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Dr. Jill Clapperton is the Rhizosphere Ecologist at the Agriculture and Agri-Food Canada Lethbridge Research Centre in Lethbridge, Alberta, Canada. She is an internationally respected lecturer presenting research findings and promoting an understanding of how soil biology and ecology interact with cropping and soil management systems to facilitate long-term soil quality and productivity. Her research group studies soil food webs, nutrient cycling, soil fauna- plant disease interactions, rhizosphere interactions, and soil biodiversity. The Rhizosphere Ecology Research Group studies rangelands, and cropping systems under low-input and organic management systems emphasizing reduced and no tillage. The aim of this research is to understand how soils function biologically so we can effectively manage and benefit from the long-term biological fertility of our soil. Jill has a keen interest in promoting science in schools and participates with other researchers and educators to develop soil ecology educational programs. The Worm Watch program (www.wormwatch.ca) she founded, has recently been cited by the National Science Teachers Association for excellence in science education. In 2000, Dr. Clapperton received the Patricia Roberts-Pichette Award from Environment Canada for enthusiastic leadership and commitment to advancing ecological monitoring and research in Canada.

The Real Dirt on No tillage

When we are standing on the ground, we are really standing on the roof top of another world. Living in the soil are plant roots, viruses, bacteria, fungi, algae, protozoa, mites, nematodes, worms, ants, maggots and other insects and insect larvae (grubs), and larger animals. Indeed, the number of living organisms below ground is often far greater than that above ground. Together with climate, these organisms are responsible for the decay of organic matter and cycling of both macro- and micro-nutrients back into forms that plants can use. Microorganisms like fungi and bacteria use the carbon, nitrogen, and other nutrients in organic matter. Microscopic soil animals like protozoa, amoebae, nematodes, and mites feed on the organic matter, fungi, bacteria, and each other. Together, these activities stabilise soil aggregates building a better soil habitat and improving soil structure, tilth and productivity. Agricultural practices such as crop rotations and tillage affect the numbers, diversity, and functioning of the micro- and larger-organisms in the soil community, which in turn affects the establishment, growth, and nutrient content of the crops we grow. In this session, you will be introduced to the activities of soil organisms (both micro and macro in size) in terms of how they affect the cycling and availability of nutrients to crops, disease cycles, weed management, and soil tilth and erosion potential. More detailed examples with mycorrhizal fungi and earthworms will demonstrate the important role of soil biology in improving soil quality and productivity. The session concludes with a discussion of how soil biological activities are influenced by soil management practices.

Managing the soil as a habitat for soil biological fertility

Soil is much more interesting than dirt. It is a complex inorganic and organic matrix, the habitat for the highly diverse community of microorganisms, soil fauna, and plants, which we learned about in the first session. Soil biota effect soil fertility and hence the primary productivity of the ecosystem that they inhabit, soil biological processes are responsible for approximately 75 percent of the available N and 65 percent of the available P in the soil. Plants can take-up and use nutrients made available through biological processes more easily and efficiently compared with chemical fertilisers. Soil fertility is largely dependent on the processing of organic substrates – residues or soil organic matter (SOM)- through the soil food-web. Soil biota require the maintenance of a suitable soil habitat, with an adequate quantity and quality of organic matter as an essential food source. In agriculture, we modify the soil habitat with tillage and crop rotation practices and so influence the ability of the soil ecosystem to provide essential services such as decomposition and nutrient cycling. This can affect the nutrient quality of the food and forages we produce, and ultimately human and animal health. This more informal workshop session will explore the use of specific soil and crop management practices that enhance soil biological properties giving us the opportunity to take advantage of soil biological fertility, and augment chemical fertilizer regimes. So bring a pen and paper, and willingness to participate in the discussion and activities. You will take home new ideas and a renewed enthusiasm for farming.

