Chapter 10

Managing the Soil Habitat for Enhanced Biological Fertility

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1. INTRODUCTION

Soil is a complex inorganic and organic matrix, the habitat for a highly diverse community of microorganisms, fauna and plants, all of which affect the fertility and hence the primary productivity of the ecosystem that they inhabit. Soil fertility is largely dependent on the processing of organic substrates - soil organic matter (SOM) - through the soil food-web (Swift 1997). The maintenance of a suitable soil habitat with adequate quality and quantity of organic substrates is therefore critical for microbial communities (Elliot *et al.* 1988, Young and Ritz 2000) and faunal communities (Tian *et al.* 1993, Lavelle *et al.* 1998, Yeates 1999) to cycle nutrients and make them available to plants. In agriculture we modify the soil habitat and so influence the ability of the soil ecosystem to provide essential services such as decomposition and nutrient cycling for food and fibre production (Constanza *et al.* 1997). Management practices such as tillage can make it harder or easier for soil organisms to cycle nutrients. Integrating cropping practices that increase plant diversity (such as inter-, mixed- and cover-

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cropping and agro-forestry) and diversified crop rotations (including annual, biennial and perennial crops) together with conservation tillage or no tillage, further increases the potential for managing the soil for enhanced biological fertility by varying the quantity and quality of plant litter (including roots). The chemical and physical quality of the residues affect the populations and diversity of soil biota (Swift *et al.* 1979, Tian *et al.* 1993), the rate of decomposition (Palm and Sanchez 1991, Tian *et al.* 1992) and the subsequent movement of nutrients through the decomposer subsystem (Bardgett *et al.* 1999).

We argue that farmers and other resource managers should consider adopting conservation tillage or no tillage together with diversified cropping practices and crop rotations to manage the soil habitat for enhanced biological fertility. These practices are among the keys to sustaining agriculture as we strive to continue to maintain yields, produce nutritious food, use inputs more effectively and efficiently, conserve natural resources including biodiversity, and reduce the environmental consequences of agriculture.

2. A SUITABLE HABITAT IS THE KEY TO ENHANCING SOIL BIOLOGICAL FERTILITY

The structural stability of the habitat space and an adequate supply of plant residues and SOM are the foundations for enhancing soil biological fertility. The soil structure can partition resource patches and isolate components of the biological community, altering predator - prey relationships. The soil pore network determines the spatial and temporal distribution of substrates and soil biota, and provides flow paths for solutes and gases. Within the habitable pore space network the spatial distribution of water films and available organic matter have the ultimate control over microbially-mediated soil processes (Young and Ritz 2000). It was suggested that these processes were being controlled at a small-scale by tillage, exploring roots, and habitat modifications by macrofauna (earthworms, termites and ants), demonstrating the importance of the interrelationships between soil biota, plants and soil management practices in terms of regulating soil processes.

The geometry and stability of the soil habitat is mostly defined by the actions of soil biota (Foster 1988, Tisdall and Oades 1982, Lavelle 2000). Ecosystem-engineering organisms modulate soil processes affecting the suitability of the habitat for other organisms including plants (Anderson 1995). Coleman and Crossley (1996) suggested that from an evolutionary and successional standpoint, the properties of an individual that improves the environment or increases the reproductive success of that individual are also likely to benefit other soil organisms. Soil organisms are continuously modifying the habitat to their advantage; earthworms do this at a macro scale and soil microorganisms at a micro scale. For example, the activities of soil invertebrates that lead to increased stability of SOM have evolved to a certain extent from the benefits of increasing the suitability of the soil they inhabit (Wolters 2000). It is likely that more time should be taken to consider the consequences of the habitat modifying behaviour of organisms on plant-organism-soil interactions (Waid 1997), and how this is affected by cropping and soil management practices.

Plants can also affect soil biota and the suitability of the soil habitat by inputs of above- and below-ground residues and root exudates, and by the removal and redistribution of water and mineral nutrients through root uptake. Clearly, any factor or soil management technique that changes the quantity and/or quality of organic material going into the soil, as either residue or root exudates, will effectively change the soil biological community. This will be followed by a myriad of consequences (both negative and positive) for the soil habitat, many of which could limit plant nutrient uptake and growth, and the quantity and quality of plant residues returned to the soil. Thus, management practices that preserve the integrity of the partnership between plants, soil biota and the soil as a habitat will enhance soil biological fertility.

