Putting Soil Health First

A Climate-Smart Idea for Ontario

November 2016

Environmental
Commissioner
of Ontario

Table of Contents

Executive Summary

Modern agriculture has achieved great success in feeding the world. Over the past few decades, yields have consistently risen as prices, on a relative basis, have dropped. New technologies and inputs have made growing crops simpler and more cost-effective. The environmental price of all this advancement, however, includes greater greenhouse gas emissions, nutrient pollution of water bodies such as Lake Erie, and increased soil degradation and erosion. Now, climate change is bringing these concerns into sharper focus, as they threaten basic food security in Ontario.

Yields have continually gone up while the price of food has, in relative terms, come down.

Fortunately, an exciting opportunity now exists to both continue to feed ourselves cost-effectively and to also protect the natural world, by building soil ecosystems and soil organic matter. This emerging opportunity is known as *the soil health approach*.

The concept of "soil health" begins with the acknowledgement that soils are living ecosystems. A handful of healthy soil contains more living organisms than there are people on the planet. These organisms, which include bacteria, fungi, protozoa, and nematodes, as well as slightly larger, visible creatures such as mites and earthworms, together make up the *soil food web*. These organisms are responsible for a myriad of beneficial functions, including soil fertility, good soil structure, water quality, toxics reduction, disease suppression, and carbon sequestration. The latter is increasingly viewed as an important method for mitigating climate change.

Unfortunately, conventional agriculture has all but ignored the soil food web. It has replaced its functions in part or in whole with synthetic inputs, such as fertilizer and pesticides. Even more importantly, it has utilized management practices, such as frequent tillage and leaving fields bare between crops, that deplete the soil food web. As a result, soil structure has suffered, leading to soil degradation and erosion. In addition, the continued over-use of synthetic inputs has led to pollution and an even further reduction in the number of soil organisms, as many pesticides are also toxic to the beneficial forms of soil life.

The soil health approach takes a completely different focus: first and foremost, it aims to *protect and enhance soil life*. This focus is crystallized in the following basic principles:

- Keep the soil covered, with plants or plant residues, at all times;
- Maximize the diversity of crops;
- Minimize soil disturbance;
- Keep live roots in the ground all year; and,
- Use organic inputs wherever possible.

Farmers who adopt the soil health approach use management practices rooted in these principles. These practices include: no-till or various types of conservation tillage; planting cover crops (crops planted to improve soil, rather than to harvest for market); using complex crop rotations; the "4Rs" of synthetic fertilizer use ("right source, right rate, right time, and right place"); producing and using compost; the integration of livestock with cropping systems; and the employment of ecological grazing systems.

Farmers who have adopted and systematically applied the principles and practices outlined above have been able to gradually but dramatically reduce synthetic inputs while at the same time becoming much more profitable. For example, Gabe Brown, a long-time soil health practitioner in North Dakota, has been able to increase his yields, improve his soil, and boost his profits – all while eliminating fertilizer inputs and reducing his pesticide use to one herbicide application every two to three years. Here in Ontario, the Belan family farm has been practicing no-till farming for 25 years and have recently introduced cover crops as well. They also have reduced their costs without lowering yields, boosting their profitability. At the same time, they have significantly reduced their environmental footprint; in fact, the Belans have increased the carbon levels in their soils by three per cent, which means that they have sequestered about 48,000 tonnes of CO_2 since changing their soil management methods.

This is all very good news. By putting soil health first, it seems likely that farmers can build on agriculture's amazingly successful modern history; they can address head-on the environmental shadow that has always been nagging at the edges of the accomplishments. It won't be easy, however. Conventional agriculture has worked very well from the perspective of the individual farmer, in part because its practices are relatively simple to execute. In contrast, a soil health approach requires greater effort by growers in terms of planning, monitoring, and managing complex rotations that often include cover or secondary crops with no obvious markets. Effectively managing disease and pest issues are another major challenge when shifting to a new approach.

Accordingly, building a wide-scale soil health focus in Ontario agriculture cannot be done overnight. Many farmers are understandably skeptical about moving away from a system that has been so successful for them and their families. They need solid evidence and successful role models to help guide the shift, along with appropriate support for financial risk as they experiment with these new ideas. The Ontario government, and especially the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), has an extremely important role to play in making all of this happen. The ministry should make the soil-health 'entrance ramp' for farmers as wide, accessible, and low-risk as possible.

To this end, the ECO is offering the following recommendations.

- The province of Ontario should become a signatory of the *4/1000 Initiative*, a climate-smart soil health commitment program championed by the Government of France.
- The OMAFRA should:
    - co-ordinate the development of a protocol, with supporting methods and technologies, for reliably estimating soil-carbon levels in Ontario; and
    - implement a program for estimating soil-carbon levels across the province every three years, and making these results public.
- The Ontario government should find a way to link the cost of crop insurance to soil-carbon levels, in recognition of the fact that, over time, high-carbon soils reduce risks to crops.
- The province should develop a program to provide financial support for up to 10 years for farmers who adopt soil health best management practices, designed to offset any yield loss due to transition issues.

The Two Stories of Modern Agriculture

Story 1 – Feeding the World

Agriculture has had a marvellous run over the past century. A modern success story, it began its most rapid ascent just after World War I, with the introduction and subsequent rapid adoption of nitrogen-based synthetic fertilizers.[1] It continued to expand through the "green revolution" of the post-WW II decades, when high-yield crop varieties were developed and deployed in conjunction with improved water-management systems, more effective pesticides, and bigger and better farm equipment. Genetically modified crops, with attributes such as herbicide (glyphosate) resistance and built-in pesticides (Bt), appeared in the 1990s[2] and have made growing common field crops, such as corn and soybeans, much simpler and less expensive. Most recently, modern technology, such as GPS-guided tractors, variable-rate fertilizer spreaders, yield-monitoring harvesters, and field-surveillance drones, are already delivering on the promise of more cost-effective, reduced-input, "precision" agriculture.

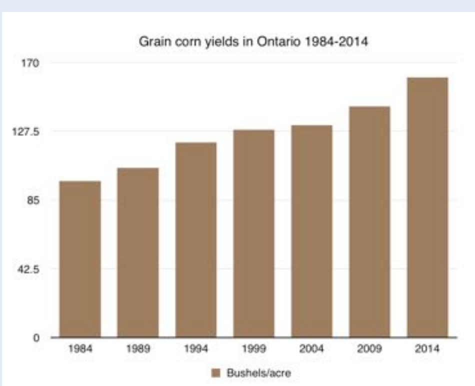


Figure 1: Grain corn yields in Ontario 1984-2014

The results of all this innovation have been remarkable. Yields have continually gone up while the price of food has, in relative terms, come down.[3,4] For instance, over the past 30 years, average grain corn yields in Ontario have risen from 102[5] bushels per acre to 170,[6] winter wheat yields have climbed from 67[7] bushels per acre to 78,[8] and soybean yields have increased from 37[9] bushels per acre to 46.[10] In terms of price, food took up almost 19 per cent of household income in Canada in 1969; forty years later, that share had dropped to slightly over 10 per cent, while offering consumers a greater variety of food options than ever before.

Savings have come from all of the factors mentioned above, but also from changes in the way farms are run. They have gotten bigger and more intensive in design and operation, a change largely driven by economies of scale.[11] Although in Ontario most farms are still family-operated, many of the elements of large-scale, intensive farming, common in other parts of the developed world, are also employed here. These include: simplified crop rotations (with few forages included);[i] control of pests and weeds primarily by means of insecticides, fungicides, and herbicides; leaving soils bare between crops; and frequent and aggressive tillage. Human management is often supplemented, or even replaced, with highly engineered inputs and "smart" equipment.

No amount of chemical input can mitigate the impacts of insufficient water at key points in crop development.

A recent increase in interest by Ontario farmers in beneficial management practices such as cover crops and conservation tillage suggests that the province may be on the verge of a transition to a lower-input model. The case studies on pp. 22-27 lend support to this position. However, the area of Ontario farmland under these better management practices is still relatively small, and the high-input, intensive model, commonly referred to worldwide as *conventional agriculture,* appears to still be the norm in our province.

Story 2 – But at What Cost?

This highly successful and constantly evolving model of agriculture has always had its doubters and detractors, especially with regard to its impact on the environment. Over the past few years, climate change has brought these concerns into sharper focus in three categories: greenhouse gas (GHG) emissions; adaptation/food security; and other environmental impacts.

GHG emissions

According to Canada's official national inventory,[12] agriculture in Ontario is responsible for about 10.0 megatonnes (Mt) of GHGs per year,[ii] or about 5.9 per cent of the province's total emissions (see Figure 1). Almost half of those emissions (4.3 Mt) result from the direct application of fertilizer to soils: nitrogen fertilizers generate nitrous oxide (N_2O) emissions (3.7 Mt of CO_{2e}), while manures (0.6 Mt CO_{2e}) give off methane (CH_4). Of the remaining 5.7 Mt CO_{2e}, almost two-thirds (3.6 Mt CO_{2e}) are due to CH_4 generated by the digestive systems of ruminants, such as cattle, (known as *enteric fermentation*) and most of the remainder (1.9 Mt CO_{2e}) are due to CH_4 from manure storage operations.

Wilting leaves show drought stress on corn

Source: Ministry of Agriculture, Food and Rural Affairs.

[i] A reduction in the number of livestock in the province over the past few years has resulted in the almost complete elimination of forages in crop rotations.

[ii] The units used for GHGs are called carbon dioxide equivalents (CO_{2e}), where CO_2 is used as the standard.