The Real Dirt on No-Till Soil

Jill Clapperton

"Whatever you can do, or dream you can, begin it. Boldness has genius, power and magic in it" - Goethe

When we are standing on the ground, we are really standing on the roof-top of another world. Soil might look like "dirt" but it is far more interesting! Living in the soil are plant roots, viruses, bacteria, fungi, algae, protozoa, mites, nematodes, worms, ants, maggots and other insects and insect larvae (grubs), and larger animals. Indeed, the volume of living organisms below ground is often far greater than that above ground. Together with climate, these organisms are responsible for the decay of organic matter and cycling of both macro- and micro-nutrients back into forms that plants can use. Microorganisms like fungi and bacteria use the carbon, nitrogen, and other nutrients in organic matter. Microscopic soil animals like protozoa, amoebae, nematodes, and mites feed on the organic matter, fungi, bacteria, and each other. Together, these activities stabilise soil aggregates building a better soil habitat and improving soil structure, tilth and productivity. Agricultural practices such as crop rotations and tillage affect the numbers, diversity, and functioning of the micro- and larger-organisms in the soil community, which in turn affects the establishment, growth, and nutrient content of the crops we grow.

In this presentation you will be introduced to the activities of soil organisms (both micro and macro in size) in terms of how they affect the cycling and availability of nutrients to crops, disease cycles, weed management, and soil structure and erosion potential. More detailed examples with mycorrhizal fungi and earthworms will demonstrate the important role of soil biology in improving soil quality and productivity. The presentation finishes with a discussion of how biodiversity of soil organisms and their activity is influenced by soil management practices, and points to ways that we use soil biological fertility to our advantage.

Background concepts

Soils are formed from a stew of geological ingredients or parent materials (rocks and minerals), water, and billions of organisms. The interactions between climate, parent material, organisms, landscape, and time affect all major ecosystem processes which leads to the development of soil properties that are unique to that soil type and climate. The activities of and chemicals produced by, soil micoorganisms, and the chemicals leached from plant residues and roots can further influence the weathering of parent materials changing the mineral nutrient content and structure of soil. Thus, farm management practices such as crop rotations, tillage, fallow, irrigation, and nutrient inputs can all affect the population and diversity of soil organisms, and in turn, soil quality.

There are three soil properties that define soil quality: chemical, physical and biological. The chemical properties of a soil are usually related to soil fertility such as available nitrogen (N), phosphorus (P), potassium (K), micronutrient uptake of Cu, Zn, Mn, and etc, as well as organic matter content (SOM) and pH. Soil structural characteristics such as aggregate formation and stability, tilth, and texture are physical properties. The biological properties of a soil unite the soil physical and chemical properties. For instance, fungi and bacteria recycle all the carbon, nitrogen, phosphorus, sulphur and other nutrients in SOM, including animal residues, into the mineral forms that can be used by plants. By breaking down the complex carbon compounds that make up SOM into simpler compounds, soil organisms acquire their energy.

At the same time, the root exudates, hyphae of the fungi and the secretions and waste products of the bacteria are binding small soil particles and organic matter together to improve soil structure. This makes a better soil habitat that attracts more soil animals, which further increases the amount of nutrient cycling. Faecal pellets from soil invertebrates and castings from earthworms increase the number of larger sized soil aggregates, allowing for more water infiltration, aeration and better rooting. The activities of soil animals mix smaller organic matter particles deeper into the soil acting to increase the water holding capacity of the soil. Thus, biological activities hold the key to maintaining or increasing soil productivity.

Soil productivity is mostly measured in terms of yield (Brady, 1974), and is a function of soil structure, fertility, and the population, species composition, and activities of soil organisms. We further suggest that health, nutrient content and value of the crops, and environmental quality both on and off the farm should also be considered as a measure of soil productivity. Studies have shown that soil bacteria and fungi regulate the destruction of toxic environmental pollutants like nitrous oxides and methane (greenhouse gases), and some pesticides. The speed at which residues decay and nutrients are released from SOM, and pollutants and pesticides are detoxified, will in turn be largely dependent on how we manage the soil.