3. ASSESSING A SUITABLE HABITAT AND ENHANCED SOIL BIOLOGICAL FERTILITY

A suitable habitat for any living organism is characterised by its physical structure and biotic properties. The primary indicator of sustainable land management is the assessment of soil health and the direction of the change with time (Karlen *et al.* 1997). There is a need for reliable and easily measured methods of assessing changes in soil structure and biotic properties that reflect soil habitat changes associated with altered cropping and soil management practices. The measurement of various soil biological properties to evaluate soil health has been proposed (Pankhurst *et al.* 1995), and the sensitivity and importance of including microbial and biochemical analyses as soil fertility indicators should not be ignored (Visser and Parkinson 1992, Brookes 1995, Svensson and Pell 2001). The use of soil fauna as indicators of soil quality has also been reviewed (Linden *et al.* 1994, Lobry de Brun 1997). There is probably a suite of biological indicators as opposed to one key organism or measurement that is most likely to reflect soil health. It is also likely that the organisms and measurements included in an indicator suite would differ between soils and climatic zones. In some cases it may be more appropriate to look for organisms that are sensitive to change in their environment, and measure change as opposed to health or quality (Day 1990).

We have chosen to use shifts and changes in earthworm populations and/or species diversity throughout this chapter to demonstrate the suitability of a habitat and the potential for crop benefit and health from enhanced soil biological fertility. However, we acknowledge that excellent arguments can also be made for considering populations and species diversity of protozoa (Foissner 1997, Bamforth 1999, Griffiths *et al.* 2001), nematodes (Porazinska *et al.* 1999, Neher and Barbercheck 1999), and enchytraeids (van Vliet *et al.* 1995) to also demonstrate the effects of soil management practices on soil biological fertility.

4. EARTHWORMS AS INDICATORS

It has been argued that we need to pay more attention to the effects of tillage and cropping practices on earthworms if we are to build and maintain soil biological nutrient cycling and the soil habitat structural stability required for enhanced biological fertility (Springett *et al.* 1992). Indeed, earthworms are considered to be ecosystem engineers (Lavelle 1997, Lavelle 2000, Anderson 2000), and have been shown to be indicators of soil health and plant growth as well as beneficial land reclamation (Linden *et al.* 1994, Pankhurst *et al.* 1995, Buckerfield *et al.* 1997). They can modify the physical, chemical, and biological properties of soil, and contribute to nutrient cycling (Blair *et al.* 1995), soil aeration and water infiltration (Ketterings *et al.* 1997). Studies have shown that earthworms can also affect the species composition of microorganisms, including protozoa in the soil and around the roots of plants (Gunn and Cheritt 1993, Stephens *et al.* 1994, Doube *et al.* 1994, Bonkowski and Schaffer 1997). Such interactions are important for nutrient cycling and plant productivity (Brown 1995).

The lining of the earthworm burrow (also known as the drilosphere) has been found to have higher populations of nitrifying bacteria than the soil outside the burrow (Parkin and Berry 1999). The increased nitrogen available in the drilosphere could preferentially encourage plant roots to explore earthworm channels. The demonstrated relationship between plant roots and earthworm burrows is complex (Springett *et al.* 1994), with some plant roots preferentially exploring earthworm burrows, while other plant roots determine the distribution of earthworm burrows (Springett and Gray 1997). High earthworm populations are not merely associated with favourable soil fertility but actively build and maintain soil fertility in tropical ecosystems (Hauser *et al.* 1997, Lavelle *et al.* 1998). It is likely that earthworms have much the same effect on soils in other climatic zones. However, there are highly productive soils around the world where earthworms do not exist, possibly because of glaciation, physical barriers to migration or for reasons that are yet unknown. In these soils it is possible that other macro invertebrates such as enchytraeids (van Vliet *et al.* 1995), microarthropods (Behan-Pelletier 1998, Clapperton *et al.* 2002), protozoa and/or nematodes could be valuable indicators of sustainable land management practices. Soil management practices that build populations and diversity of earthworms or other soil fauna that modulate the soil ecosystem are likely to have far-reaching consequences on soil health and productivity.