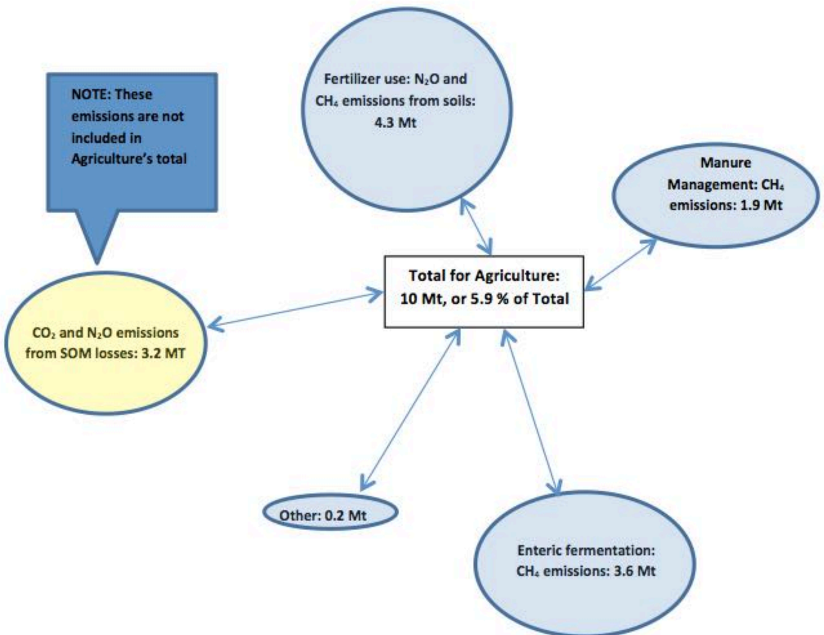


Figure 2: Agriculture's Contributions to Ontario's GHG Emissions

A new approach is required, one that is sufficient to solve the many environmental problems outlined here…without foregoing the productivity and profitability of modern agriculture.

Another 3.2 Mt CO_{2e} of greenhouse gas emissions arise as a result of the loss of soil organic matter (SOM) from agricultural land. These emissions, which are comprised of CO_2 (2.7 Mt of CO_{2e}), and N_2O (0.5 Mt of CO_{2e}) result from management practices, such as aggressive tillage and summer fallow (i.e., "resting" a field for a planting season), which tend to reduce SOM levels.[13] Agriculture and Agri-Food Canada (AAFC) estimates that 82 per cent of Ontario farmland is losing SOM annually, with over 50 per cent of that land losing at least 90 kg of CO_{2e} per hectare per year.[14]

Note that these emissions are classified under the Land Use, Land Use Change and Forestry (LULUCF) sector, rather than the agricultural sector, of the National Inventory Report,[15] and are therefore not included in the latter's 10 Mt CO_{2e} contribution. Nor are they included in Ontario's official emissions for the purpose of meeting national emission-reduction targets; however, they are tracked and recorded in Canada's National Inventory Reports.[iii]

The reductions in soil carbon represented by these figures can be considered as both an important loss and a major opportunity and will be discussed in significant detail in the pages that follow.

Food security and ecological resilience

The term "food security" refers to a situation where people have physical, social and economic access to sufficient safe and nutritious food.[16] The ability of any jurisdiction, such as Ontario, to produce enough to feed

[iii] See Chapter 3 of the ECO's 2016 GHG Report, entitled *Facing Climate Change*.

its own population is dependent on a variety of physical, economic, and social factors. One very important physical factor is *ecological resilience*, which is the ability of a system (in this case our agricultural lands) to tolerate disturbances without changing to a different, less productive, state (i.e., collapsing) and/or to recover from such disruptions in a reasonable period of time.[17]

In a changing climate, resilience is extremely important. Resilient agricultural systems could allow Ontario to maintain, or even exceed, current levels of agricultural productivity in the face of significant change.[18,19] Temperatures in Ontario will not only be higher on average, but will hit extreme levels (i.e., above 30^{o}C) more often and for longer periods of time. High daily maximum temperatures are very dangerous, as yields for crops like corn and soybeans drop precipitously with the number of days (and even more so, nights) above 30^{o}C.[20]

Another significant threat to agricultural yields is the potential lack of timely availability of moisture. No amount of chemical input can mitigate the impacts of insufficient water at key points in crop development. Climate change is expected to create much more variability with longer periods of drought mixed with extreme precipitation events. This is potentially devastating to crop yields.[21, 22]

As will be discussed in some detail below, Ontario's ability to cope with drought and heat, mixed with extreme storms, depends heavily on the health of our topsoil. This makes it particularly dangerous that soil-carbon levels are dropping on more than 80 per cent of Ontario farms. Soil organic matter is essential to the ability of the soil to allow the rapid infiltration of rain water, to better retain its structure under intense rainfall, and to resist erosion.[23, 24] Therefore, it is not surprising that Ontario farms are also subject to an increasing risk of erosion (see "Soil: Ontario's Eroding Asset" in the ECO's 2008/2009 Annual Report). The resulting sedimentation of lakes and rivers is the mirror problem to the loss of productive topsoil, and both are related to the declining levels of organic matter on Ontario farms.

Algae bloom in Lake St. Clair, July 28, 2015.

Source: Landsat imagery courtesy of NASA Goddard Space Flight Centre and U.S. Geological Survey

Another closely related concern is the potential for crop loss due to flooding. Soils low in organic matter cannot absorb rainfall quickly enough to prevent the rapid run-off of surface water. This can result in heavy flooding of lower-lying fields, especially during the kinds of extreme weather expected with climate change.[25]

In addition, as average temperatures rise and the growing season lengthens, many new plant species, including invasive weed species and herbicide-resistant weeds, will find Ontario's climate to their liking.[26] Together, these climate-related factors pose a significant threat to Ontario's agriculture sector, raising issues of negative impacts on both the province's economy and its food security.

Other impacts: water, pesticides, etc.

Impaired water quality, primarily in Lake Erie but to a lesser degree in surface waters generally, has been the environmental issue receiving the most attention in recent years. Algal blooms are the visual trademark of this problem, which is known as eutrophication.[27] Phosphorus run-off from agricultural fields in Ontario, and to an even greater extent several northern American states, is one of the causes of this problem. The ECO wrote about phosphorus in our 2012/2013 Annual Report ("From Peak P to P Soup: The Phosphorus Challenge on Ontario Farms"), recommending that the Ministry of Agriculture, Food and Rural Affairs (OMAFRA) place more emphasis on soil health and less on after-the-fact solutions, such as physical barriers to P run-off. Eutrophication is both a hazard to human health and a threat to biodiversity.

Other threats to biodiversity include loss of habitat, pollution of surface and ground water by nitrogen fertilizer run-off, and the impacts of pesticides, such as the neonicotinoids (see "Neonicotinoids – A Primer" in the ECO's 2014/2015 Annual Report). Biodiversity loss is a major issue, both in Ontario and internationally, with many species and even classes of creatures (e.g., amphibians) experiencing various levels of population decline.[28, 29] Not all of these problems are directly attributable solely to agricultural practices, but all of them are impacted to some degree by the way in which we grow our food. Moreover, many of these threats (if not all) may be exacerbated by climate change, and in particular the potential increase in frequency of extreme weather events.

Time to Change Course

The combined effects of climate change and growing environmental harm present a substantial challenge to modern agriculture. The steady stream of agricultural innovations has to date not been sufficient to fully address all of these environmental problems.[30] This may be the result of the fact that many conventional solutions address the symptoms, rather than the causes, of a particular environmental problem. For example, buffer strips (areas of permanent vegetation designed to trap sediment and slow down run-off) have long been advocated as a way to control phosphorus pollution from farms. However, some experts[31] feel that they are simply band-aid solutions, marginally effective at best, because they don't address the roots of the problem, which vary from farm to farm.[32] Accordingly, they are subject to failure under certain circumstances, such as in winter, when the ground is frozen and phosphorus-laden water can flow right over them, and they do not address in any manner at all phosphorus loss through tile drains.[33, iv] Moreover, they impose a penalty on the farmer (a loss of arable land) without offering any personal pay-back in

If you scoop a handful of soil from an average home garden, you will hold in your palm more organisms than there are humans on the planet.

[iv] Farms in Ontario vary considerably with respect to the amount of phosphorus in their soils: some have excessive levels; some have levels appropriate for crop needs; and some are deficient and require supplementation. Also, some P is in organic form, while other P is soluble, and it is primarily the latter that is leaving farms. Cover crops (see p. 20) are a more

return. As a result, the land these buffers take up may be brought back into agricultural production by farmers if the economic environment changes.

Some modern agricultural methods work against, or at least in ignorance of, the natural processes that underlie sustainable ecosystems. If their main purpose is to optimize yield or reduce labour costs, they often don't take sustainability into account. Alternatively, if they are meant to address a sustainability issue like erosion, they often do so by trying to control the symptom, rather than addressing the cause, as in the example above. A new approach is required, one that is sufficient to solve the many environmental problems outlined here, particularly those related to climate change, without foregoing the productivity and profitability of modern agriculture.[34]

---

efficient way to deal with phosphorus issues, as they take up excess P and hold it for future crops, regardless of the circumstances on an individual farm. This approach benefits both the farmer and the environment.

Putting Soil Health First

The “new” way forward already exists: the *soil health approach*. Failure to understand, and respect, basic soil biology has been the biggest weakness of conventional agriculture.[35,36] Addressing this weakness offers significant good news, for greenhouse gas emissions, adaptation to climate change, and for the environment in general.[37] The ECO has been following this agricultural management trend, with growing optimism, for almost a decade. Here, we share what we have learned and explain why we think that soil health is such a big deal.

