SOIL BIODIVERSITY AND GRASS CROPPING SYSTEMS

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ABSTRACT
Grass cropping in the rotation and the use of no-till seeding appear to be important components for developing sustainable cropping systems. Grass cropping and no-till seeding improve soil organic matter content, increase the soil microbial biomass, increase earthworm numbers, likely cause a buildup of fungivorous microarthropods and nematodes, and greatly increases the resistance of soil to erodibility. Grasses in the rotation usually result in a large rotational effect. All of these factors point to beneficial effects on soil biodiversity. It is unlikely that soil biodiversity is increased but more likely that the beneficial portions of the diverse population are encouraged. Methods for measuring many components of soil biodiversity on a temporal basis are unavailable. Combinations of microbial biomass, enzyme activity, genetic probes and markers, measurement of mRNA and more precise methods for separating individual micro and mesofaunal groups are potential approaches. In this manner procedures may be developed to follow key groups as indicators of healthy biodiversity. Counts of bacteria and fungi have not been particularly useful. Earthworm counts appear to be a sensitive indicator to the biodiversity of an agricultural system.

More studies are needed regarding tillage and cropping interactions as they affect the microflora, microfauna, mesofauna, and macrofauna. Tillage reduces the soil organic matter content, the microbial biomass content, earthworm numbers, and generally greatly increases soil susceptibility to erosion. Tillage can be very damaging to soil structure. Tillage disrupts micro and mesofaunal relationships but results are not clear at this time. It appears that protecting soil from the negative impacts of tillage is essential for preserving soil biodiversity. Grasses in the rotation appear to protect soil biodiversity and are an important component of sustainable cropping systems. Being able to define components of soil biodiversity that promote soil health and sustainable cropping systems are very important to users and policymakers. This knowledge will provide a basis for appropriate decisions based on fact.

KEYWORDS
biodiversity, cropping systems, sustainable, soil quality, erosion, rotation, no-till

INTRODUCTION

The development of sustainable cropping systems is a top priority international goal. The ability to define the components of and regulation of biodiversity in the soil will be an important aspect in the development of sustainable cropping systems. Collection of these data will allow tracking cropping systems so that beneficial practices can be integrated into systems and these systems can then be analyzed economically.

This discussion is limited to biodiversity in the soil. It is recognized that there are many non-soil factors that affect biodiversity. Many of the non-soil factors were covered in a review by McLaughlin and Mineau (1995).

Biodiversity is felt to have a primary role in controlling the sustainability of a cropping system through regulation of nutrient cycling, soil function, and biological interactions. Much of the activity resulting from soil biodiversity functions at the micro, meso, and macrofaunal level. Unfortunately, it has been difficult to identify many of the interrelationships of these organisms that adequately reflect changes in soil biodiversity that can be linked to management and cropping sequence.

Biodiversity was defined as: richness of life as indicated by the variety of biota and interrelated biochemical processes in a habitat (Elliott and Lynch, 1994). More broadly, soil biodiversity might be defined as a specific grouping of macro and microbiota and their associated functions to sustain selected soil properties and processes that sustain plant production, reduce erosion, resist environmental perturbations, protect the environment, or some other important function under given soil and climatic conditions. A goal for soil biodiversity should not only mean maximizing the number of species in an ecosystem. More likely it means the ability to retain the current macrofauna, mesofauna and microflora and to emphasize certain groups of species and processes to accomplish specific and beneficial objectives.

It can be questioned whether changes in biodiversity reflect the addition or subtraction of species or changes in the prominance of certain groups of organisms. It is more likely that the latter situation is the case.