5. REDUCED SOIL DISTURBANCE TO MANAGE THE INTEGRITY OF THE HABITAT

For thousands of years humans have manipulated the soil in various ways to improve the conditions for crop growth, Tull (1751) advocated modifying the soil physical properties with tillage as a reasonable way to enhance soil fertility and increase yields. However, experiments comparing tillage practices have shown that plant productivity is not related to the tillage implement that was used but rather to the soil environment which it created (Carter 1994). In the last two decades, a Worldwide revolution in tillage practices has taken place. Conservation tillage (ie. minimum tillage or reduced tillage) as defined by Carter (1994) and no tillage are rapidly becoming the norm, and conventional tillage, which relies on intensive soil manipulation (inversion and mixing), has lost favour. Conservation tillage and no tillage were initially adopted for their role in reducing soil degradation by wind and water erosion. In addition, no tillage protects soil from biological degradation (Aslam *et al.* 1999). The benefits of conservation tillage and no tillage to soil biological properties have been well documented (Hendrix *et al.* 1986, Doran and Linn 1994, Beare 1997, Young and Ritz 2000, Ferreira *et al.* 2000). No tillage and to a lesser extent conservation tillage retain the soil surface layers which contain those aggregates richest in SOM, preserving the soil biological component (Dick *et al.* 1997, Peters *et al.* 1997) important to soil fertility and crop productivity.

Conventional tillage affects the placement of residues, collapses the pores and tunnels that were constructed by soil animals and plant roots, and changes the water holding, gas and nutrient exchange capacities of the soil. Conservation tillage (Carter 1994) and particularly no tillage (direct-seeding) create soils that are favourable habitats for soil- and litter-dwelling organisms. Significantly greater earthworm populations have also been reported in soils under no tillage compared with conventional-tillage in Australia (Buckerfield 1992), New Zealand (Francis and Knight 1993), Canada (Clapperton *et al.* 1997), United States of America (Parmelee *et al.* 1990), Finland (Nuutinen 1992), Great Britain (Edwards and Lofty 1982) and Germany (Tebrugge and During 1999) demonstrating the generally positive response of earthworm populations to reduced soil disturbance. Soils with less tillage also have buffered temperatures, improved structure, increased organic matter content, more biologically active and diverse biotic communities, higher nutrient loading capacities, and release nutrients gradually and continuously (Alvarez and Alvarez 2000, Beare *et al.* 1994, Doran and Linn 1994, Angers *et al.* 1993, Arshad *et al.* 1990, Hendrix *et al.* 1986, House *et al.* 1984).

5.1 Making the Transition to a Reduced Tillage System

Conservation tillage and particularly no tillage have been considered the key to enhancing agricultural sustainability (Papendick and Parr 1997), and the benefit to soil health has been documented. However, there are social, economic and agronomic limitations to farmers adopting conservation tillage. In making the change from conventional tillage to conservation tillage or no tillage, farmers must begin applying some of the principles of integrated weed, disease and insect management, and overcome yield-limiting factors that are related to rebuilding the habitat. In humid regions, high yields of crop residues can cause problems for seed germination and establishment. However, this is now considered to be a mechanical constraint (Carter 1994). Decreased plant growth and vigour have also been reported under no tillage systems because of water soluble toxins from the residue and/or toxins released as a consequence of microbial decomposition (Kimber 1967). Alternating the sequence of crops in the rotation can ameliorate these effects from residues (Wolfe and Eckert 1999). This means that reducing the amount of disturbance alone is not sufficient to fully exploit soil biological fertility.

Farmers in the United States of America reported that many of the yield-limiting problems in the first years of the transition to a no tillage system were temporary (Papendick and Parr 1997). In German agriculture, it was suggested that conservation tillage would only be likely to replace ploughing if there were appropriate machinery, diversified crop rotations, and an increased awareness of plant health (Tebrugge and During 1999). There is a documented need for crop rotation in conservation tillage and especially in no tillage systems to provide the soil biological activity to suppress the build-up of rhizoorganisms deleterious to plants, and provide sufficient biodiversity to maintain optimum soil and crop productivity regardless of climate and soil type (Carter 1994). Indeed, researchers increasingly agree that crop rotations and cover crops can be used in conservation tillage and no tillage systems to maintain yields (Papendick and Parr 1997, Hao *et al.* 2000, Tebrugge and During 1999, Drinkwater *et al.* 2000), reduce weed populations (Liebman and Dyck 1993, Blackshaw *et al.* 2000), and increase plant health (Vargas-Ayala *et al.* 2000) to reduce the agronomic risk associated with the transition to no tillage.