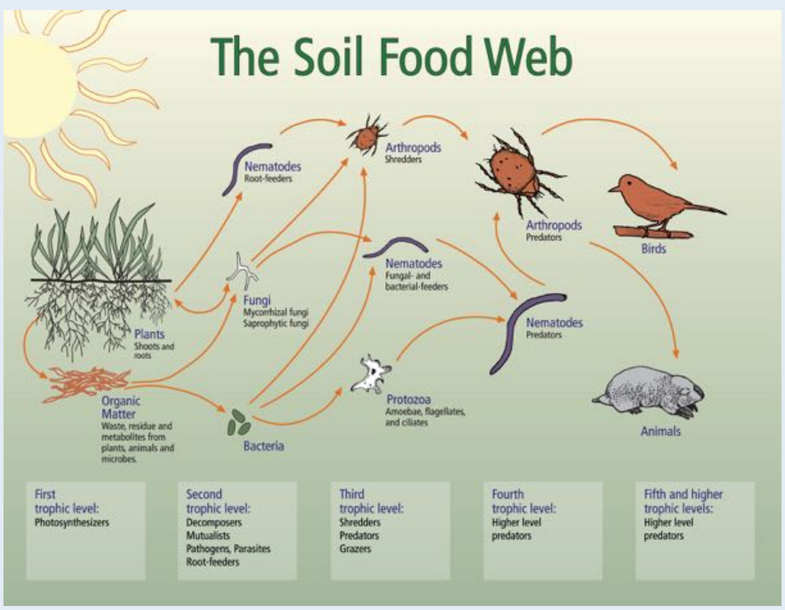


Figure 3: The Soil Food Web.

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society.

What is Soil Health?

The complex, busy world beneath our feet

First of all, let’s consider what the term “soil health” means. The word “health” is not usually associated with inanimate objects, let alone complex mixes of ground-up minerals, organic matter, water, and air. However, inherent in the term *soil health* is an obvious hint at a not-so-obvious truth: *soil is alive.*[38] Not alive in the same sense as an organism, but rather in the sense of an ecosystem.[39,40]

The thin layer of topsoil that covers most of the dryland surface of the planet constitutes a varied set of enormously productive and dynamic ecosystems.[41] If

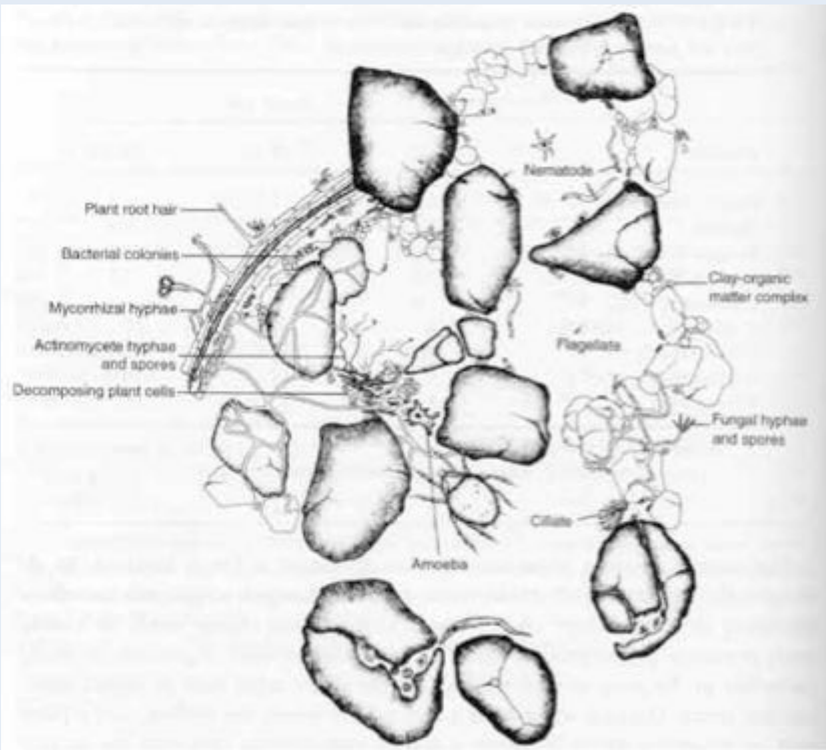


Figure 4: Soil organisms within a soil aggregate

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society.

you scoop a handful of soil from an average home garden, you will hold in your palm more organisms than there are humans on the planet.[42] Moreover, they are very busy organisms. As one noted soil ecologist puts it: "It's like Times Square on New Year's Eve all the time" in the soil.[43]

It is the myriad of tiny creatures living in the water/air mixture that fills the pore spaces between grains of sand, silt, or clay that determine whether a soil is healthy. Scientists refer to this underground society of microbes, arthropods (e.g., insects, spiders, crustaceans), worms and other organisms as the *soil food web* (see Figure 3). Like the above-ground food web, the soil food web can be thought of as a multitude of different types of organisms and the set of ecological relationships between them. Some are predators, some are prey, but many are both.

At the very bottom of the food chain are the bacteria and fungi, who are the principal decomposers, breaking down and consuming dead organic matter. These microscopic organisms constitute the main food source for larger predators such as nematodes, protozoa and the smaller arthropods, which in turn are the prey of the predatory nematodes and larger arthropods. These latter creatures, along with various types of earthworms, occupy the top rung of the soil ecosystem underground, but they themselves are prey to many above-ground creatures, such as insectivorous birds and burrowing mammals. In fact, the connection between soils and the ecosystems above them is so strong that scientists usually find that population and biodiversity levels above ground reflect those below, and vice-versa.[44,45]

The substantial benefits of healthy soils

Humans have been aware of the importance of this complicated below-ground world for a very long time. Aristotle referred to earthworms as "the intestines of the earth,"[46] because of their ability to cleanse the soil (e.g., destroy pathogenic organisms) and recycle organic residuals into nutrients. However, despite the fact that soils provide many important ecological benefits (see discussion below), including many related to human health,[47] modern agriculture's focus, for the most part, has been restricted to soil's ability to recycle nutrients, and even that role has been almost totally usurped by synthetic fertilizers. Only recently has awareness of other important soil-food-web functions started to seep into the world of conventional agriculture.

A soil "function" is a regular ecological service provided by the soil to the environment at large.[48] Ninety per cent of these functions are biologically driven,[49] which is why the soil food web is so important. The organisms of the soil food web create what we define as healthy soils by:

- making nutrients available to plants in a variety of unique and effective ways (see "The Original Carbon Trading Scheme," pp.15-16);
- building and enhancing soil aggregation and porosity (good soil structure), which allows better water infiltration and holding capacity (see "The Soil's Structural Engineers," below);
- sequestering nitrogen and other nutrients in their bodies, reducing nutrient loss as pollution;
- preying on and/or out-competing disease and pest organisms, enhancing plant health and increasing crop yields; and
- increasing organic matter in soils, a basic activity that not only supports all of the above functions, but also reduces carbon levels in the atmosphere, mitigating climate change.[50]

Bacteria and Fungi: The Soil's Structural Engineers

By far the most numerous members of the soil food web are the bacteria and fungi. Yet despite their tiny size and their lowly position at the bottom of the food web, these microbes are the soils most important engineers, because they build good soil structure.[51]

Soil consists of particles of various sizes, from tiny, barely visible clay particles (less than 0.02 mm), through slightly larger silt particles (up to 0.05 mm), to large and easy-to-see grains of sand (up to 2 mm). Soil with more than 50 per cent clay particles is considered a "clay soil". In these soils, the small particles can fit very closely together, leaving only very tiny pore spaces. In fact, clay soils often compact so much that water just sits on top of them as though they were made of concrete. At the other extreme are sandy soils, where the spaces between the grains are larger (imagine golf balls in a jar). These soils can often be dry, because water drains through them very easily. The best soils have a good balanced mixture of clay (20 per cent), silt, and sand (40 per cent each); these are known as loam soils.[52]

All types of soils, however, require good internal structure to be healthy. This structure can vary from poor to excellent, and although it is influenced by soil type, chemistry, and the environment, its final form is largely the result of biological activity. Bacteria, fungi, and earthworms all secrete organic glues, which stick to the tiniest particles and cause them to cling to each other, forming small aggregates. In particular, a substance call *glomalin,*[53] produced by mycorrhizal fungi, seems to be very important in this process.[54, 55] Fungi of all types then enhance this process by wrapping their hyphae (filaments) around the smaller aggregates, bunching them together into larger ones.[56,57] It is this mix of aggregates of various sizes that gives soil its optimum structure. In a well-aggregated soil, water can infiltrate freely, preventing puddling, run-off and flooding. The water is also held tightly in the pore spaces, where it is available for later use by plants.[58] Finally, and perhaps most importantly, these aggregates don't break down when the soil gets wet, because the glues and the hyphae are strong and water-resistant. In summary, a soil with good structure prevents flooding and run-off, resists drought, and does not easily erode. It is roomy, stable, and well stocked with water and air – an ideal home for both microbes and plant roots.[59,60]

The Original Carbon Trading Scheme

How plants get their nutrition

As Ontario gets ready to initiate a "cap and trade" carbon market, it might be instructive to take a look at the *original* carbon market – the one that has been going on underground since plant life first appeared on the planet.

Any review of underground carbon trading should begin with a look at how plants obtain their soil-based nutrients. The first two concepts to understand are *mass flow* and *diffusion*.

Soil particles are usually surrounded by a thin film of water. As plant roots take up water from the surrounding soil they create a moisture gradient, i.e., the soil is drier closer to the roots. Water gradually moves along this gradient, from areas of higher moisture towards the lower moisture levels near the roots; this natural process is called *mass flow*. This water carries many nutrients with it.

