Important Roles of Soil Micro-organisms in Organic Farming

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Abstract : *Organic and nature farming systems are driven by nature. In these farming systems, soil micro-organisms play a pivotal role as the main driving forces. The use of soil microbial technologies to improve the efficiency of farming and to ensure the safe management of the environment is an important development because the ultimate success of humankind and the health of the planet relies on the development of efficient and sustainable agricultural systems and improved environmental stewardship. Many important processes in soils (e.g. biological nitrogen fixation, residue decomposition, mineralization/immobilization turnover, nutrient cycling, denitrification) are mediated by soil micro-organisms. Although these processes at the cellular level are well understood and documented, less is known about them in practical farming systems especially in organic farming. Microbial interactions and activity in soils are complex and are affected not only by environmental factors (e.g. temperature, soil moisture, soil pH) but also by soil management practices. The latter is generally within the control of farmers and thus provides a means for farmers to manipulate microbial activity and processes to enhance crop yields and long-term soil productivity.*

This review discusses the major roles of soil micro-organisms in organic farming and the impact of soil management practices on microbial population and functions in soils. The manipulation of soil microbial activity to benefit organic farming systems through soil management practices is emphasized. Recent research findings are highlighted.

Introduction

Soil micro-organisms play a pivotal role in organic and nature farming systems. There are many definitions of organic farming (e.g. USDA, 1980; Lampkin, 1990; IFOAM, 1998; New Zealand Biological Producers Council, 1998; Tinker, 2001) but most systems rely on the following:

- legumes to supply nitrogen (N) to crops instead of synthetic fertilizers;
- use of crop residues, crop rotations and cycling of animal manures, green manures, composts and off-farm wastes to provide nutrients and improve soil tilth;
- use of aspects of biological control to control insects, weeds and other pests.

All these processes require the mediation of soil micro-organisms to carry out several important soil functions (e.g. biological N_2 fixation, residue decomposition, mineralization/immobilization turnover, nutrient cycling). Most of the processes are well understood and documented at cellular level but less is known about them in practical farming, especially in organic farming. Microbial interactions and activity in soils are complex and are affected by environmental (e.g. temperature, soil moisture, soil pH) and soil management practices (e.g. cultivation, ploughing, mulching). The latter provides a means for organic farmers to manipulate soil microbial activity and processes to enhance crop yields and long-term productivity.

This paper discusses the major roles of soil micro-organisms in organic farming and the impact of soil management practices on these roles as revealed by recent research findings. The emphasis is on the manipulation of soil microbial activity to benefit organic farming.

Biological Nitrogen Fixation

The key to successful organic farming is to fix sufficient N by biological N_2 fixation. The bacteria that fix N_2 are taxonomically diverse depending on their source of energy (mostly chemotrophs, some phototrophs), carbon (C) (mostly heterotrophs, some autotrophs), oxygen tolerance and degree of association with other organisms (Myrold et al., 1999). Free-living bacteria (e.g. Azotobacter) fix typically < 5 kg N ha^{-1} yr^{-1} while bacteria intimately associated with plant roots (e.g. Azospirillum) may fix up to 50 kg N ha^{-1} yr^{-1} whereas root nodule-forming symbioses of Rhizobium can fix considerable amounts. The Rhizobium association with legumes is of significance to practical farming. It provides the main source of N in organic farming and conventional legume-based pastures in New Zealand (Goh and Williams, 1999).
The amount of N fixed varies (Cookson et al., 1990; People et al., 1995; Whitehead, 1995), depending on locality, methods of measurements (Goh et al., 1978; Chalk, 1985), legume type, yield and persistence, soil N status, fertilizer application and competition with other plant species present (Ledgard et al., 1996). In improved legume-based pastures in New Zealand, it has been estimated that approximately 1 million tonnes of N is fixed annually, equivalent to almost that (1.6 million tonnes) applied annually as fertilizers to crops in the United Kingdom. The usual range reported is between 100 to 350 kg N ha^{-1} yr^{-1} and <100 kg N ha^{-1} yr^{-1} in unimproved pastures (Goh and Williams, 1999). In the United Kingdom, the amount of N fixed in clover-based pastures varies from nil to 400 kg ha^{-1} yr^{-1} (Whitehead, 1995) while in Switzerland 270-370 kg N ha^{-1} yr^{-1} has been reported (Boller and Nosberger, 1987).