6. PLANTS DIRECTLY AND INDIRECTLY INFLUENCE THE SUITABILITY OF THE SOIL HABITAT FOR ENHANCED BIOLOGICAL FERTILITY

Crop rotation presents soil organisms with varied living conditions and a greater variety of substrates. Plants regulate the activities of soil biota (Swift and Anderson 1996) both directly and indirectly. The roots modify the soil structure, and alter the vertical distribution of nutrients, water and soil organisms. The quantity and quality of above- and below- ground residues determines the composition of microbial and faunal communities affecting the formation of soil aggregates and stabilising or destabilising SOM. Populations and the activities of earthworms and other soil ‘ecosystem engineers’ are strongly influenced by residues, root exudates, and products of decomposition. Therefore, diversified crop rotations are essential for creating a suitable environment for enhanced biological fertility.

6.1 Root Architecture and Root Residues

Diversified crop rotations present a range of root architectures. Root architecture is an important element affecting plant nutrient uptake. The patterns of root response to soil factors such as soil physical structure can vary depending on the plant species and even different genotypes and cultivars within the same species (Zobel 1992). Root ramification and decaying roots add more continuity to the network of soil pores. There is a relationship between the density and distribution of roots and the size and density of aggregates. The length of root in aggregates decreased exponentially with increasing aggregate density, and root growth shifted from within micropores to macropores with increasing aggregate size (de Frietas *et al.* 1999). Root distribution can affect nematode distribution, and root diameter can determine nematode species composition (Yeates 1987). The quantity of carbon (C) allocated to structural biomass, respiration and exudation are also influenced by root architecture (Nielsen *et al.* 1994). This can have an effect on the microbial populations and mineralisation of SOM, as plant structural materials and exudates have very different rates of decomposition.

Roots left in the soil are often ignored source of organic matter, and root architecture and biomass vary dramatically between crop species (Zobel 1975), affecting aggregate stability (Tisdall and Oades 1982), habitat and nutrient dynamics (Jobbagy and Jackson 2001). Heal *et al.* (1997) pointed to the important contribution that roots make to C flow in the soil, and complained that there was little research aimed at determining how root residues contribute to replenishing SOM in arable cropping systems. Recently, it has been reported that root-derived materials are more rapidly occluded by aggregates than shoot-derived residues, and are more likely to contribute to humic materials where roots are concentrated (Wander and Yang 2000). These researchers further concluded that root derived soil organic C in occluded particulate organic matter and humic fractions were more likely to be persistent in the long-term compared with shoot derived soil organic C. There is a demonstrated need to include the contribution of roots to organic matter dynamics and nutrient cycling in agroecosystems.

6.2 Living Roots

Differences in the rates of litter decomposition and nutrient cycling have been reported in the presence of living roots (Bottner *et al.* 1999, Pare *et al.* 2000). Pare *et al.* (2000) showed that 38% of the ^{15}N in alfalfa or lucerne (*Medicago sativa* L.) shoot residues were mineralised when maize plants were present compared with 23% when no plants were included. Interestingly, in the early rapid decomposition stage, competition between plants and microbes for inorganic N reduced the ^{14}C mineralisation of crop residues and decreased plant productivity (Bottner *et al.* 1999). In the same study after 3-6 months, the presence of living roots stimulated ^{14}C mineralisation in the remaining more recalcitrant residues. These results reinforce the importance of roots as a source of SOM, and show that roots possibly have some control over the recycling of nutrients. Therefore, it may be possible to manipulate the plant species and sequence of crops in a rotation, to synchronise the nutrient release from residues with subsequent crop uptake.

6.3 Root Exudates

Root exudates are probably the most labile form of SOM and one of the determining factors in maintaining soil fertility and structural stability in agricultural soils. Root age and type, and the nutritional status of the plant can alter the quality and quantity of root exudates (Yang and Crowley 2000). Nutrient availability in the rhizosphere is in turn affected by the species composition and activities of the biotic community.