Bacteria swarm root tip (rhyzosphere)

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society.

At the same time, a similar process is occurring for all nutrients within the soil water. Diffusion is the tendency for substances in solution to move from regions of high concentration to those of lower concentration, thus evening out their distribution. Because plants are regularly absorbing nutrients in the root zone (known as the "rhizosphere"), nutrient concentrations near the roots are usually low compared to the soil in general. Accordingly, nutrients diffuse toward the roots, independent of (and supplementing) mass flow. Together, these two processes result in a steady movement of dissolved nutrients towards plant roots. In effect, roots "suck up" water-soluble nutrients for the plant from the surrounding soil.[61]

When these nutrients reach the roots, they are absorbed, in what is largely a passive manner, via diffusion across the root cell walls.[v]

The above description of how plants get their nutrition used to be considered the full story; however, that view has changed with the emergence of new information from the discipline of soil ecology. To understand how the above system is substantially enhanced by the soil food web, we can start with a couple of questions: first, where do nutrients originate in soil and how are they replenished? And second, how do relatively slow and passive processes like

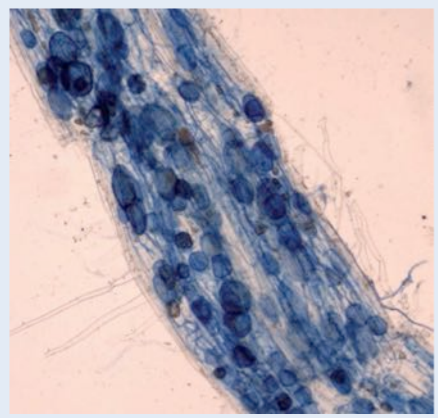
[v] Plants do have some specialty mechanisms for controlling this process, but in general nutrient take-up is passive in nature. The movement of nutrients upwards to the plant from the roots creates a lower concentration in the root cells than in the surrounding soil water, resulting in diffusion.

…plants use photosynthesis to fix carbon in an organic form from CO_2 in the atmosphere. They then trade a portion of that carbon currency to microbes, in return for fast and efficient nutrient delivery.

diffusion and mass flow possibly provide enough nutrients for the lush growth of a prairie, or a forest? The answers to these questions are closely related; both involve soil microbes.

Nutrient sources

Plant nutrients (e.g., phosphorus, potassium, calcium, boron, manganese, zinc, etc.) come primarily from two sources in natural systems: mineral rock (in the form of clay, silt, or sand particles), or, in the case of nitrogen, atmospheric nitrogen gas; and dead organic matter.[62] Nutrients contained in a rock particle or in organic matter (e.g., a dead root) are insoluble and cannot diffuse into plant root cells.[63] Weathering breaks down the minerals over time, but this process is extremely slow. Fortunately, however, microbes such as bacteria and fungi have the ability to break down both mineral and organic materials fairly quickly and incorporate the various constituent nutrients in their bodies. When these smaller microbes are later consumed by larger microbial predators, such as protozoa and nematodes, some of these nutrients are released, in a soluble form, in the predator's excrement. These nutrients are now "plant-available"; that is, they are water-soluble. Mass flow and diffusion can now deliver them to the rhizosphere, where they diffuse into plant root cells.[64] In nature, most plant nutrients are cycled and recycled in this way.[65]



Vesicular Arbuscular Mycorrhizal (VAM) fungi are the most common type in farming systems; there are about 240 different species. They are often numerous, and can comprise 20 to 30 per cent of all soil microbial biomass. They invade root cells, where they create vesicles, or storage structures. This picture shows the mycorrhizal structures (vesicles) within root cells.

Source: Source: S.L. Sturmer and M. Brundrett. 2016, Global Soil Biodiversity Atlas. European Commission, Publications Office of the European Union, Luxembourg.

Faster nutrient delivery

Freeing nutrients from their mineral and organic forms is not all that microbes do. They also provide plants with some faster delivery mechanisms. This is where carbon comes in; plants use photosynthesis to fix carbon in an organic form from CO_2 in the atmosphere. They then trade a portion of that carbon currency to microbes, in return for fast and efficient nutrient delivery. Two basic systems exist to do this.

One system involves the release of carbon-rich compounds, such as sugars and amino acids, from plant roots ("root exudates") into the soil of the rhizosphere.[66,67,68] Microbes are attracted to the roots by this high-energy feedstock and, in turn, microbe predators (e.g., nematodes) are also drawn in to feast on the microbes. As they do so, they excrete soluble nutrients right where the plant needs them – just outside the root cell walls.[69] On average, 17 per cent[70] of the carbon compounds that plants produce through photosynthesis are dedicated to this purpose (the amount can go as high as 44 per cent).[71]

The second system consists of an even more direct type of symbiosis. A type of fungi called "mycorrhizae" (Latin for "fungus roots") burrows into plant roots (some types even penetrate the root cells) and create the equivalent of a two-way pipeline, with carbon-based substances from the plant flowing outwards to provide energy for fungal growth, and water and nutrients flowing back through those strands to the plant. These mycorrhizal filaments (called "hyphae") greatly extend the foraging area of the plant while speeding up and enhancing its access to nutrients.[72,73]

In summary, the original carbon trading system is an important and ubiquitous underground activity that benefits all participants, both below and above the surface. Plants trade with microbes, providing a significant portion of the carbon compounds that they produce through photosynthesis in return for greater and faster access to nutrients and water.

Carbon trading and sequestration

This complex system of underground carbon trading results in a pool of "labile" or active soil carbon that is always in flux. Microbes respire, just as animals do, and they release carbon back into the atmosphere as CO_2 on an on-going, regular basis. However, if the carbon coming in from the plants is greater than carbon going out through microbe respiration, soil-carbon levels rise overall.[74] This accumulation of carbon in the soil is what we call *soil-carbon sequestration,*[75,76] and it is very important in both mitigating and adapting to climate change.[77]

Carbon-nutrient exchange systems are extremely susceptible to disruption by poor soil management practices by humans. Some, such as aggressive tillage, increase carbon losses by making more oxygen available, increasing microbial respiration and releasing more CO_2; others, such as leaving soil bare for long periods of time, or using chemical inputs indiscriminately, slow down the carbon trading system between plants and microbes by limiting photosynthetic inputs and/or reducing microbial numbers and diversity (see "Throwing Sand in the Gears," p.19).

The Soil Health Approach – Principles and Practices

The many benefits of healthy soils, as described above, are readily available to farmers, provided that the size and diversity of the soil food web is maintained. The next logical question, therefore, is how best to manage the soil in a manner that supports and enhances its living components, in order to maximize their potential. As it happens, leaders in the soil health field have been formulating key management principles and practices for the past couple of decades.[78]

Principles

Key soil health principles include the following:

- **Keep the soil covered at all times.** Good soil cover (crops, cover crops, and/or crop residues) means that soil moisture is conserved and temperatures are moderated. This practice protects the underground habitat of soil organisms, encouraging their growth and activity. Surface residues feed the soil food web by providing organic matter for microbes to feed on; main crops and cover crops feed the microbes with their root exudates (as discussed above).
- **Maximize diversity.**[79] A wide diversity of plants above ground leads to a greater diversity of food for beneficial soil microbes.[80] This is because different crops release different types of root exudates, attracting and supporting more below-ground diversity.[81,82] They also have different types of roots, with varying lengths and forms, improving the soil over a greater range of depths. This greater microbial diversity results in a deeper and more resilient set of soil functions;[83] therefore, growers experience higher levels of productivity,[84] increased disease resistance in crops, reduced pest problems, and overall greater resilience[85] to environmental impacts such as drought, extreme weather events, and temperature fluctuation.

> The many benefits of healthy soils….are readily available to farmers, provided that the size and diversity of the soil food web is maintained

- **Minimize soil disturbance.** (i.e., no-till, or minimum tillage). Tillage disturbs the soil food web, altering the balance between bacteria and fungi. Ploughing breaks the fungal hyphae, slowing fungal growth and reproduction.[86] Fungi are very important for soil structure (see "The Soil's Structure Engineers," p.12) and also for disease suppression, as beneficial fungi can out-compete and suppress pathogenic (disease-causing) fungi under good soil conditions. Tillage also exposes decomposer bacteria to higher levels of oxygen, speeding up the decomposition of organic matter. This releases CO_2 to the atmosphere too quickly (i.e., faster than it can be replaced), reducing overall soil organic matter levels. Reduced soil organic matter then depletes the fungal populations further, resulting in a loss of stable soil aggregates. This leads to further carbon loss, as well as erosion and compacted soils.
- **Keep live roots in the ground** for as much of the year as possible (including over winter). Live roots feed the soil food web, via exudates. In particular, mycorrhizal fungi cannot survive without live roots as hosts; bare fields deplete mycorrhizal populations, depriving the following year's crop of their abundant benefits.[87]
- **Use organic inputs.** Organic materials, such as crop residues, manures and compost, provide habitat and feed for the soil food web while generating fewer of the potential harmful side-effects of synthetic inputs (see "Throwing Sand in the Gears," below). However, any nutrient, whether natural or synthetic, can cause problems if not applied wisely (see Best Management Practices below).