A major portion of soil biotic activity is based on the food web. The decomposer based food web felt to apply to most terrestrial ecosystems was reviewed by Wardle (1995). In it bacteria and fungi feed on a resource base (detritus). The detritus is made up of roots, crop residues, and organic matter. Protozoa and bacterial feeding nematodes feed on bacteria and are in turn fed on by predatory nematodes. Fungi are fed on by fungal feeding nematodes which are fed on by predatory nematodes which are fed on by earthworms. Fungi are also fed on by saprophagous macrofauna and saprophagous mesofauna. Saprophagous mesofauna are fed on by predatory mesofauna. Saprophagous macrofauna, predatory mesofauna and earthworms are fed on by predatory macrofauna. Wardle (1995) pointed out that the food web is poorly understood. It is evident that perturbations such as tillage likely will have a differential effect on the balance of these organisms thereby affecting nutrient cycling and availability, organic matter decomposition and accumulation, and many mineral transformations.

Pankhurst and Lynch (1994) reviewed the definitions and functions of the soil biota. For the soil microflora they used the definition of Foster (1988). The soil microflora, made up of bacteria, fungi, actinomycetes and algae are involved in many functional processes in the soil. Pankhurst and Lynch (1994) defined the soil microfauna as containing primarily protozoa, nematodes and some small mites (*Acanina*). Soil mesofauna are composed of mites, collembola, and other microarthropods and enchytraeids. They defined the major groups of the macrofauna to include the earthworms, the larger enchytraeides, the macroarthropods (spiders), isopods, (slaters), centipedes, millipeds, adult and larval insects (ants, termites), and molluscs (snails and slugs). This group includes herbivores, detritivores and predators. They also reviewed the activities of each group.

Obviously, the broad main objective is to manage biodiversity for maximum sustainable soil health and productivity. Initially it may mean emphasizing more easily understandable components of soil resilience or health such as resistance to erosion in order to gain an understanding of the associated processes (Elliott and Lynch, 1994)." Insight into the role of soil biodiversity in the development of sustainable cropping systems and improved or sustained soil health is not only important from the standpoint of users but also for regulators. The importance for users is the development of cropping practices that are sustainable which includes economic feasibility. Regulators need this information to develop beneficial land use policies that also include economic feasibility and societal acceptance. In this discussion, I shall discuss the relationship of soil biodiversity to soil structure, soil organic matter content (as affected by management), rhizosphere relationships, the potential for weed biocontrol, and potential approaches for defining and following soil biodiversity.

The effect of soil biodiversity on soil structure. The activities of organisms in soil and their diversity have many wide-ranging effects on soil structure. These include: water infiltration rate, water holding capacity, crusting, erodibility, aggregate stability, strength, and aeration. Soil structure is important in terms of water infiltration, a rooting medium, aeration, and resistance to erosion.

Soil structure can be increased in many ways such as by the addition of organic residues or by decreasing tillage. The quality of the residue will determine the effect on soil structure and aggregation (Gilmour et al., 1948; Martin and Waksman, 1940; Martin, 1971). Residue management and chemical composition of the residue could serve different roles regulating soil structure depending on environment and management. For example, it was postulated that if a crop residue contained low N and if external N was limited during decomposition of the crop residue, extracellular polysaccharide production by microbes would be the dominate by-product and ability to aggregate soil would increase. Elliott and Lynch (1984) aerobically degraded three wheat (*Triticum aestivum* L.) straws containing 1.09, 0.5, and 0.25% N in the absence of added N. After a degradation period, the 0.25% N straw treatment resulted in significantly greater aggregation of the soils tested than the other treatments, while the 0.5% N straw treatment generally caused more aggregation than the 1.09% N straw. The aggregation was caused primarily by polysaccharide production.

Lynch and Bragg (1985) showed the potential for improving the structure of cultivated soils through manipulation of the microbiota. Fungal hyphae are important for soil structure by physically binding soil particles. Gupta and Germida (1988) showed after 6 yr of cultivation there was a reduction in macroaggregates in a grassland soil which correlated with a loss of fungal hyphae normally associated with the macroaggregates. The results of these studies show there is potential for improving soil aggregation through residue management on the soil surface with no-till farming practices. These principles should hold for grass straw management.