Root exudates are the high energy source substrates that support the abundant microbial community in and around the rhizosphere. Microbial activity in the rhizosphere contributes directly and indirectly to plant nutrition by fixing and cycling N, solubilising P (Clarholm 1994), and binding soil particles into larger water stable aggregates (Lee and Foster 1991). Bacteria- and fungal- feeding protozoa and nematodes attracted to the rhizosphere can make significantly more nutrients available to the plant. For example, non-parasitic protozoa and nematodes have been shown to increase N content and shoot biomass (Neher and Barbercheck 1999). The intense biotic activity in the rhizosphere also attracts other larger fauna such as earthworms (Binet *et al.* 1997), the activities of which subsequently modify the soil habitat, and further increase N-mineralisation (Willems *et al.* 1996).

Evidence clearly supports the possibility that plants can regulate both the quantity and quality of C substrate in the rhizosphere as exudates, and affect plant-specific colonisation by rhizosphere microorganisms (Nehl *et al.* 1996). This could then affect plant health because the activities of individual colonies of rhizobacteria can be positive, negative, or neutral to plant growth, depending on habitat characteristics, host genotype, and mycorrhizal status (Nehl *et al.* 1996). The microbial community associated with the rhizosphere of plants colonised by mycorrhizae has been shown to be significantly different from that of non-mycorrhizal plants (Ames *et al.* 1984), this is likely because plants colonised by mycorrhizae partition more photosynthate to the roots (Wang *et al.* 1989, Clapperton and Reid 1992). It has also been shown that mycorrhizal plants can have a higher proportion of amino and organic acids in the roots compared with roots of non-mycorrhizal plants (Clapperton and Reid 1992). A thorough review of the interactions between root exudation, microbial activity and nutrient cycling is provided by Grayston *et al.* (1996).

6.4 Crop Residues

The crop species used, and the sequence of these crops in rotation can affect the quantity and quality of residues. It is well established that the chemical composition and lignin content of plant residues varies with species. This can limit the population and diversity of decomposer organisms, altering the rate of decomposition and soil nutrient cycling (Tian *et al.* 1992, Tian *et al.* 1993, Watkins and Barraclough 1996, Cookson *et al.* 1998). It was suggested that soil invertebrates preferentially ingest high-quality residues (Brussaard 1998). Later, Tian *et al.* (1997) demonstrated that invertebrates significantly affect the turn-over of low quality residues by stimulating microbial activity. Thus, the ability of invertebrates to destabilise and stabilise SOM can be highly dependent on residue quality.

6.5 Summary

In summary, plants provide the substrate, as residues and exudates, for soil organisms to stabilise aggregates and recycle soil nutrients. It is the quantity and quality of crop residues that largely determine the population and diversity of soil biota. Together, plants and soil biota continuously modify the soil as a habitat to further enhance nutrient cycling and plant growth. Therefore, any factor or agricultural practice that changes the amount and/or quality of organic material going into the soil will alter the activities and population dynamics of the soil biota. This in turn can have both short- and long- term positive or negative consequences for plant health and productivity. It is unfortunate that plant residues are often viewed as a nuisance or a medium that harbours disease rather than a resource for soil biota to recycle.

7. CROPPING PRACTICES THAT RETAIN ADEQUATE SOM ARE THE KEY TO REBUILDING THE HABITAT UNDER REDUCED TILLAGE

In order to restore and enhance soil biological fertility in soils that have been conventionally managed, there is a need to reduce the amount of tillage, and supply the optimum amount and quality of residue required to fuel the increased biological activity. Cropping practices that include pastures and perennial crops (including legumes), vary the quantity and quality of SOM and restore populations of soil biota and habitat stability.

For example, a continuous source of fresh plant litter is required to maintain populations and diversity of litter macrofauna (Vohland and Schroth 1999) including earthworms (Lavelle *et al.* 1998). Saprophages consume approximately 15-30% of the annual input of organic matter and Oligochaetes like earthworms and enchytraeids take the biggest share (Wolters 2000). Earthworms stimulate microbial activity and can accelerate the turnover and loss of C if adequate quantities of litter and SOM are not maintained. Therefore, the cost of earthworm activity in terms of organic C needs to be accounted for in agroecosystems (Lavelle *et al.* 1998). This example also illustrates the need to monitor and manage the quantity and quality of SOM going into agroecosystems to maintain biological fertility.

7.1 Pasture and Perennial Crops

In a long-term cropping study, Wardle *et al.* (1999) showed that soil arthropods were most responsive to cropping and soil management practices that affected the nature and quality of the substrate input. Including a perennial crop or pasture phase in the rotation has been shown to restore soil health and the habitat (Paustian *et al.* 1990, Gebhart *et al.* 1994). Short-term pasture (up to 5 yrs) can have a positive effect on the quantity and quality of SOM which is associated with benefits to N fertility and soil structural stability (Haynes 1999).