Throwing Sand in the Gears: How the Inappropriate or Over Use of Synthetic Inputs Can Impair the Natural System

Heavy use of synthetic fertilizers is de-emphasized in the soil-health approach.[88,89] This is because these chemicals can do more damage than good if they are not carefully deployed (see Klaas Martens case study, pp. 23-24). When not used in this careful manner, the negative impacts of fertilizers can be direct or indirect. Direct impacts include: the release of N_2O, a very potent greenhouse gas[90] (as in Figure 2); pollution of groundwater;[91] depletion of soil carbon by decomposer microbes stimulated by excess nutrient availability;[92,93] reduced diversity of soil organisms;[94,95,96] and increased weed pressure, also caused by an excess of readily plant-available nutrients.[97, 98]

An important indirect problem involves plant-root exudates. One of the main reasons that plants release these exudates is to feed microbes in their root zone[99] (see "The Original Carbon Trading System"). This comes at an energy cost to the plant, so if it can acquire the nutrients it needs without having to attract the microbes, it gradually reduces the quantity of exudates.[100] This reduces one of the soil food web's major food sources, which in turn limits the quantity and quality of the services that the soil food web can provide.

Pesticides can also be problematic, in that many of them impact the soil food web negatively, usually by reducing diversity.[101,102] Fungicides, for instance, hurt many beneficial fungi as well as the target pests.[103] Since fungi are increasingly recognized by scientists as crucial to soil health, carbon sequestration,[104,105,106] and natural productivity,[107,108] (as well as having been shown to suppress some aggressive weeds),[109] knocking them back with fungicides on a regular basis will reduce these benefits. The soil health approach depends on the natural defenses of soil and of plants for the bulk of its crop protection; accordingly, pesticides of any kind are used very carefully and/or infrequently.[110,111]

Best Management Practices

The underlying theme to all of the above principles is *protect and enhance soil life*. The soil health approach is strongly focused on maximizing the benefits of a healthy, diverse, and productive soil ecosystem. These basic soil health principles can be implemented by means of a variety of soil health best management practices (BMPs). The following is a brief summary of the most important BMPs.

Equipment adapted for no-till by the Belans (see pp. 24-25).

Source: Glenn Munroe

- **Conservation tillage.** This practice consists of a number of methods of soil cultivation that leave the previous year's residues on the field. The most common examples are no-till and strip-till. The former involves planting crops into residue that has not been tilled at all; the latter involves planting crops into narrow strips of tilled soil, with the rest of the soil and residues left untouched. These practices address to varying degrees[112] the principle of minimizing soil disturbance, thus supporting and enhancing the soil food web in a variety of ways.
- **Crop rotations.** This is the practice of planting different crops in the same field following a defined order (e.g., corn-wheat-soybean). Rotating crops has been shown to have a number of benefits, including increased overall production,[113] reduced pests and diseases,[114] weed control,[115] and improved soil health.[116] This practice addresses the principle of maximizing diversity, while also minimizing the disease pressure that can arise from having the same crop in the same soil year after year.

- **Cover crops.** Growing crops intended for purposes other than harvesting them for sale can have substantial benefits. They can reduce soil erosion, add organic matter, reduce nutrient losses, improve soil fertility, reduce pest populations, reduce soil compaction, and generally improve soil health.[117] They accomplish these benefits by addressing three important soil-health principles: keeping the soil covered, maximizing diversity and keeping live roots in the ground.

> …focusing on soil health is not just good environmental practice; it is good business practice as well

- **The 4Rs of fertilizer use.** The 4Rs approach represents a sustainable way of applying synthetic fertilizers to crops. It means: right source (balanced nutrients in plant-available form); right rate (based on soil nutrient supply and plant demand); right time (based on dynamics of crop uptake, soil supply, nutrient loss risk, etc.); and right place (where roots can access the nutrient and losses are limited).[118] This practice addresses the concerns expressed in "Throwing Sand in the Gears" on p. 19, while ensuring that the crop has the level of plant-available nutrients required to produce a good yield.
- **Composting and compost utilization.** Wherever feasible, composting an organic amendment before applying it to the soil is preferable because composting stabilizes materials such as manure, reducing run-off (and thus nutrient loss and pollution) and increasing soil-carbon sequestration rates.[119, 120]
- **Livestock integration.** The modern approach to raising livestock, in which animals have been separated from crop production, has, as farmer/writer Wendell Berry puts it, taken "a solution and divided it neatly into two problems."[121] By appropriately re-integrating livestock with growing crops, farmers can reduce the use of synthetic fertilizer, boost soil health, and increase soil organic matter. At the same time, one of agriculture's largest methane sources (from stored manure) would be greatly reduced. This practice addresses the principle of adding organic soil amendments, as well as keeping the soil covered and live roots in the ground (because livestock can graze on cover crops).
- **Use an ecological approach to grazing management.** Farmers who raise livestock on dedicated pasture lands also have the ability to improve soil health and increase soil carbon. Both the method and the duration of the grazing are important. Rotational or "mob" grazing is a system whereby animals are kept in small grazing areas for short periods of time (as opposed to having the entire, large grazing area available to them all of the time). Having to compete for what they eat ensures that they graze all the vegetation (rather than just selecting the plants they like most), while moving them frequently to new grazing areas prevents over-grazing. The prevention of over-grazing ensures the retention of a significant capacity for photosynthesis, allowing the vegetation to recover quickly when the animals have moved on. In addition, livestock manures provide readily available nutrients, creating greater soil fertility. This approach mimics the way large herbivores lived on the prairies before humans began to interfere: grazing animals were kept bunched up and moving by predators, eliminating over-grazing and reducing selective grazing. Properly managed rotational grazing systems have been shown to significantly increase soil carbon, reduce and even reverse degradation, maximize diversity, and promote healthier soils.[122,123]

Farmers who adopt and systematically apply the principles and practices outlined above are able to gradually but dramatically reduce inputs, maintain or increase their yields, increase the water-holding capacity of their soils, virtually eliminate environmental problems, and become much more profitable – all at the same time.[124] As the examples that follow demonstrate, focusing on soil health is not just good environmental practice; it is good business practice as well.

Champions of Soil Health

The most well-known North American champions of soil health farm in the United States, where the Natural Resources Conservation Service (NRCS – see p. 29) has been working with innovative farmers to lead, foster and promote the soil health movement over the past few years. Meet two leading U.S. soil health champions, one conventional and the other organic. Their stories show the inspiring extent of what can be accomplished by farmers who put soil health first.

U.S. Soil Health Champions

A no-till farmer shows a multitude of worm middens, a characteristic of healthy soil

Source: Glenn Munroe

Brown Ranch, North Dakota

Gabe Brown and family operate a 5,400-acre ranch, including 2,000 acres of cropland, near Bismarck, North Dakota.[125] Brown began his gradual transition to a soil-health focused approach in 1993, when he converted his cropland to a no-till operation. At that time, his soil's organic matter levels (which correspond closely to soil carbon content) averaged less than two per cent. In 1995 he took his next step, which was to begin to diversify his rotation. By that time he had noticed a slight improvement in his soil. Encouraged by this improvement, in 1997 he introduced cover crops. His soil continued to improve, with organic-matter levels rising and water-holding capacity and infiltration rates increasing year after year. In 2006, he began to experiment with multi-species cover crops (to further increase diversity) and since then he has also integrated his grazing animals (cattle, sheep, pigs) into his cropland management. In the slightly more than two decades that he has been managing for soil health, the average organic-matter levels in his fields have risen to between 5.3 and 6.1 per cent, with one field recently reaching 11.1 per cent.[vi]

Brown has calculated that he can produce more calories per acre with his soil-health-based system than any other farming system that he knows of, and at less cost

These management practices, however, have done a lot more than just sequester carbon. Brown states that they have demonstrably increased the size and diversity of the food web in his soil, with all the associated benefits. His land can now absorb over eight inches of rain per hour, a precipitation rate almost never reached in his area. Accordingly, when his neighbour's land is flooded after a heavy rain, he does not even see puddling on the surface of his land. Nor does his land generate any run-off, regardless of the time of year. In fact, Brown states that the water-holding capacity of his land has increased to about 20 inches, which is 5 inches more than the average annual rainfall in the Bismarck area. What this means is that his soil is able to capture and hold all of the rain that falls each year in his region, protecting his crops from drought and increasing his yields.

With respect to the efficiency of his yields, Brown has calculated that he can produce more calories per acre with his soil-health-based system than any other farming system that he knows of, and at less cost. His yields are about 25 per cent higher than the county average, yet he uses no fertilizer, no insecticides, and no fungicides; he stated in 2015 that he makes only one herbicide pass on some of his fields every two to three years, and that he is working to eliminate that. His per-acre costs are much lower than average and he believes that he is easily the most profitable operation in his area.

Klaas and Mary-Howell Martens, organic farmers, New York State

Most conventional farmers would be more than pleased with a yield of 200 bushels of corn per acre,[126] a figure well above the 2015 New York state average of 143.[127] Yet the Martens achieve this high yield level while growing organically, without the assistance of any synthetic fertilizer or pesticides. Usually, organic farmers struggle to meet the average yield in their area, let alone exceed it by 40 per cent. How do the Martens accomplish this apparent anomaly? The answer is that they do it by focusing on soil health.[128]

The Martens, who farm in upper New York State, embrace the organic philosophy but also the concept of soil health and the practices that sustain it. They expand on the usual definition of soil health by adding that it is also important to create an environment in the soil that is suitable for the crop being grown. They believe that the lower yields (compared to conventional) that many organic farmers have come to expect is due to the way in which they farm, which is to farm conventionally but with organic inputs. The Martens take a different

---

[vi] North Dakota has a very different climate than Ontario, with less rain and drier soils, conditions considered more amenable to soil organic matter accumulation. However, the soil-health benefits experienced by farmers in Ontario will be similar to those in North Dakota, if not necessarily to the same extent or scale.

approach; they strive to create the most suitable soil environment for each crop by mimicking natural succession. Accordingly, they plan both their type and timing of soil management (amount of tillage, cover crops, etc.) and their crop rotations to ensure that each crop they plant is growing in a soil that is best suited for it.