The macrofauna can have a large effect on aggregate stability, water infiltration rate and aeration. Earthworms are encouraged by pastures (Hayes et al, 1995) and no till cropping (Rovira et al., 1987) and their burrows increase water infiltration and their casts confer stable soil aggregation. Termites can hasten the decomposition of straw residues. Soil crusting is strongly affected by the content and quality of soil organic matter (Lynch and Bragg, 1985). Soil crusting is also greatly affected by chemical relations as discussed by (Summer and Miller, 1992). The soil biota influences and controls many soil chemical relations (Pankhurst and Lynch, 1994; Wardle, 1995). Unfortunately the microbial and other soil biota influences have not been well integrated.

Loss of soil by water or wind erosion will negatively affect biodiversity because of soil, fertility, and soil organic matter losses and associated losses in soil structure. Crop rotations and no-till seeding will have a large beneficial effect on soil erosion processes. Cropping systems such as sod- or forage legume-based rotations reduce soil loss in two main ways. First, soil loss by erosion during the meadow sequence is negligible after establishment because of the characteristic dense vegetative cover and rooting of these crops. If crop establishment into the meadow or other previous crop residues is by no-till with a properly designed drill, soil loss is almost eliminated. Second, when the sod or legume is broken out, the residual effects improve water infiltration and leave the soil less erodible for several years (Stewart et al., 1976).

Experiments show that with conventional tillage and planting systems, soil losses from maize (*Zea mays* L.) following meadow ranged from 14 to 68% of the corresponding losses from maize without meadow in the rotation. The residual effect of meadow in reducing soil loss with conventional tillage cropping may continue, though on a declining level, for 2 to 3 yr after take-out. The annual soil loss from a 4-yr rotation of wheat, hay, and 2 yr of conventionally planted maize averages about one-third of that from a conventionally planted continuous maize (Stewart et al., 1976). It is certain that incorporation of no-till seeding into these cropping systems would prolong and maintain the beneficial effect. It is very likely that biodiversity benefitted from the meadow sequence and the crop rotation. Grass in the rotation appears to provide an exaggerated rotational effect. The beneficial effects of grass on stable aggregation have been known for sometime. Some of the mechanisms of stabilization of aggregation by roots and grass root systems are now understood (Tisdall and Oades, 1982; Oades, 1984, 1987).

The value of crop rotation, and of green manure in the rotation on soil biological properties, and erodibility was shown by Bolton et al.(1985) and Reganold et al. (1987). The soil that had an increased crop rotation including green manure had significantly greater microbial biomass, selected soil enzymes, and less soil erosion. Both farms used conventional tillage. These results indicate the potential for managing biodiversity for improving soil structure and developing sustainable cropping systems. The inclusion of no-till in this system should only strengthen the positive benefits.

The relationship of tillage to soil organic matter and soil biodiversity. The organic matter content of agricultural soils is highly related to their potential productivity, tilth, and fertility. Intensive cropping and tillage systems have led to substantial decreases in organic matter levels with parallel declines in soil productivity (Smith and Elliott, 1990). Decreases in soil organic matter result in decreases in soil nutrient content, water holding capacity, and nutrient cycling capability and increases in soil crusting.

There is evidence that tillage affects the food web, however, many effects are not clear. The changes likely reflect changes in the soil organic matter, changes in soil structure and the physical effects of tillage on some of the larger flora. In Georgia, the no-till system was dominated by fungi and earthworms while bacteria, nematodes, and enchytraeids dominated the conventional till system (Hendrix et al., 1986). Tillage reduces soil organic matter content and the amount of microbial biomass. Soil microorganisms including bacteria, actinomycetes fungi, algae and protozoa comprise the main part of the soil microbial biomass (Lee, 1991). Follett and Schimel (1989) studied microbial biomass as affected by no-till, stubble mulch and moldboard plow after 16 years. Soil microbial biomass was 57, 52, and 36% for the corresponding tillage treatments as compared to native sod. Also, increased tillage intensity decreased the ability of the soil to immobilize and conserve mineral N. Campbell et al. (1976) showed that crop utilization of native soil nitrogen with tillage is very low. Woods and Schuman (1986) showed soil organic matter concentrations controlled microbial biomass C concentrations. Tiessen et al. (1983) showed significant losses in labile P fractions in the soil as a result of cultivation. Soil organic matter loss is a function of degree of tillage, the environment and crop residue management (Collins et al., 1992; Smith et al., 1946).