Earthworm population and species diversity also increase significantly under pasture (Baker *et al.* 1999) and pasture phases in the rotation (Fraser *et al.* 1996, Haynes 1999). The increase in population and diversity in all cases was attributed to the increase in organic matter input under pasture compared with intensive arable cropping. It appears that maintaining an adequate level of SOM can increase the resistance and resilience of soil organisms and processes to disturbance. The pasture or perennial phase in a rotation also represents a cropping phase with reduced soil disturbance that would benefit soil organisms, much like no tillage.

7.2 Cover Crops

The use of cover crops and living mulches in rotation is an effective cropping practice to increase SOM, and depending on the plant species used they can control weeds (Blackshaw *et al.* 2000) and insects too (Vandermeer 1995). However, microbial metabolic diversity has been shown to increase more under pastures and perennial crop phases than under annual cropping sequences including legume cover crops because of tillage (Bending *et al.* 2000). Unfortunately, cover cropping is mostly associated with extensive tillage to incorporate the residues (green manuring). On the contrary, tillage is not always necessary for maximum biological and nutrient cycling benefit (Mohr *et al.* 1998, Drinkwater *et al.* 2000).

Increasing the diversity of residues and quantity of SOM using legume and cereal cover crops under reduced tillage, has the potential to increase the population and diversity of soil biota. Indeed, high densities of microarthropods have been associated with the higher SOM inputs from cover crops, and clover under-sown cereals (Axelsen and Kristensen 2000). Still, there is a paucity of information with respect to interactions between cover crops, soil biota and soil physical and chemical properties.

This lack of information continues to make it difficult to predict where and when cover crops function best (Vandermeer 1995).

7.3 Agroforestry

The added leaf litter and organic substrate from tree roots, combined with crop roots in agroforestry practices, has been shown to increase SOM, stimulating soil microbial activity and increasing soil nutrient pools (Chander *et al.* 1998, Seiter *et al.* 1999). Fine tree roots within alley cropping systems can also significantly influence nutrient cycling because their decomposition releases N and P faster than that of leaves (Jose *et al.* 2000). Tree prunings in tropical ecosystems, unlike temperate ecosystems, can significantly increase SOM content and nutrient cycling (Seiter *et al.* 1999). The maintenance of semi-natural habitats such as strips of trees have the added benefit of harbouring bacteria, fungi (Seiter *et al.* 1999) and beneficial insects (Pfiffner and Luka 2000).

8. CROP BREEDING FOR BIOLOGICALLY ACTIVE SOILS UNDER CONSERVATION TILLAGE

As more farmers and resource managers consider the transition to conservation tillage and no tillage, they must also contemplate the associated transition to low-input agriculture. Consumers and the public continue to demand food that has been produced in an environmentally acceptable manner with less chemical input. The availability of crop varieties specifically bred to extract nutrients more efficiently and effectively in low input or no chemcial input reduced tillage conditions, would likely be an advantage to producers given the differences in the ways nutrients are recycled between tilled and no tillage systems (Beare 1997). No tillage systems tend to have lower mineralisation and more retained N, and the activities of the soil biota tend to be more seasonally dependent compared with tillage systems (Beare 1997). Ideally, these crops would extract and use mineral nutrients that were made available through soil food webs, and be adapted to inter- and mixed- cropping.

Crop breeding has often compromised root growth for shoot growth and seed production (Zobel 1992, Klepper 1992). Klepper (1992) concluded that crop breeding programs need to consider designing crop rooting systems with traits that would enhance rhizosphere processes. She also suggested that agricultural managers think more about using mixed cropping systems and more diversified rotations to manipulate root system distributions in the soil profile, optimising the capacities of roots to obtain water and nutrients. For example, when we create an above-ground plant canopy structure with inter- and mixed cropping and agro-forestry practices, we also create a root canopy structure (Klepper 1992). Root architecture can shape vertical nutrient profiles, and nutrient distribution patterns along the root (Jobbagy and Jackson 2001). This change in the vertical stratification of roots and nutrients would likely cause a complimentary stratification of SOM affecting the spatial distribution of rhizosphere communities. Thus, the soil-food web becomes more vertically stratified, as do the soil aggregates that provide a more suitable soil habitat for root growth and nutrient uptake. In order to take full advantage of structured root canopies, we need more information linking plant genetics to root architecture and the amount and quality of root exudates. Clearly, this information is critical if we are to manipulate the rhizosphere for crop productivity and also enhance desirable soil properties.