Farm management practices, and the effect they have on soil organisms will also influence the processes that determine the health of our environment on a broader scale. Soil erosion or leaching of soluble nutrients contributes towards the contamination of rivers with nutrients (eutrophication). For instance, the nitrogen from incorporated residues is released and readily leached by rain and melt water making its way into surface and ground water. Incorporating nitrogen rich green manures into the soil using tillage in the summer or fall and then leaving these residues until the following spring may therefore affect eutrophication. Residues left on the surface initially release more atmospheric emissions than incorporated residues but are less subject to leaching, releasing nutrients more gradually. Soils are also less likely to erode when residues are retained. Drinkwater et al. (1998) suggested that using low carbon to nitrogen residues like those used in organic legume-based cropping systems to maintain soil fertility, when combined with more diverse cropping rotations can increase the amount of carbon and nitrogen that is retained in the soil. This could have positive effects on regional and global carbon and nitrogen budgets, sustained productivity, and environmental quality.

I. The Rhizosphere

In undisturbed soil, most of the nutrient cycling, roots, and biological activity are found in the top 20 to 30 cm, called the rooting zone. The rhizosphere is characterised as a zone of intense microbial activity, and represents a close relationship between the plant, soil and soil organisms.

The rhizosphere is bathed in energy-rich carbon compounds, the products of plant photosynthesis, which have leaked from the roots. These include sugars, amino acids and organic acids and are called root exudates. Every plant species leaks a unique signature of compounds from their roots. The quantity and quality of these compounds depends to a certain extent on the soil chemical and physical properties, but in all cases determines the microbial community of the rhizosphere. Symbionts like the bacteria *Rhizobium* that fix nitrogen in legumes, and disease-causing pathogens, may be particularly well tuned to the composition and quantity of root exudates and be attracted to a particular plant. This means that it is also important to carefully match legume crop species with the appropriate commercial microbial inoculants**.**

More generally, bacteria and fungi use root exudates and the dead sloughed cells from the root to grow and reproduce, but competition for a space on or near the root is stiff. In the battle for carbon compounds, bacteria often produce antibiotics and poisonous chemicals and gases that remove the competition (which on occasion can also reduce plant growth), and/or plant growth promoting substances that increase root growth, the amount of root area available for colonisation, and root exudates. The sticky secretions from the bacteria in combination with exudates and dead and decaying root cells create tiny soil aggregates and a habitat for scavenging and predator protozoa, nematodes and mites that feed on the large numbers of bacteria and fungi. In turn, the faecal pellets from these microscopic animals add to the structure of soil and are a rich source of nutrients for bacteria and fungi, and plants. For instance, in greenhouse studies, plants grown in soil with added bacterial- and fungal- feeding nematodes had more shoot growth and a higher yield than plants grown in soil without the nematodes. Mega fauna like earthworms feed in the nutrient rich matrix around the rhizosphere consuming large quantities of dead plant material, fungi, protozoa and bacteria. The castings left by earthworms are rich in available nitrogen for plants and bind and stabilise smaller soil particles into larger aggregates improving soil fertility and structure. Plant roots can move easily through earthworm channels allowing the plant to take advantage of the available nitrogen that lines earthworm burrows. The sticky secretions and webs of fungal hyphae bind smaller soil particles, like those formed by bacteria, into larger aggregates further improving soil structure.

In review, the rhizosphere is a partnership between the plant, soil and soil organisms. Plants provide the carbon food source for soil organisms that bind the soil particles into aggregates and recycle soil nutrients, and soil provides the habitat, water, and mineral nutrients for both soil organisms and plants. This means that any factor or soil management technique that changes the amount and quality of carbon going into the soil, as either residue or root exudates, will effect change in the soil biological community. Understanding and then managing rhizosphere processes could have far-reaching advantages in agriculture in terms of increasing plant growth and nutrient uptake and soil habitat structure and health, and reducing the environmental consequences of agriculture.