Tillage is detrimental to soil organic matter content and causes changes in soil biodiversity. Reduced tillage and/or no-till cropping appear to be essential to the development of sustainable cropping systems that protect biodiversity. Grass in the cropping system appears favorable to maintaining soil biodiversity. For example, in Australia, pastures were the only crop that increased soil organic matter content, (Russell and Clarke, 1977).

Management and biodiversity in the soil biota. As mentioned earlier in regard to soil organic matter, management has a large effect on the soil biota. Wardle (1995) summarized the literature on the effect of tillage on the soil biota and concluded where bacteria and fungi (microflora) were considered separately they responded to tillage similarly i.e. both are often inhibited to about the same degree by tillage. However, plant residues on the soil surface of no-till tend to be dominated by fungi. Also, microbial biomass levels are stimulated in no-till often greater than would be expected by the elevation of soil organic matter. The ratio of microbial biomass carbon to soil organic matter levels is frequently higher under no-till. He speculated that this may in part be due to the quality of soil organic matter being higher in the no-till systemns.

The microfaunal groups are major components of the detritus food web and play an integral role in releasing plant available nutrients. However, the effect of the soil tillage on this group is not clear with some authors showing beneficial and others showing negative effects (Wardle, 1995). Likely more refined taxonomic and/or associated activity measurements are needed to describe differences if they exist. Tillage should affect these organisms because they feed on the microflora and soil organic matter. This is an important group in the soil biota because they also feed on plant roots. The soil biota play a major role in nutrient cycling.

Mesofauna consist mainly of springtails, mites, Protura, and Pauropoda. Springtails are usually inhibited by cultivation but in certain cases may be favored by cultivation. Part of the difference in response may be caused by the response of different groups of springtails. Cryptostigmatid and mesostigmatid mites tolerate soil disturbance poorly and are inhibited by tillage. Microarthropod populations in general do not respond well to tillage because of disrupted pore size and channel continuity (Wardle 1995).

The members of the macrofauna that have been studied the most in regard to tillage are the earthworms. Not only does the size of the earthworm population decline but there is also a reduction in diversity of species when pasture is converted to arable cultivation (Fraser, 1994). Fraser (1994) reviewed the effects of soil and crop management practices on the soil macrofauna. Pastures are beneficial particularly to earthworms and appear related to productivity. Tillage decreases soil organic matter, earthworm population, and the diversity of the earthworm population. No-till seeding favors earthworm populations when compared with conventional tillage. The use of surface mulches or surface management of crop residues with no-till seeding is beneficial to earthworm populations. The use of fertilizers particularly to pastures can be beneficial to earthworm populations when the practice results in increased biomass production. Haynes et al. (1994) found with over 3 yrs of pasture, earth worm numbers were over 800m^{-2}, while with over 3 yrs arable cropping, numbers were less than 400m^{-2} and fell to below 200m^{-2} with over 9 yrs continuous arable cultivation. Microbial biomass was less than 400mgCkg^{-1} and with over 6 yrs in pasture it was over 500mgCkg^{-1}. Similar relationships exist in croplands. Rovira et al. (1987) showed no-till seeded plots contained twice the earthworm numbers than those conventionally seeded regardless of rotation. Karlen et al. (1994) compared no-till, chisel, and plow treatments for 12 yrs and found earthworm populations were highest in the no-till treatments. They also showed that the no-till plots had more water stable aggregates which imparts resistance to erosion, aids root penetration, improves aeration, and aids water infiltration. Wardle (1995) stated that tillage has a more dramatic effect on the macrofaunal than the microfaunal groups at the species level.