Root exudation has been studied in some modern cereal crops and pasture grasses. However, there are few studies that have compared modern lines of agricultural crops to their ancestors, so we do not know how or if crop selection has changed assimilate partitioning between shoots, roots and the rhizosphere (Hoffman and Carroll 1995). This has implications for the use of transgenic crops (Altieri 2000), of which we know even less. It has been reported that wild type wheat and tetraploid wheat transport proportionally more assimilates to the roots after anthesis than hexaploid wheat (Hoffman and Carroll 1995). The land races from which modern wheat varieties were bred have also been shown to have a higher dependency on symbionts like mycorrhizae compared with more recent plant varieties (Hetrick and Bloom 1983).

Most breeding lines are grown under optimal conditions, where competition between plants for nutrients, water, space and light does not exist. Therefore, symbionts no longer afford these plants a competitive advantage. Parke and Kaeppler (2000) concluded that plant breeders should evaluate the contribution of mycorrhizal fungi to nutrient uptake, drought and disease resistance when selecting germplasm, and that ultimately the genes responsible for mycorrhizal colonisation and responsiveness should be mapped and used when developing new cultivars. This would allow us to exploit both the mycorrhizal symbiosis and the associated benefits to rhizosphere processes, including enhanced plant nutrient uptake and increased habitat structural stability in low input agricultural systems. There needs to be a concerted effort to breed crops with root characteristics and properties that are: adapted to minimum soil disturbance, responsive and encourage beneficial microbial associations, and produce the minimum required amount of root and shoot biomass to maintain adequate levels of SOM.

9. A WHOLE SYSTEM PERSPECTIVE ON SOIL HABITAT MANAGEMENT

There is ample scientific literature advocating agroecosystem management strategies (organic, biodynamic, low-input, alternative) that foster a more ecological approach to agriculture (see Chapter 12 this volume). These systems all incorporate practices that maintain or increase SOM inputs to enhance biological activity and optimise nutrient cycling. Knowledge of the structure and function of below-ground food webs and their temporal and spatial variation has been considered crucial to understanding the potential for agricultural practices to manipulate and sustain soil fertility and productivity (Beare 1997).

Ideally, agroecosystems should be managed to maintain the structural integrity of the habitat, increase SOM, and optimise the C:N ratios in SOM using cover crops and/or crop sequence to synchronise nutrient release with plant uptake. The quantity and quality of organic matter input and soil disturbance are the factors that most affect soil biota (Swift 1994), and soil biota play a key part in the processes of decomposition and nutrient cycling. This makes an understanding of the relationship between the spatial and temporal abundance and diversity of biotic communities with their effects on habitat, SOM, and nutrient cycling critical for designing soil management practices (Lavelle 2000). The agroecosystem models described by Lavelle (2000) placed importance on soil structure, but focused on biogenic structures, or the voids and organo- mineral structures (e.g. casts and faecal pellets) produced by soil invertebrate engineers, as the components of soil structure that promote a more suitable habitat for plant growth.

It has also been argued that we should consider modelling soil and crop management practices in a way that would allow agricultural soils to more closely resemble soils in natural ecosystems (Soule and Piper 1992, Piper 1999) and optimise the nutrient cycling and soil habitat building activities of soil biota (Neher 1999). This would mean reduced tillage and pesticide use, and more emphasis on perennial and SOM-building crops in the rotation, application of manure and compost for increasing SOM, and synchronising nutrient release and water availability with plant demand (Vandermeer 1995, Neher 1999).

10. CONCLUSION

Agricultural practices that maintain the integrity of the soil habitat and the optimum amount of diverse residues to sustain soil biota will likely enhance soil biological fertility. The availability and immobilisation of nutrients associated with the stability of SOM within an agroecosystem is largely a function of cropping and soil management practices. The ability of farmers and resource managers to successfully make the transition to an agroecosystem relying more on soil biological fertility, will require a greater understanding of rhizosphere processes and how soil food-webs function in these agroecosystems.

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