Direct field measurements of the amount of N fixed in organic farming systems are rare. A recent study (Goh et al., 2001) comparing pairs of conventional and organic mixed cropping farms under farmers' field conditions in Canterbury, New Zealand showed no significant differences between pastures of different ages and types of farms (Table 1).

Table 1. Annual Amounts (kg N ha^{-1} yr^{-1}) of Biologically-fixed Nitrogen in Pastures of Different Ages and in Pairs of Conventional and Organic Arable Farms in Canterbury, New Zealand.

Pasture	Amount of Nitrogen Fixed (kg N ha^{-1} yr^{-1})			
	Conventional		Organic	
	Pasture Age			
New	32	(6.0)	19	(3.0)
One-year	68	(10.6)	30	(4.7)
Established	46	(7.2)	59	(8.4)
	Paired Farms			
Hinds	41	(19.1)	19	(8.7)
Highbank	51	(23.8)	33	(13.3)
Rakaia	62	(35.4)	32	(14.7)
Halswell	44	(20.3)	67	(31.1)

Standard of error of means are given in parenthesis

Recent field studies showed that N derived from N_2 fixation (i.e. %Ndfa) and amounts of N fixed in conventional farms in New Zealand varied between leguminous crops (Haynes et al., 1993; Kumar and Goh, 2000a). Grain legumes not only fixed considerably less N than white clover but also removed more fixed N, thus resulting in negative N balances (Table 2).

Table 2. Proportion of Total Plant N Derived from N_2 Fixation (% Ndfa), Amounts of N_2 Fixed and Removed Grain Crops and White Clover and N Balance

Parameter	Crop					
	Lupin	Lentil	Field pea		Field bean	White clover+
Ndfa (%)	38	23	22	(69)	28	90
Fixed N_2 accumulated	111	32	28	(286)	48	327
Soil N	137	82	71	(37)	74	1
Fixed N_2 removed	83	24	21	(77)	24	13
N_2 fixed - Total N Removed (N balance)	-109	-74	-64	(172)	-50	313

The strategy for enhancing N_2 fixation in organic farming is to incorporate pasture legumes in crop rotations using ley farming or mixed cropping systems (Keeney, 1990; Haynes and Francis, 1992; Karlen et al., 1994; Goh and Williams, 1999). In this, the restorative pasture phase compensates for the N depletion and soil structural breakdown which occurred during the cropping phase. The control of the length of the pasture and cropping phases provides the key to the sustainability of these systems (Greenland, 1971; Russell, 1980; Haynes and Francis, 1992; Goh and Williams, 1999). Other strategies for improving N_2 fixation in organic farming rely on maximizing the numbers and effectiveness of rhizobia in soil, reducing soil nitrate level and plant sensitivity to soil nitrate, and maximizing legume growth by overcoming soil acidity and phosphorus (P) deficiency and exploiting genotypic variability in host-rhizobia interactions.

Decomposition of Crop Residues and Manures

Organic farming necessarily involves the addition of large quantities of crop residues and animal manures as fixed C to soils. This supplies the energy which drives the functions of soil organisms, especially the soil microbial biomass (SMB). The SMB is a living component of the soil (1-3% of soil organic C, 2-6% soil organic N), comprising mainly of fungi and bacteria including micro-fauna and algae. It plays a key role in nutrient cycling and dynamics by acting both as a source and sink of plant nutrients (Jenkinson, 1987; Jarvis et al., 1996).

Decomposer organisms of plant and animal residues generally consist of a complex community of soil biota, including microflora and soil fauna. The microbial decomposer community is extremely diverse and bacteria and fungi are the major decomposers (Coleman and Crossley, 1996). Actinomycetes are responsible for residue breakdown mainly at high temperatures whereas bacteria and fungi function at lower temperatures (Parr and Papendick, 1978).

The decomposition processes involve the mineralization and immobilization (or humification) of residue C compounds with the ultimate release of CO_2 to the atmosphere and N as ammonium (NH_4^+) and nitrate (NO_3^-) (Figure 1) and other associated nutrients. The mineralization is always accompanied concurrently by immobilization in the opposite directions. Thus, the mineralization-immobilization turnover (MIT) determines whether nutrients and C are released or retained in the soil (Jansson, 1971). As the application of animal manures and slurry containing substantial inputs of carbonaceous materials, this usually results in immobilization, at least temporarily. In the long run, mineralization is favoured. Thus, additions of crop and animal residues most often result in net immobilization followed by net re-mineralization.