They have worked closely with researchers at Cornell University to expand on their knowledge of soil health and the practices that promote it. In doing so, they have discovered that too much fertilizer, even organic manure, is not only a waste of money and an environmental risk, it is also an invitation to weeds, which thrive in soils rich in readily available nutrients. At the same time, they have discovered that nitrogen is almost never a limiting factor in healthy soils, where nitrogen-fixing legumes are part of the mix of covers and/or rotation. Therefore, by applying only modest amounts of manure (1.5 tons per acre) at the right time (on an actively growing crop the season before), they get significantly less weed pressure, lower costs, no environmental impacts, and good yields.

The Martens have learned a lot about soil health, and their knowledge allows them to out-perform most conventional growers without using any synthetic inputs. They report that their soils are so healthy that diseases that plague their neighbours' conventional crops bypass their own crops, and sometimes actually attack only the weeds on their fields. Klaas Martens feels that this is because they have not only optimized the health of their soils, but also fine-tuned them for each specific crop. This means that their crops are able to withstand pest and disease pressure much better than the weeds.

Ontario Soil Health Champions

Here in Ontario, a small but growing group of farmers are putting more of a focus on soil health and are reaping the benefits of higher yields, lower costs, and fewer environmental impacts. The ECO profiled three such innovative soil health leaders in a previous report[vii] and we are pleased to celebrate two more: the Belan farm, located north of Chatham, and the Rogers farm, in Lambton Shores.

Mike Belan demonstrates the excellent structure of his healthy soil

Source: Glenn Munroe

The Belan family farm, near Inwood, Ontario.

As Mike Belan describes it, his family was led into the world of soil health by financial circumstance. The high interest rates in the 1980s forced them to sell off some land and equipment in order to pay some debts to the bank; at the same time, it caused them to rethink the way they were farming. Mike's father, a young man at the time, was in the process of taking over the management of the farm from his father. He found that he didn't like working so many hours just to pay interest to the bank. So, in

[vii] See "Healthy Soils Yield Benefits for Ontario Farmers" on page 63 of *Managing New Challenges*, the ECO's 2013/2014 Annual Report.

1991, when an equipment manufacturer introduced a 30-foot no-till drill to the Ontario farming community, they decided to give it a try. The next year, they converted to a full no-till operation and sold all of their tillage equipment and unnecessary tractors. Then, as Belan says, they "began the adventure that is no-till farming."

…"our low cost of production with no-till" means that "we don't need to hit a homerun with yields every year"

– Mike Belan

They endured some difficulties, including what the agricultural community calls "yield drag" (a reduction in yield in the first few years often experienced in the conversion to no-till). However, the family persevered, and Belan is very grateful that they did, for their yield is now slightly above average for their region, while their productions costs are much lower than they would be if they were tilling. They also notice that their soils are better able to handle weather extremes; they don't experience drought conditions and their land can handle noticeably more rain than can their neighbours.

Belans seeding corn into a green cover

Source: Mike Belan

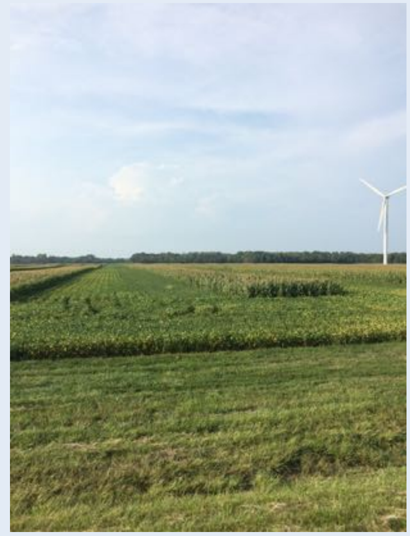
After no-tilling for more than 20 years, the Belans' first experience with cover crops came in 2013, when they allowed volunteer wheat to remain in the field after wheat harvest (their normal practice was to spray in the late fall to have a clean field in the spring). They liked what they saw in the spring, so in 2014 they planted a four-way mix of cover crops after the wheat harvest in August. This stayed green through the winter and they planted corn right into it in the spring of 2105. Since then, they have introduced the practices of inter-seeding into standing corn (so that the cover crop will have a head start when the corn is harvested) and also planting into a green cover crop in the spring. Belan states that although they have been very successful with the cover crops so far, this approach takes a great deal of management in the springtime, making it a "very stressful time of year."

They are now planting some sort of cover crop on all of their acreage, both owned and rented, and recently tried a 14-way mix in a test plot. One of the first noticeable benefits of the cover crops has been the condition of the soil in spring; the top two inches of the soil is more "mellow" and allows better seed-to-soil contact. They also introduced grid sampling about four years ago. They do a basic soil test, which includes macro and micro nutrient availability as well as soil organic matter. This allows them to fine-tune their fertilizer applications across the entire farm.

Mike Belan says that they are quite pleased with their current situation, because the "low cost of production with no-till" means that they "don't need to hit a homerun with yields every year" and they are content to see their production "consistently trending upwards." Their levels of soil organic matter have gone up from around 2 per cent when they started no-tilling 25 years ago, to around 5 per cent (high 4s to low 5s) in 2016.

The Rogers farm, Lambton Shores, Ontario

Doug Rogers and his family grow soy, corn and wheat on 700 acres of land (owned and rented) situated less than two kilometers from Lake Huron. He transitioned in 1990 to a combination of ridge till and no till but has been strictly no till for the past 16 years. He uses a "controlled traffic" system on his fields to avoid soil compaction, which means that he has planted in the same rows year after year. He planted his first cover crop in 2010, following winter wheat with oats and tillage radish. He has since evolved into a multi-species cover cropper (8-10 species). For the past two years he has been inter-seeding several covers into standing corn and a single cover of annual rye into his soy crops. As of 2016, he is also adding municipally derived "green bin" compost to his fields, applied after winter wheat harvest and prior to planting the cover crops. His goal is to increase the organic matter on his light loam soils as quickly as he can.



Rogers Farm: This is one method used to stop surface erosion. This farm has ten feet of fall from front to the back of the field of brisbane loam soil

Source: Doug Rogers

Rogers initially introduced cover crops as a way to increase soil health, build organic matter, and to drought-proof some of his lighter soils by building up their water-holding capacity. Now he is seeing other benefits as well, including weed suppression and more biological life in his soils. He is hoping to be able to start cutting back on all of his synthetic fertilizers in the next few years. In 2013, Rogers became interested in finding out whether he is holding on to more of his topsoil and phosphorus as a result of his efforts. He approached the St. Clair Conservation Authority and asked if they would set up a small water quality project testing tile outlets of different fields to compare their results during precipitation events. They agreed. Early results, from 2014 and 2015, show that water from tile drains coming off Rogers's land, compared to that of nearby conventionally worked fields, contained: less than half the level of total dissolved solids (TDS); a fraction <10 per cent) of the total suspended solids (TSS) in 2014 and half in 2015; 29 per cent (2014) and 46 per cent (2015) of the nitrogen; and 36 per cent (2014) and 67 per cent (2015) of the phosphorus.[129]

"We now strive to maintain a 'living crop' on our fields year round"

– Doug Rogers

These are good results and are likely to get better over time, as he has only been doing multi-species cover crops for a few years and he has not yet started to reduce his fertilizer inputs. Rogers recently authored an article for the St. Clair Region Soil and Crop Newsletter, where he wrote: "We now strive to maintain a 'living crop' on our fields year round…The residue left behind is a food source for the biological network under our feet. Soil micro-organisms help improve soil structure, and create better soil aggregates. This provides better water infiltration into the soil profile so it will not run off the fields."[130]

Like the Belans, Rogers reports that his yields are just as good or better than township averages and he does not feel that he has experienced any long-term yield drag. Most importantly, his net return is higher than that of his neighbours because of lower input costs and less equipment overhead. This improved financial status has been the case with all of the soil-health focused farmers that the ECO has profiled over the past few years; it really does appear that when it comes to healthy soils, there is synergy, rather than conflict, between the environment and the economy.[131]

Realizing the Promise of Soil Health

A Role for Research

These soil health champions provide compelling, if anecdotal, evidence that the adoption of soil-health based systems by farmers could make a significant impact on the environmental footprint of agriculture, while maintaining the high productivity and low costs that the market demands. Now what is needed is more focused research on the specific mechanisms at work in healthy soils, and a respectful conversation with farmers on how to implement these principles and practices.

Beneficial nematodes: These creatures enhance soil fertility by preying on bacteria and fungi, releasing nutrients

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society.

Soil biology is complicated and difficult to study. However, recent advances in molecular technologies and DNA sequencing are allowing researchers to gain a more detailed and comprehensive view into the world of soil and soil organisms.[132] This type of research is in its infancy, but already producing fascinating results.[133] For instance, researchers have discovered that it takes a consortium of 17 microbes, rather than a single species, to reliably and consistently suppress a commercially important root disease of sugar beets.[134] With this kind of information, suppliers may be able to come up with biological solutions that can be counted on to effectively address specific pests and diseases.[135] In fact, large multinational companies like Monsanto have already set up biological research arms that are working to develop these types of products.[136,137]

While an important role for commercial suppliers is inevitable in the soil health movement, the fundamentals of soil health should not be left entirely to the profit motive. The ECO believes that the OMAFRA should take a stronger role in identifying, supporting and communicating the soil-health research that Ontario farmers need to help them make management decisions.

What are Other Jurisdictions Doing?

Two leading jurisdictions on soil health are the United States and France.

