasing soil microbial activity and so increases the likelihood of competition effects in the soil. The placement of the residue in soil can lead to the displacement of a pathogen from its preferred niche, diminishing the pathogen's ability to survive (Bailey & Lazarovits, 2003). Therefore, soil microbial biomass changes as a consequence of switching to organic land management (Shannon *et al.*, 2002). Application of organic matter and all treatments that increase the total microbial activity in the soil might enhance the general suppression of pathogens by increasing competition for nutrients. Crop rotation may also yield microbial benefits beyond those normally associated with pathogen host range and saprophytic survival. Rotation is most successful in limiting the impact of biotrophic pathogens that require living host tissues, or those pathogens with low saprophytic survival capability (Bailey & Duczek, 1996).

Agricultural practices can have major short- or long-term impacts on mycorrhizal fungi, as well as on other soil microorganisms. Scullion *et al.* (1998) studied the effectiveness of VAM spores from organically and conventionally managed soils and found that white clover only benefited from mycorrhizal infection in a low-fertility (organically-managed) soil. Furthermore, inocula from organic soils were more effective in both achieving mycorrhizal infection and in allowing more efficient P uptake by the crop. Application of composts may enhance beneficial soil microorganisms. As the active microbial biomass increases, the capacity to utilize carbon, nutrients and energy in the soil is increased and thus these resources might be limited for soil-borne pathogens (Sullivan, 2001).

Conclusion

It is clear that soil microorganisms play a fundamental role in soil health and sustainability. Microbial population density and diversity are affected by the level of organic matter indirectly by providing energy for soil microorganisms, improving soil structure and stability, soil moisture and plant nutrient availability and by preventing soil-borne disease incidence. Crop and soil management practices designed to support soil microorganisms i.e. minimum tillage, cover cropping, composting, eliminating pesticide and fertilizer use, and maintaining biodiversity, will inevitably lead to soil improvements and stability. The need for replenishing organic matter in the soil after harvesting is thus of great importance. In ecological farming systems, organic matter is maintained by mixed farming, rotations, recycling, compost and farm yard and green manures and bought-in organic sources. Including legumes and cover crops in the rotation should help balanced soil fertility, disease management, and avoid leaching nutrients and soil pollution. Crop and soil management practices designed to support soil microorganisms have been shown to lead to improvements in soil structure and stability. Although the great diversity of soil microorganisms is now well appreciated, studies over the past twenty years have established that a number of other soil organisms, apart from mycorrhizal fungi, not only play an active role in suppressing pathogens but also mediate the activity of a range of beneficial organisms. Apart from farming in ways that support indigenous microbes, the use of proprietary cultures of beneficial microorganisms as soil and compost amendments, root dips, feed additives or sprays in order to supplement or reinforce the indigenous micro-flora are being considered.

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