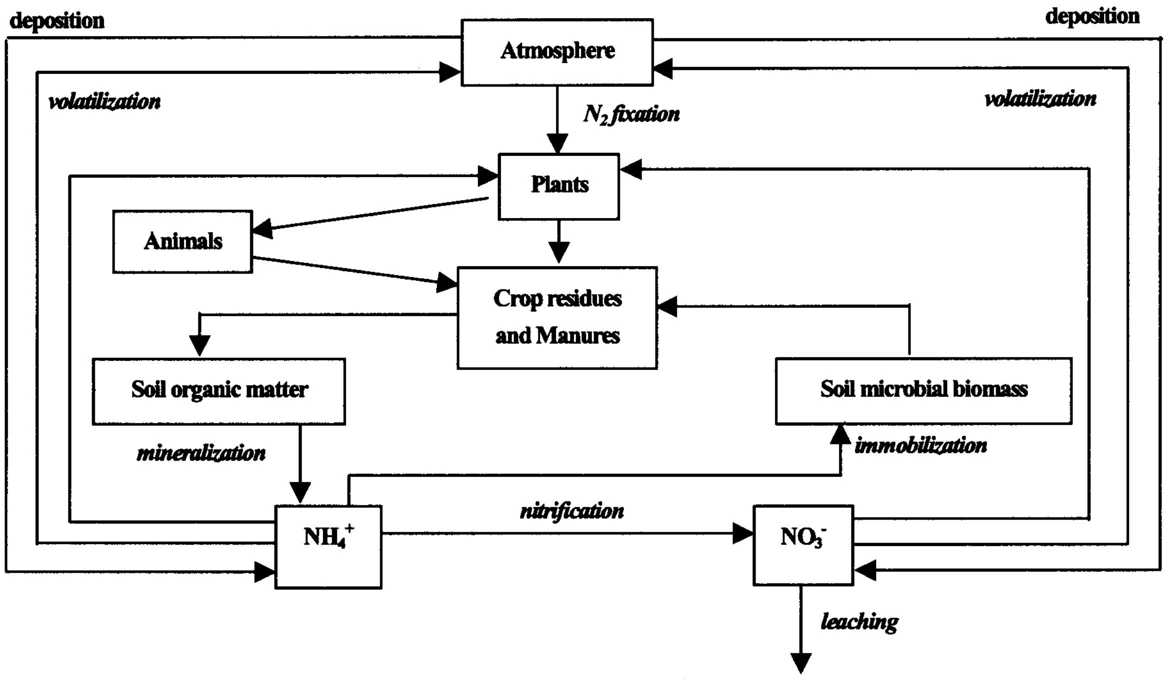

Figure 1. The Soil Nitrogen Cycle (Jarvis et al., 1996) Modified to Represent that in an Organic Farm

The C/N ratio has long been recognised as an important residue quality for determining whether N is released from crop residues (Kumar and Goh, 2000b). The threshold C/N ratio, above which decomposition is suppressed, is about 20 to 30. However, threshold C/N ratio does not reveal the availability of C or N to soil micro-organisms. Other residue quality parameters (e.g. lignin, polyphenols) have recently been integrated with C/N ratio as a plant quality index (PRQI) to predict the N release from crop residues and organic materials (Tian et al., 1995; Kumar and Goh, 2000b). Recently, Kumar and Goh (2002) found that by modifying the PRQI to PRQIM to include C/N, lignin/N and polyphenol/N ratios as

$$PRQIM = [1/(a\ C/N + b\ lignin/N + c\ polyphenol/N)] \times 100$$

improves the prediction of N release for a wide range of organic materials.

Other than crop residue quality, environmental and soil factors (e.g. pH, soil moisture, temperature) and residue management practices (e.g. ploughing, direct drilling, mulching, residue burning) also affect the rate of residue decomposition. Different management practices affect soil differently (Kumar and Goh, 2000b). For example, although the burning of crop residues is thought to be a good option for disease control (Burgess et al., 1993), the increase in soil temperature due to burning can reduce both harmful and beneficial soil microbes (Biederbeck et al., 1980) and cause shifts in microbial communities (Beare et al., 1996). Recent field results comparing the effects of different soil management practices (ploughed, rotary hoed, mulched, burning) of leguminous and non-leguminous residues in Canterbury, New Zealand showed that burning did not provide any added advantage to grain yield (Table 3) or N benefits in subsequent wheat crops (Kumar et al., 2001).