United States

The Natural Resources Conservation Services (NRCS), a branch of the United States Department of Agriculture (USDA), has a lengthy and distinguished history. In the early 1930s, persistent drought, failed crops, and lack of soil cover on the Great Plains of America created what came to be called the Dust Bowl: huge clouds of topsoil were blown across America, over top of Washington, D.C., and out into the Atlantic Ocean. In response to this crisis, the Roosevelt administration passed the *Soil Conservation Act*, which, among other things, created the Soil Conservation Service. The mandate of the service was to promote soil conservation, which it has done by means of an ever-expanding variety of programs and incentives over the past eight decades.[138] Its name was changed to NRCS in 1994.

Alternating strips of corn and soybeans on a no-till farm in Ontario

Dean Glenney's "fence-row" farming system, which combines no-till, crop rotations, and precision agriculture to achieve extremely high yields, was featured in the ECO's 2013/2014 Annual Report: *Managing New Challenges*.

Source: Glenn Munroe

Recently, NRCS has become a prominent leader in the soil-health movement, influencing many other organizations and jurisdictions, including Ontario. In 2012, NRCS launched a soil health campaign, which included providing soil health training to thousands of its own field officers, as well as to thousands of farmers and ranchers. Then, in 2014, NRCS created a training team of soil health experts, which delivered training and outreach at more than 200 soil health events across the United States in its first few months. It has also developed a series of webinars and YouTube videos promoting the basic concepts of soil health. Most recently (early 2016), the USDA announced a further funding increase of $70 million to NRCS[139] for the delivery of even more soil health and nutrient management strategies to U.S. farmers. This new funding is a direct result of the significant success that the agency has realized working with farmers on the ground, including the two U.S. farmers profiled in the previous section.

"The world's capacity to feed 9.5 billion people in 2050 in a context of climate change will depend in particular on our ability to keep our soils alive"

– French Ministry of Agriculture, Agrifood, and Forestry

The NRCS website[viii] contains a wealth of information on everything related to soil health, from the basics of soil biology to details on how to implement best management practices.

France

The French Ministry of Agriculture, Agrifood, and Forestry has recently become an outspoken champion of soil health, particularly as expressed in higher levels of soil organic matter, stating that the world's "capacity to feed 9.5 billion people in 2050 in a context of climate change will depend in particular on our ability to keep our soils alive".[140] The *4/1000 Initiative* is a voluntary action plan, sponsored and promoted by the French government.[141] Its goal is to obtain commitments from other governments, international organizations, research institutions and universities, agricultural organizations, civil society and the private sector to promote practices that increase soil carbon.[142]

White fungal mycellium surrounding a leaf.

Source: Y. Kries. 2016, Global Soil Biodiversity Atlas. European Commission, Publications Office of the European Union, Luxembourg.

The name of the initiative was chosen because scientists have calculated that an annual growth rate in soil carbon stocks of 0.4 per cent "would make it possible to stop the present increase in atmospheric CO_2."[143,144] This is not to say that the initiative necessarily believes that this is an achievable goal; rather, the intent is to show that even a modest increase in soil carbon could have a significant effect. Stakeholders who sign on to the initiative are expected to commit together to a voluntary action plan to: implement BMPs that sequester carbon on as many agricultural sites as possible; work to preserve carbon-rich soils;[145] and financially support an international research program focusing on soil health and carbon sequestration in soils.[146] As of August 2016, 33 countries and/or regions had signed on. Neither Canada nor Ontario are among these political signatories, nor are any of Ontario's agricultural organizations.[147]

The Climate Adaptation and Mitigation Potential of Soil Health for Ontario

Adaptation

If we consider the theory and practices of soil health in combination with the increasing number of success stories, it becomes clear that this approach offers significant benefits to Ontario in terms of our ability to adapt to a changing climate. We know that climate change will bring more extreme weather events to Ontario, with more intense precipitation. The ability of soils to absorb and hold much larger quantities of rain water is crucial to preparing for a number of climate-related risks, including increased flooding, soil erosion, water pollution, and drought. In addition, covered soils are less susceptible to damage from extreme temperatures and weather events.[148] If most Ontario farms were managed in the way that leading soil health practitioners

[viii] See: http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/

manage their land, we could all breathe a lot easier with respect to issues such as water quality and food security.

> **The ECO is encouraged by the recent announcement of a new soil monitoring laboratory at the Elora Research Farm.**

One of the remaining obstacles is the shortage of peer-reviewed, scientific studies that would supply the credible, documented evidence of the practical benefits of soil health. Some of this research has been done in Ontario,[149,150] but more is needed. The ECO is encouraged by the recent announcement of a new soil monitoring laboratory at the Elora Research Farm. The lab will be undertaking a comparison of two cropping systems: a conventional corn-soy rotation; and another system called perennially enhanced rotation (PER), where winter wheat is included along with cover crops and intercrops, in order to keep the ground covered with green vegetation for as much of the year as possible.[ix, 151]

Mitigation

The ECO has written before on the potential for soils to sequester enough carbon to have a significant impact on GHG emissions.[x] In 2011, we concluded, based on our own analysis, that a combination of recommended management practices, such as cover crops, conservation tillage, and crop rotations, could provide the province with almost ten per cent of the GHG reductions needed to meet Ontario's 2020 target, or 2.9 Mt of CO_{2e} per year. This figure assumed take-up of these practices on 40 per cent of the province's cropland and a rate of sequestration of 2 tonnes of CO_{2e} per hectare per year. The 2-tonne/hectare target is considered ambitious by some soil scientists; however, similar (or even higher) figures have been documented by a number of credible sources and the science on this subject is rapidly evolving.[xi, 152]

However, the difficulties with accurately measuring soil-carbon sequestration rates (both potential and actual) are many. This is probably one of the major reasons why Ontario does not yet include soil carbon storage in its long-term GHG mitigation planning. The possibility of future reversal is also a major concern, because carbon held in soils can very easily be released if management practices change (e.g., tilling is resumed). The ECO acknowledges these difficulties. However, the potential for GHG reductions through sequestering carbon in our agricultural soils is real and significant,[153] even if it is difficult to quantify and hard to ensure over the long

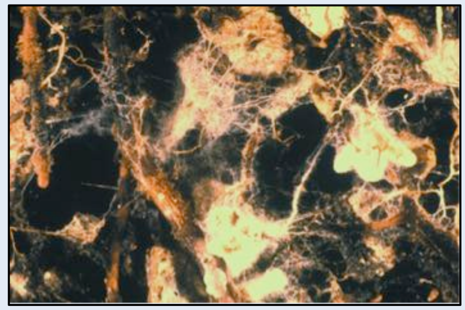
---

[ix] The Elora Research Farm is one of five research sites in Ontario. Some very important research work has already been done at these sites on the benefits of various BMPs. The ECO believes that the new program is a step forward because it will evaluate cropping systems, as opposed to individual BMPs.

[x] In particular, see "Soil Carbon Opportunities," Section 4.3 of our 2011 GHG Report, and "The Roots of Sustainability: Engaging the Soil Carbon Solution," Section 6.2 of our 2010/2011 Annual Report.

[xi] The International Panel on Climate Change (IPCC) estimates the potential annual rate for carbon sequestration in croplands to be between 1.1 and 1.8 tonnes of CO_{2e} per hectare, and a 2007 study on the potential for Canadian agriculture put the estimates even lower. However, recent scientific work has thrown new light on the mechanisms by which soil sequesters carbon, and this new view suggests that the models used for the above estimates may be generating figures that are too low, mainly because they do not take into account the activities of the soil food web (in particular, the ability to "hide" carbon in aggregates).

term. The ECO believes that it is worth making the effort to overcome these problems and develop protocols that can be used both to measure progress and, eventually, support financial incentive programs.



Mycorrhizal Structure in soil (extremely important for good soil aggregation)

Source: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA: Soil and Water Conservation Society.

As an example of this potential, consider the benefit accrued from just one farm over the past 25 years. The Belans (see pp. 24-25) have been measuring the organic matter in their soils since they moved away from tillage in 1991. The average soil organic matter levels on their land have risen by about three per cent, from about two per cent to about five per cent. Soil organic matter is about 60 per cent soil organic carbon, so the increase in soil carbon over that time is about 1.8 per cent (i.e., 60 per cent of 3). This represents about 32.4 tonnes of additional carbon per hectare,[xii] which is equivalent to about 119 tonnes of CO_{2e} per hectare (one tonne of soil organic carbon = 3.67 tonnes CO_{2e}). Therefore, in total they have sequestered around 48,000 tonnes of CO_{2e} in the top 15 centimeters of their 405 hectares of soil since changing their approach to farming.

The Belans have sequestered around 48,000 tonnes of CO2e in the top 15 centimeters of their 405 hectares of soil since changing their approach to farming.

At this point, the reader should note that the ECO is not suggesting that the Belan's situation should be taken as definitive from a soil-carbon sequestration perspective. Although their measurements were done by accredited soil labs, they did not follow any specific soil-carbon sequestration protocols as to depth of the soil profile or location of sampling, and the figures only represent an estimate of what has happened in the top 15 centimeters of their soils. However, 25 years is long enough that the tillage practices employed have had sufficient time to effect change, enhancing the likely accuracy of the estimate. In addition, the cover cropping, adopted only recently, has not been practiced long enough to have had much of an impact on organic matter levels. The latter point suggests that considerably more sequestration may be possible.

The data suggest a soil-carbon sequestration rate of about 4.75 tonnes of CO_{2e}/hectare/year, which is more than twice the rate of 2 tonnes CO_{2e}/hectare/year the ECO used in our 2011 analysis. Perhaps most importantly, the Belans provide a useful example of what can be accomplished by the average Ontario farmer.