II. The Rhizosphere and Vesicular-Arbuscular Mycorrhizal (VAM) Fungi

VAM fungi probably form the most intimate relationship between the plant, soil and soil organisms, best illustrating the potential for using rhizosphere processes to improve soil quality and productivity. VAM fungi form a mutually beneficial or symbiotic relationship with 80 percent of all land plants, including warm- and cool-season cereals, pulses, forages, and some oilseeds. They appear to be essential to the establishment, growth and survival of many plant species. For instance, VAM fungi are critical in the early establishment and growth most cereals and particularly warm season grasses like maize, sweet corn, and sorghum. They are also important for early establishment and growth of some non-cereal crops like sunflower, flax, and potatoes.

VAM fungi penetrate the cells of the root without harming the plant. From the root, the microscopic hyphae extend like a network of silk threads through the bulk soil. VAM fungi can be considered a highly effective transport system, like a pipeline, between the soil and the plant, moving water and nutrients to the plant in exchange for direct access to the carbon-rich products of photosynthesis. VAM fungi are most well known for their ability to increase the uptake and plant content of less available mineral nutrients such as phosphorus (P), calcium (Ca), zinc (Zn), and copper (Cu). For instance, increasing colonisation by VAM fungi can in turn increase the mineral nutrient content of wheat (Clapperton et al., 1997a). The degree to which a particular plant relies on VAM for access to nutrients is termed its level of dependency. Highly dependent crops often have limited root systems, with thick roots and few root hairs. Less dependent plants will have larger fibrous root systems that are well adapted to competing for nutrients. Even less dependent plant species may rely on VAM fungi when under environmental stresses such as drought. VAM fungi are also known to increase resistance of the plant host to root diseases. VAM hyphae will tie and glomulin secreted by the hyphae glue soil particles into more erosion-resistant aggregates.

Table 1. The relationship between some crop species and VAM fungi

High dependency	Low dependency	Non-hosts
Peas, Beans, and other legumes	Wheat and other cereals	Canola, Mustard and other brassicas
Flax		Lupins
Sunflowers		
Maize and other warm season cereals		

Once plant roots are colonised by VAM fungi, their physiology and biochemistry change. They have higher rates of photosynthesis, better water use efficiency, and move more and different kinds of carbon compounds to the roots. Consequently, there is a different rhizosphere community associated with the roots of VAM-colonised plants; a rhizosphere with fewer pathogens, more nitrifiers, and other changes that we still don't know about (nitrifying bacteria convert ammonia to nitrate, which is easier for the plant to absorb).

The degree of colonisation by VAM fungi and the benefits of having plants colonised by VAM fungi can be reduced by tillage and incompatible crops in rotation including non-mycorrhizal host plants, such as canola (Table 2). Although, populations of soil fauna like earthworms and nematodes tend to increase under canola. The addition of fertilisers containing easily soluble phosphorus, including non-composted manure, will greatly reduce VAM colonisation.

Table 2. The percentage of root length colonised by VAM fungi at tillering for wheat grown after three different previous crops in SE Australia.

Previous crop	Wheat	Peas	Mustard
VAM %	58	58	30

From: M. Ryan (unpublished data)

Populations of VAM fungi can be rebuilt under reduced tillage by using only the required amount of composted manure or poorly soluble phosphorus fertilisers such as rock phosphate. Furthermore, including pasture and perennial crop phases, legumes, and other highly dependent crops such as maize, sorghum, flax and sunflower in the rotation can dramatically increase populations and networks of VAM fungi. Research has shown that some species of VAM fungi can promote growth in one crop and inhibit it in another in two and three phase rotations. This is another demonstration of how important soil biodiversity is to creating flexible cropping systems. The interaction between crop rotation, VAM fungi, soil animals, and plant establishment and growth needs more research so we can take better advantage of the benefits that VAM fungi confer on some crops.