Wardle (1995) also, addressed the role of alternative agricultural systems which include "low input" and "organic systems". These systems frequently contain higher levels of soil biota than comparable conventionally farmed systems. He stated that differences between conventional and alternative farming systems, when they occur, most likely result from differences in cultivation, used biomass, mulching and residue management practices, and quantities of organic matter input. It also may be added in many cases that the alternate system practices a more intensive crop rotation than the conventional (Bolton et al. 1985). While few concrete data exist, it seems reasonable that crop rotation would benefit the soil biota.

Haynes et al. (1995) compared wilderness, 11 yr arable cultivation and 38 yr of grazed improved pasture with 3 rates of superphosphate 0, 188 and 376 kg ha^{-1} yr^{-1}. Earthworm numbers and microbial biomass C increased in the order arable < wilderness <0<188<376. These data clearly show the benefit of pasture for improving micro and macrofauna. Miller and Dick (1995a) showed in a 2-yr study that a legume green manure in a vegetable rotation resulted in a large increase in microbial biomass to soil carbon ratio. Furthermore, the labile organic matter pools were increased. In the same study, (Miller and Dick, 1995b) followed the enzyme activities and thermal stabilities of L-asparaginase, amidase and B-glucosidase and concluded enzyme activity is a sensitive biological indicator of the effects of soil management practices. The question is one of being able to link these enzyme activities with specific elements of the soil biota. Hassink et al. (1991a, b) showed management practices also affected the rhizosphere community. In the top 25cm, the size and activity of the microbial biomass was greater in the reduced input field. The diversity of the fungal and bacterial populations decreased in July and August with the strongest decrease in the rhizosphere of the conventional field. Gupta et al. (1994) showed residue retention when compared with burned, increased the size of the labile mineralizable C and N pools. They found that continuous retention of high C/N ratio cereal residues increased microbial activity but not the size of the microbial biomass. However, with a cereal-legume rotation, microbial biomass was increased but its activity was decreased resulting in an accumulation of particulate organic matter. Soils which have been degraded by tillage or erosion so that aggregate structure has been altered have low levels of soil microorganisms, particularly fungi (Gupta and Germida, 1988). They felt that a measure of microbial activity must be considered when defining changes in the quality of organic matter and health of a soil.

Management such as fallow can be extremely damaging to microbial diversity and likely the total soil biota. Soil microorganims including bacteria actinomycetes, fungi, algae (mostly blue-green algae) and protozoa comprise the major portion of the soil microbial biomass

(Lee 1991) Schnurer et al. (1985) found a bare fallow field that had received no fresh C for 27 yr had a microbial biomass of 230 µg g^{-1} as compared with 604 µg g^{1} for a field that regularly received straw and N additions. These results show the close link of microbial biomass with tillage and residue return.

Reduced tillage protects soil organic matter, nutrients, soil microbial biomass and greatly decreases soil erosion (Doran, 1980a, b; Lynch and Panting, 1980). Biochemical activity also increased near the soil surface when no-till planted soil was compared with conventional managed soil. Soil microbial biomass and selected enzyme levels also responded similarly to tillage in the subarctic (Cochran et al., 1989). As with the diversity of microorganisms, management greatly affects the diversity of the soil fauna (Wardle, 1995).

A legume in the rotation can be very beneficial for increasing crop productivity. Elliott et al. (1987) included several legumes in the rotation. While red clover (*Trifolium pratense* L. produced the smallest biomass and amount of N fixed by the legumes tested, winter wheat following the red clover outyielded winter wheat following the other legumes tested such as Austrian winter peas (*Pisum sativum* spp., *arvense* L., Poir) which fixed greater quantities of N. The effect was obviously not due to fixed N. It is tempting to postulate the yield increase resulted from a more favorable soil biodiversity resulting from the clover. The factors responsible for these beneficial relationships need to be identified

Biodiversity rhizosphere relationships. The beneficial effects of grasses and legumes in the rotation and the use of green manures are likely due, at least in part, to the interruption of soil-borne disease cycles and of deleterious rhizobacteria cycles (Rovira et al., 1990). For example, in most instances, a proper three crop rotation will alleviate most soil-borne disease problems. It is tempting to postulate that these practices cause shifts in biodiversity of the soil biota and these shifts in the microbiota are unfavorable to the harmful or undesirable organisms.