Table 3. Grain Yield (g/m^2) of three Sequential Wheat Crops as Affected by Different Residue and Management Practices.

Management Treatment	First sequential wheat grain yield	Second sequential wheat grain yield	Third sequential wheat grain yield
Ploughed	577	303	290
Rotary hoed	544	301	280
Mulched	426	362	298
Burned	536	329	289
S.E. (D.F.)	17.7(54)	14.1(54)	12.4(18)
Interaction	ns	ns	ns
CV (%)	17	17	14

Although several options are available to farmers in managing crop residues, residue management practices should be chosen based on environment and farm constraints as shown in Figure 2. Ideally, the aim is to enhance crop yields with minimum adverse effects on the environment.

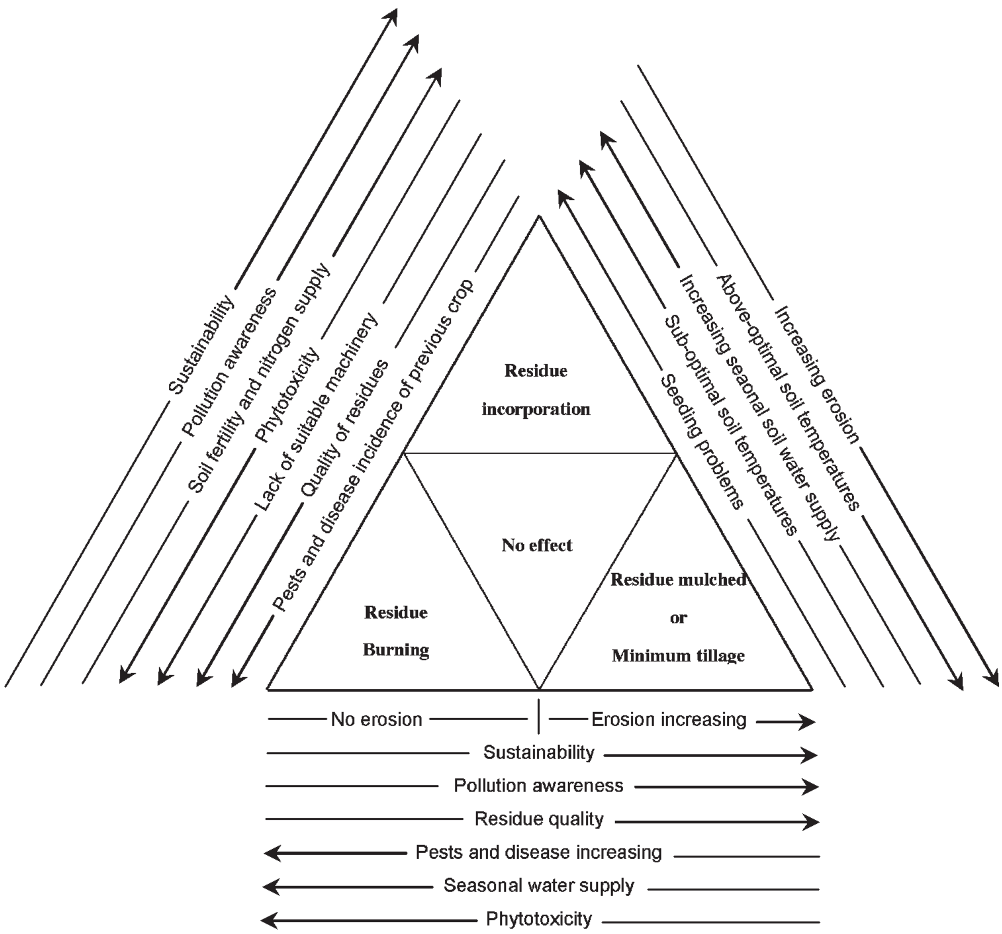

Figure 2. Conceptual Diagram for Selecting Crop Residue Management Practices Based on Environmental and Visualized Farm Constraints (Kumar and Goh, 2000b)