III. Earthworms are soil mega fauna

The presence of earthworms in the soil is often considered to be a positive indicator of soil quality and productivity. Earthworm numbers increase dramatically with no tillage and in undisturbed systems. The burrowing activities of earthworms increase soil aeration, water infiltration, nitrogen availability to plants, and the microbial activity in the soil. 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. The increased nitrogen available in the drilosphere may be another reason why roots often grow in earthworm channels. Earthworm burrows can be stable for years, acting to increase the extent and density of plant roots as well as stabilising soil aggregates to improve soil structure and limit erosion. It has been suggested by a number of researchers that earthworms are major contributors to the breakdown of organic matter and N cycling in reduced tillage systems. Earthworms prefer plant material that has been colonised by fungi and bacteria, which can lead to the reduced incidence of fungal diseases in crops. Indeed, earthworms are probably most important in reduced tillage systems, not only because these systems encourage earthworm populations but, because without mechanical mixing and loosening, earthworm casts and burrows are left intact to encourage better root development. In long-term dryland tillage experiments at the Lethbridge Research Centre, we have found as many as 300 earthworms per square meter under no tillage compared with none under conventional tillage (Clapperton et al., 1997b). In this same field experiment there was a significantly lower incidence of common root rot under no tillage compared with conventional tillage, demonstrating the long-term benefit of maintaining the soil habitat. In Australia, the same earthworm species that are common in North and South America agriculture were found to increase perennial pasture productivity by 30 percent over pastures without earthworms (Baker et al., 1999).

Earthworm populations can be increased by reduced tillage in combination with crop rotation. Introducing earthworms into soil is not recommended because we presently understand very little about the ecology of the earthworms in North America. The earthworms (*Eisenia foetida* or red wigglers) used for vermicomposting are not native to the Americas neither are they earth-working earthworms and therefore are not appropriate for field agriculture. The dew worm or night crawler (*Lumbricus terrestris*) used for bait is not appropriate for introduction into Prairie soils because it deposits casts containing high amounts of clay on the soil surface that when unmulched can create a clay hard-pan and problems with surface water erosion. The fastest way to increase earthworm populations is by reducing soil disturbance, and direct-seeding crops for as many years in a row as possible, and/or including perennial crops and/or pasture into the rotation. You can further increase earthworm populations by adding oilseed crops and retaining legumes in rotations under no tillage. Research has shown that there are more and bigger earthworms under no tillage after oilseed (particularly flax and canola), and legume crops compared with cereals (Clapperton and Lee, 1998).

IV. Managing the soil as a Habitat

Soil management is defined by Nyle Brady (1984) as the sum of all tillage operations, cropping practices, fertilizer, soil amendments, and other treatments applied to the soil for the production of plants. Once again, the emphasis is on the interconnectedness between all farming practices and the soil.

a) Tillage

Management practices that affect the placement and incorporation of residues like tillage can make it harder or easier for the soil organisms responsible for cycling nutrients. Tillage directly affects soil porosity and the placement of residues. Porosity determines the amount of air and water the soil can hold. Placement of residues affects the soil surface temperature, rate of evaporation and water content, and nutrient loading and rate of decay. In other words, tillage collapses the pores and tunnels that were constructed by soil animals, and changes the water holding, gas, and nutrient exchange capacities of the soil. Reduced tillage and particularly no tillage reduce soil disturbance, increase organic matter content, improve soil structure, buffer soil temperatures, and allow soil to catch and hold more melt and rain water. No tillage soils are more biologically active and biologically diverse, have higher nutrient loading capacities, release nutrients gradually and continuously, and have better soil structure than reduced or cultivated soils.