There is evidence that certain cropping systems such as no-till seeding and monoculture can increase deleterious rhizosphere microorganisms (DRMO). DRMO were defined as minor pathogens that affect plants with their metabolites without parasitizing plant tissues (Schippers et al., 1987) and include both bacteria and fungi (Suslow and Schroth, 1982). Schippers et al. (1987) found that yields of wheat and especially potatoes (*Solanum tuberosum*) were sensitive to the frequency of the rotation but were unable to attribute the low yields to known soil-borne pathogens. They postulated the yield reductions resulted from nonspore-forming DRMO. Studies in the Pacific Northwest on DRMO pseudomonads indicated that as the frequency of winter wheat in the rotation increased, the populations of DRMO (pseudomonads) increased on the wheat rhizoplane (Rovira et al., 1990). Other causes of the plant growth retardation cannot be ruled out, and the direct effect of DRMO cannot be established in soil with current technology.

Possibly some of these adverse reactions can be alleviated by changing tillage, residue management, and crop rotation. However, it may be possible to alter rhizosphere colonization by other means. Neal et al. (1973) showed that spring wheat exercised some control over colonization of its roots by physiological groups of bacteria. Mawdsley and Burns (1994) presented data that inoculation of wheat seedlings with a *Flavobacterium sp.* resulted in altered rhizosphere enzyme activities. Residue placement has physical, chemical, and biological implications on rhizosphere colonization and thus biodiversity. Crop residues serve as a secondary food base or energy source (assuming hosts or roots are the primary food sources) for potential rhizosphere colonists, whether they are pathogens or nonpathogens. Continuous no-till situations normally have more soil moisture than conventional till which will also influence the flora (Wardle, 1995).

The rate of degradation of crop residues depends on whether they are placed on the surface or buried (Stroo et al., 1989). The position of the residue affects microbial colonization and substrate availability and in turn influences rhizosphere colonization. Buried residues are diluted and usually have a more stable temperature and moisture environment than surface-managed residues.

No-till seeding, at least as we now know it, may not be useful in all cases. Farmers moved away from direct drilling of wheat in many of the higher rainfall areas in New South Wales of Australia because of a disorder termed "poor early growth." Chan et al. (1987) made plant measurements that indicated the poor plant growth in no-till, with or without fallow, was due to poor growth after germination rather than poor seedling emergence. When bacterial isolates from root rhizospheres were tested for their ability to inhibit root growth, inhibitory populations were higher from the rhizosphere of plants direct seeded than where the soil had been cultivated. They concluded the cause was physical or biological and made no reference to root pathogens such as *Phythium* and *Rhizoctonia* sp. which can cause poor seedling growth of direct drilled wheat. It is possible that DRMO were involved.

The detrimental organisms appear to be associated with the previous crop residue, especially when the straw remains on the soil surface. When nonsterile winter wheat straw was inoculated with a rifampicin-marked DRMO at 1/1000th the population of the native bacterial flora and incubated at 5 and 15°C, the organism multiplied rapidly to almost the same numbers as the indigenous bacterial flora (Fredrickson et al., 1987). While no-till cropping systems appear to develop favorable situations for microbial biodiversity, these results indicate there are circumstances where problems can occur. Stroo et al., (1988) found that DRMO inoculated on barley residues in the field in October maintained populations greater than 10^{6} cfu g^{-1} of surface straw and declined in mid-March. Populations on residues in no-till plots were approximately 10-fold higher than those in the tilled plots. Undoubtedly this problem can be solved by using alternate surface residue management approaches and by devising appropriate crop rotations. In many cases DRMO problems appear to be associated with lack of crop rotation.