Effects of Soil Management Practices on Soil Microbial Number

Numerous studies have reported higher microbial populations and activity in organic than conventional managed soils, in rotation than monoculture crops and under a ley than wheat crops (Dick, 1992; Sivapalan et al., 1993; Elmholt, 1996; Gunapala and Scow, 1998; Stockdale et al., 2000). Increased active fungal population, fungal and activity diversity, species richness of Fusarium and non-parasitic nematodes occurred in organic than conventional management. These are all driven by higher soil organic matter levels in organic systems (Stockdale et al., 2000). Evidence from long-term field experiments suggests that the loss of crop yield during the conversion of conventional to organic and alternative farming systems was due to reduced biological potential to effectively cycle and mineralise organic sources of nutrients (Doran et al., 1987). Soil enzymes are predominantly of microbial origin and are related to microbial abundance and activity. Several studies have also shown that soil enzyme activities are higher in crop rotations than monocultured crops (Dick, 1984). Nguyen et al. (1995) found higher sulphatase, phosphatase and urease activity in organic than conventional mixed cropping farms in Canterbury, New Zealand (Table 4).

Table 4. Enzyme Activity (pmol g^{-1} soil s^{-1}) in Conventional and Organic or Biodynamic Cropped and Pastoral soils (0-75 mm depth) in Canterbury, New Zealand

Site and farming system	Soil	Sulphatase	Phosphatase	Urease
Kowai				
Conventional	Cropped	194 (6.6)	1090 (42.8)	643 (75.6)
	Pastoral	194 (8.4)	1202 (14.2)	610 (49.6)
Biodynamic	Cropped	196 (4.4)	1232 (35.0)	672 (45.5)
	Pastoral	236 (5.6)	1542 (40.4)	862 (30.2)
Temuka				
Conventional	Cropped	110 (4.4)	2100 (103.2)	400 (19.7)
	Pastoral	110 (6.8)	2330 (139.0)	418 (36.7)
Organic	Cropped	122 (9.1)	2122 (126.8)	398 (13.5)
	Pastoral	112 (7.4)	2316 (116.8)	410 (21.0)
Templeton				
Conventional	Cropped	98 (9.2)	1720 (70.4)	536 (40.3)
	Pastoral	98 (3.8)	1804 (93.1)	554 (50.1)
Organic	Cropped	104 (11.1)	1750 (82.8)	546 (47.9)
	Pastoral	124 (7.2)	1850 (122.4)	640 (42.4)

Cultivation has been shown to decrease sulphatase and phosphatase activity in soils (Dick, 1992). This was attributed to the destruction of macro-aggregates by long-term cultivation as macro-aggregates are important micro-habitat for microbial activity. Conservation tillage which retains crop residue on soil surface maintains microbial activity in the surface soil. Soil amendments such as animal and green manures are more important in maintaining soil microbial activity/diversity than conservation tillage in monocultural systems.

The type of crop residue is more important than residue management practices (e.g. ploughing, rotary hoeing, mulching, burning) in affecting N mineralization in soils (Kumar et al., 1996). Soil type (e.g. soil pH, aeration) is more important in affecting microbial biomass and activity in the rhizosphere than plant species (Groffman et al., 1996; Marschner et al., 2001). Rhizosphere bacteria are fundamentally important and have been described as a microbial loop where the bacteria are grazed by protozoa, which release one third of the bacterial N for plant uptake while the remainder forms protozoan biomass or egested in organic forms, not available to plants (Clarholm, 1994). Continuous monoculturing of a single crop species usually results in reduced crop yield compared to crop rotation (Dick, 1992). The rotation effect has been attributed to the suppression of deleterious rhizobacteria which build up under monocultures.

Driven by Methods

The study of soil microbiology in the past has been limited mainly by methodology (Insam, 2001). Simply extracting soils for plate counting of soil micro-organisms is insufficient to characterize soil microbiota and its important functions in soils (Macura, 1974) as this accounts for only a small fraction of the total number of soil microbes and fails to reveal its activity. In the last decade, major development in molecular approaches employing DNA analysis allowed new insights on soil micro-organisms and their important roles in soils.

Conclusions

Microbial mediated processes are central to organic farming. Many of the important functions of soil micro-organisms in organic farming are affected by environmental and soil management practices. The latter provides a means for the practical farmer to modify soil conditions to favour microbial activity to enhance crop yields.

There is no one single soil management practice suitable for all organic farming situations. Some practices are more beneficial than others. The choice of suitable practical soil management options relies on an understanding of the environmental and farm constraints in each particular farming system.

The rapid development of molecular microbiological methodology such as DNA analysis in recent years will provide a means of not only identifying the microbes and their sites of activities in soils but will also allow organic farmers to better target appropriate soil management practices to establish desirable soil microbial populations in the future. Such development will lead to the enhanced sustainability of organic farming systems in the long-term .

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