No tillage dramatically increases the population and diversity of soil animals, particularly soil mites that feed on fungi. Under no tillage, litter or residue is primarily decomposed by fungi that accumulate nitrogen in their hyphae, in response the population of fungal feeding mites increases rapidly, using some of the nitrogen from the fungi and releasing the remainder into the soil to be used by plants and other organisms. No tillage systems and rotations with perennial crops or pasture show greater resilience (they can recover faster after disturbances such as drought, flood or tillage). The populations and species diversity of soil animals are higher, there is more SOM, and nitrogen is recycled into the system at a greater rate compared with conventionally tilled systems.

b) Soil amendments and crop residues

Higher organic matter content of soils from using no tillage and rotations, and/or the direct applications of manure or composts may reduce disease. Many of the soil organisms that are rapid colonisers of organic matter are antagonistic to disease-causing organisms. For instance, in agricultural trial plots, Sivapalan et al. (1993) found a number of soil-borne fungi that cause root diseases, including *Rhizoctonia solani*, only on conventional vegetable plots. Fungi that are antagonistic to such disease-causing fungi, such as *Trichoderma* and *Penicillium*, were found more frequently in the organic pots, where 80-120 tonnes per hectare of compost had been applied.

Residues from some crops inhibit the growth of other plants either directly, or indirectly, from the by-products produced from the microbial decay of the residues (allelopathy). Fall rye, mustard, oats, George Black medic, hairy vetch, sunflower, oil seed hemp, and sweet clover have all been reported to inhibit the growth of weeds. Most of these crops will also increase populations of VAM fungi.

c) Rotations

The benefits of diversified crop rotations together with reduced tillage and especially no tillage can dramatically increase soil productivity while reducing off-farm costs. Low residue crops like peas, lentils, mustard, tomatoes, dry beans or canola can be rotated with higher residue cereals to reduce the trash loading. Rotating cereals and oilseeds with peas, forages, or underseeding cereals with annual or biennial legumes, which fix nitrogen, increase the amount of nitrogen available to plants in the cropping systems. The bacteria associated with legumes take N directly from the air, a process that obviously does not require large amounts of fossil fuels, like the manufacturing of commercial nitrogenous fertilisers. The residual benefits of nitrogen from these crops can be persistent for a number of years depending on the legume. Note that legumes are dependent on two symbionts, a nitrogen-fixing bacterium like *Rhizobium* as well as VAM fungi to supply the increased phosphorus required to more efficiently fix nitrogen. Many species of N-fixing bacteria like *Rhizobium* also live freely in the soil and have been shown to act as plant growth promoting bacteria. Cover cropped soil has been shown to have the largest and most diverse populations of microorganisms, compared with manure amended plots that had had a less diverse but more metabolically active population of microorganisms (Wander et al., 1995).

Soils after pasture phases and perennial crops are more structured and biologically active, have higher organic matter content, and turnover nitrogen more rapidly. Including a deep-rooted legume like alfalfa or lucerne can help increase the rate of nitrogen cycling and reduce plow-layer compaction. Mixed- and inter-cropping systems increase aboveground diversity which in turn increases diversity in the below ground community. Scientists and farmers alike speculate that a more diverse soil community results in a more flexible soil. This means a soil that has the ability to successfully grow a number of crops, and is resilient in drought, low nutrient conditions, and after disturbance.

In Conclusion ………

Creating a soil habitat is the first step to managing soil biological properties for long-term soil quality and productivity. This means using soil management practices that reduce soil disturbance, managing weeds and disease with crop rotation, mixed cropping, and underseeding, and using high quality compost and composted manure. For instance, unstructured soils with low organic matter content that have fine aggregates or clay within the plow-layer will take between 3-5 years to build the soil biological properties necessary to improve soil structure and stability depending on climate and previous soil management. It is better to start the transition to a conservation tillage system after a perennial crop or pasture phase of 2-5 years. As an added bonus, conservation tillage and having pasture and perennial crops phases in the rotation uses less fossil fuel, and with less time on the tractor, growers have more time to consider farm management details that will improve the biological activity of soil. It is generally understood that the soil biological community benefits soil productivity, yet we know so little about the organisms that live in the soil and the functioning of the soil ecosystem. Continued research aimed at understanding the interactions between soil management practices and the soil biological, chemical and physical properties of soil will be the key to sustaining the soil, environment and our future generations.

This paper was written with the intent to increase awareness among growers and the public that soils are living, breathing, and ever changing, and that the potential exists to manage and use soil properties more effectively for producing nutritious food at less environmental cost.

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