There is potential for using DRMO for weed biocontrol. The move to no-till cropping systems will demand environmentally friendly weed control approaches. Weeds are the main cause of failure of conservation tillage systems. One weed that has been troublesome in the Pacific Northwest is downy brome (*Bromus tectorum*). Laboratory studies found DRMO inhibitory to downy brome but not winter wheat (Cherrington and Elliott, 1987). Later field studies with difference DRMO showed significant reduction of downy brome growth and increased winter wheat yields (Kennedy et al., 1991). More recent studies have shown the potential for using DRMOs to control downy brome infestations in Kentucky bluegrass (*Poa pratensis*) seed production fields (Elliott and Mueller-Warrant, unpublished data). Currently the efficacy of DRMOs for weed control is unpredictable. However, this is the case for many biocontrol agents (Elliott and Lynch, 1995). More knowledge on the relationship of biodiversity to the efficacy of biocontrol agents and the effects of rotation, soil type, and residue management is needed. This approach to weed control shows promise and is environmentally friendly. It also offers an alternative approach for removing volunteer seedlings in certified grass stands which are weeds which must be removed to preserve certified seed quality.

Measuring microbial biodiversity or indicators of biodiversity. There are several possibilities for measuring microbiological biodiversity. Enumeration of microorganisms or groups of microorganisms, enzyme levels and/or activity, microbial biomass, and genetic markers and/or gene expression can provide measures of biodiversity (Lynch and Elliott, 1996). However, the measurement must be accurate and measure temporal changes. In this manner, cropping systems and rotations can be followed and desirable characteristics integrated into sustainable cropping systems. For example, we know grass is very beneficial in the rotation. Soil structure, resistance to erosion, a large rotational effect, and increases in soil organic matter and microbial biomass are well established benefits from grass sod and grass in the rotation. In order to capitalize on these benefits, we must be able to measure the interactions.

Counting of microorganisms has not been successful. With plating techniques only about 1% are estimated to be enumerated (Hawksworth and Mound, 1991). Some organisms appear unculturable with current techniques. Plate counting approaches have a large error also. More organisms can be counted microscopically but this is tedious and it is difficult to differentiate viable organisms and no information can be gathered on activity. Bolton et al., 1985, showed farming practices significantly affected soil microbial biomass and certain enzyme levels but microbial counts did not reflect these differences. If it can be established that a group of microorganisms are responsible for a function of biodiversity, and the organisms are culturable, enumeration would be quite useful. At this time, this kind of clear relationship does not exist. With the larger soil biota these relationships can be measured by developing better classification and means for identifying activity.

Soil enzymes can be measured quite accurately and many will reflect increased soil organic matter because generally as soil organic matter increases, the size of the microbial biomass increases. It would stand to reason that as biomass fluctuates so will specific associated enzymes. The problem is that it is difficult to identify the sources of the enzymes in many cases, and we cannot measure the activity of the enzyme directly. Naseby and Lynch (1997) have suggested it may be possible to measure differences in systems more precisely by measuring enzyme activity in the rhizosphere. In some cases it may be possible to follow substrate conversion as an activity measurement. Generally this approach is difficult.

Jordan and Kremer (1994) showed microbial biomass C and N, phosphatase activity, and total fungal biomass showed measurable differences in cropping histories at the Sanborn field site. However, these practices have been established for long-term plots and likely do not represent temporal changes. Miller and Dick (1995a,b) were able to show differences in enzymes as affected by vegetable cropping over a relatively short period of time. Nannipieri (1994) points out the need for more study.

As discussed earlier, the size of the microbial biomass correlates with many measurements that relate to microbial biodiversity. The problems with microbial biomass measurements are that no information is provided on the population affected, the determination can be subject to large errors, and in many cases, several years are needed to detect differences in the size of microbial biomass as affected by tillage and crop rotation.

Lynch and Elliott (1996) described molecular approaches for assessing microbiological biodiversity. These include marker or reporter genes and nucleic acid probing. Using a marker or a reporter gene one can follow a specific organisms as an indicator for the behavior of a population. Rattray et al. (1995) used the lux marker to follow *Enterobacter cloacae* in soil and on the rhizosphere. Markers have been used to successfully describe genetic exchange in soil and within the rhizosphere. The use of a DNA probe only provides information that a gene is present. It provides no information on function. A mRNA probe potentially provides information on function. To use mRNA for this role, it must be identified with a specific group or groups of soil biota. Function also depends on the presence of the substrate which is usually present if the enzyme is induced. The difficulties that can be encountered with these approaches was shown by Kimura et al. (1992). They isolated bacteria from soil under facultatively anaerobic conditions and found the *nif*-gene was present in about 50% of the bacteria isolated on an N-free medium. Obviously the gene was present but not functioning in a large number of the isolates.

Other specific experimental approaches to identifying factors indicative of soil health or soil quality were outlined by Doran et al. (1994). These indicators include soil physical and chemical characteristics which are relatively easy to measure. The biological indicators include: microbial biomass, potentially mineralizable N, and soil respiration. These indicators will provide information that is directly related to soil microbial biodiversity. However, as we have seen, these relationships are not always proportional to each other. Also, these quantities do not always provide good temporal information. They will be useful only if the changes in these measurements can be equated with changes in the microflora, microfauna, mesofauna, or macrofauna or in some combination there of. Then these relationships must correlate with soil tillage and/or cropping system.

For better descriptions of faunal interactions better taxonomic descriptions are needed to separate groups of the microfauna and for some components of the mesofauna. Measures of activity of these organisms would be very useful to better describe their role in the food web and to assess their response to perturbations. Conflicting data for these organisms as affected by tillage appear in some cases (Wardle, 1995). Better definition of the different groups might resolve these differences. Also, care must be exercised that data are collected from stable systems i.e., cropping systems that have been in place for at least 5 yrs before comparisons are made.

The value of soil biodiversity relationships. The development of sustainable cropping systems is a high priority goal. Maintaining soil productivity and health is an important component of sustainable agricultural systems. Other components include economic viability, social acceptance, environmental and non-renewable resource protection and the production of healthy nutritious food.

Defining a sustainable cropping system is difficult. We can measure environmental effects, economic viability, quantities of soil erosion, and crop production to mention some characteristics. We know that grass based cropping systems are beneficial to these characteristics as are many no-till cropping systems. If we can develop the ability to accurately characterize soil biodiversity relationships in regard to these characteristics, we should be able to track changes in the biodiversity possibly by an approach similar to that proposed by (Wardle, 1995). The approach places the soil animals into groups ranging from -1 to +1 with the groups most damaged by tillage being ascribed more negative values and those benefitted by tillage having a more positive value.

Being able to track changes in biodiversity will be extremely valuable for users and policy makers. Users will be able to implement cropping practices that will benefit soil quality and beneficial biodiversity relationships. Policy makers will have guidelines that should help prevent policy decisions that inadvertantly have negative effects on soil quality and biodiversity. These kinds of decision aides could be extremely valuable for land reclamation policies for example. They would be valuable for policy guidelines that would discourage decisions that would encourage practices such as monoculture or extensive tillage.

Research needs.

1. Studies are needed to investigate the response of the several trophic levels (microflora, microfauna, mesofauna, and macrofauna) of the detritus food web with agricultural management practices.

2. We need better understanding of the linkages between the macrofauna and the microflora, microfauna, and mesofauna.

3. We need better Taxonomic descriptions of flora and fauna groups and integration with activity measurements.

4. The linkage of arbuscular mycorrhizae with microbial systems and the detritus food web is poorly understood. More information is needed because this could be an important link to nutrient cycling and soil structure.

5. Information is needed to define soil organic matter quality in order to establish relationships to the food web, tillage, and cropping system.

6. Research is needed to link soil enzymes with activity and with the soil biota.

7. Studies are needed to link efficacy of biocontrol treatments (inoculum) with soil biotic factors, soil management, inoculum preparation, and inoculum carriers.

8. The soil biota must be linked with tillage, cropping system, nutrient cycling, soil stability, water infiltration, soil erodibility, soil crusting, and soil organic matter.

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