[xii] This assumes a sampling depth of 15 centimetres (cm), which is typical for Ontario soil testing, and a soil bulk density of 1.2 grams/cm^3 – the bulk density of an average soil with a reasonable amount of organic matter. If a depth of 30 cm or more were used, the sequestration rate could change, depending on the carbon levels in the lower levels of soil.

Table 1 compares the Belans' data with the *4/1000 Initiative*'s aspirational rate of 0.4 per cent of existing carbon and puts both rates in the perspective of their potential for impacting Ontario's GHG reduction targets. Again, the ECO does not mean to suggest these numbers should be taken as the basis for future planning purposes. Like the title of the *4/1000 Initiative*, this is meant more to inspire and motivate than to set actual targets. Nevertheless, the ECO believes that it is fair to say that the data suggest significant potential for soil carbon sequestration in Ontario. For instance, the Belan numbers suggest that 40 per cent of cropland, managed for soil health, has at least *the potential* to sequester enough carbon to meet 12.5 per cent of the gap between current GHG emissions and the target for 2030.

Table 1 also shows that the Belan's average increase in soil organic carbon over the past 25 years is about 9.5 times the rate proposed by the *4/1000 Initiative*. Accordingly, even if the Belan's carbon storage numbers prove to be an overestimation, or an outlier, the data suggest that the *4/1000 Initiative* is not promoting a program based on an unachievable or unrealistic number, something out of reach by the average land manager. An achievement of this level of sequestration over 90 per cent of Ontario's farmland would reduce the 2030 gap by 3 per cent – a worthwhile accomplishment, particularly when viewed in light of all the other benefits that would accrue.

Table 1: Comparison of the GHG Reduction Impacts of Two Soil Carbon Sequestration Rates

Rate (tCO_{2e}/ha/yr)	Per cent of cropland participating	Total hectares under BMPs	Amount sequestered (Mt CO_2e/yr)	Per cent of 2030 target gap
4.75	40	1,440,000	6.84	12.5
0.5	90	3,240,000	1.6	3

NOTE: Number of hectares of Ontario cropland = 3,600,000; 2030 target + 115 $MtCO_{2e}$/yr; Gap: 55 $MtCO_{2e}$

**This is a rough estimate of the rate of C sequestration promoted by the *4 per 1000 Initiative* (converted into tCO_{2e}/ha/yr). Since the 0.4 per cent figure represents an increase *in existing stocks* (rather than an absolute increase), the rate will vary from place to place depending on the starting soil carbon level.

From Champions to a New Normal

Scientists have identified many advantages for farmers associated with soil health (and continue to do so). Moreover, these findings are being corroborated by a growing number of farmers (as shown in the successful case studies above) and policies in leading jurisdictions, such as the U.S. and France, are evolving rapidly to reflect this emerging consensus.

This is all very good news. By putting soil health first, farmers can build on agriculture's amazingly successful modern history by addressing head-on the environmental shadow that has always been nagging at the edges of their accomplishments. They can help their own bottom line and reduce their risk, while at the same time playing a major role in addressing the sustainability issues facing humanity, from plummeting levels of biodiversity to a changing climate. Adopting a soil health focus is not simply an interesting option for Ontario's farmers; it is at once an economic opportunity and an environmental imperative.

It won't be easy, however. Conventional agriculture has worked very well from the perspective of the individual farmer, in part because its practices are relatively simple to execute. In contrast, a soil health approach requires greater effort by growers in terms of planning, monitoring, and managing complex rotations that often include cover or secondary crops with no obvious markets. Effectively managing disease and pest issues are another major concern when shifting to a new approach.

Furthermore, a strong culture has grown up around conventional agriculture. Clean, weed-free fields with green crops clearly highlighted against dark earth are the well-respected norm. By comparison, fields where the soil is never visible, always covered by residues and/or multi-species cover crops, may appear messy and chaotic. Some soil health BMPs, such as no-till and cover cropping, were not held in high esteem by previous generation of farmers. In terms of practical applications of the principles and BMPs of the soil health approach, technical questions still abound.[154]

A soil health focus requires a farmer to tolerate more uncertainty, with no one to backstop the risk. Risk management is a crucial issue for farmers; their livelihoods depend on being able to harvest an adequate yield each year. We don't blame farmers for wanting to minimize their risks and maximize their chances for success.[155] Current crop insurance programs don't protect or support farmers who experiment with soil health, even though it can take three years or more to see the benefits from a soil health focus. Soil-health measurement techniques have not yet developed to the same point as chemical soil tests.[156] With the latter, nutrient requirements, for instance, are easy to assess and straightforward to address. Soil-health assessments,[157] on the other hand, are usually measurements related to soil characteristics, such as infiltration rates for rainfall, and any prescriptions that result from these tests may be more qualitative than quantitative (e.g., reduce tillage).[158,159] From this perspective, it is easy to see why farmers might ask "How do I know for sure that this will work for me?", or "If it's not broken, why fix it?"

On top of all this, the commercial network that supplies Ontario agriculture with inputs will have significant adjustments to make. Conventional agriculture depends on synthetic fertilizers for nutrition and pesticides for crop protection. Since these inputs can cause some damage to the creatures of the soil food web (see "Throwing Sand in the Gears," p.19), soil health practitioners use them sparingly and carefully. This de-emphasis on traditional inputs is likely to reduce demand for these products, while increasing demand for others (e.g., cover crop seed, various inoculants, compost). This change will undoubtedly create some economic disruption as product suppliers and crop advisors work to adapt. As mentioned above (see p. 19), some major suppliers are already working on developing new products that are more in line with the soil-health approach.[160] Developing these new and effective products will take time, however, and getting through the transition period will be challenging for the agriculture industry as a whole.

Building a wide-scale, soil health focus in Ontario agriculture cannot be done overnight. Farmers have every right to be skeptical about moving away from a system that has been so successful for them and their families.

An Important Role for the OMAFRA

Building a wide-scale, soil health focus in Ontario agriculture cannot be done overnight. Farmers have every right to be skeptical about moving away from a system that has been so successful for them and their families. They also have a right to expect solid evidence and successful role models, with appropriate support for financial risk as they experiment with these new ideas

The OMAFRA should make the soil health "entrance ramp" for farmers as wide, accessible, and low-risk as possible. The OMAFRA should take on a leading role in the following areas:

- *Address doubts and get wide buy-in, via research, demonstration projects, champions, and social marketing campaigns*. As discussed above, changing a culture is not easy. The ECO recommended in our 2013/2014 Annual Report that the OMAFRA "identify Ontario's leaders in soil health and systematically integrate their key success factors in the ministry's farm educational materials and research priorities." The ministry has started to do this by having local soil health practitioners speak at a growing number of soil health workshops being held in Ontario (organized by both the OMAFRA and various farming organizations) and by increasing the amount of research being done in the area of soil health. However, much remains to be done in this area.

- *Help farmers to manage transition risks, via potential changes to crop insurance rules, removing disincentives and replacing them with incentives to drive change, and funding innovation in research and in the field.* This is a very important area that has not yet been addressed by the government. However, in response to an application for review by two Ontario citizens concerned about the health of Ontario's soils, the ministry has launched a soil health initiative (see "The OMAFRA's Soil Health Initiative," at right), which the ECO is hopeful will address these concerns. In addition, the Ministry of the Environment and Climate Change recently released its Five Year Climate Change Action Plan, which identifies intended Greenhouse Gas Reduction Account funding of $30 million to support long-term soil health.[161]
- *Resolve technical issues.* Specifically, farmers need better methods for measuring carbon and soil health that are quick and inexpensive.[162 ,xiii] Once these have been developed, government could employ citizen scientists (farmers and other soil managers) to collect the baseline data needed to launch new programs, as well as to monitor their progress and success.
- *Manage the "disruptive innovation" that defines the soil-health approach*. This area of activity should include dealing with issues such as: industry sectors that may lose business; the need to retrain professionals; dealing with land ownership issues; and bringing existing laws like the *Drainage Act,* the *Endangered Species Act,* and the *Nutrient Management Act* into sync with the new vision of agriculture.
- *Promote the concept of a level playing field*. More generally, the OMAFRA should champion the concept of a level playing field for a sustainable economy and how that applies to agriculture in general and soil health in particular. This concept incorporates issues such as full-cost accounting, where the ecological costs and benefits of an activity are considered on an equal footing with the standard economic parameters. For instance, the costs of planting cover crops are borne by the individual farmer, while many of the benefits are enjoyed by society at large, via reduced pollution. Farmers who do not employ cover crops do not incur these additional costs; a level playing field would involve some mechanism for recognizing the societal benefits provided by BMPs, so that the practitioners are not punished economically for doing the right thing.

The OMAFRA's Soil-Health Initiative

In December, 2014, the ECO received an Application for Review from two Ontario citizens, asking for a review of the need for a comprehensive "soil-care" policy and regulatory framework in Ontario. The ECO sent this application to the OMAFRA, the Ministry of the Environment and Climate Change, and the Ministry of Municipal Affairs and Housing. The OMAFRA agreed to conduct this review and the other two ministries agreed to lend support. This review is currently in progress. In the interim, the ECO has learned from briefings with the OMAFRA that the ministry has adopted soil health as a high priority and has created a multi-stakeholder advisory group to provide a wide range of expert input. The first results of this consultation were posted on the Environmental Registry on August 29, 2016, in the form of an initial discussion document for developing a Soil Health and Conservation Strategy for Ontario, titled Sustaining Ontario's Agricultural Soils: Towards a Shared Vision.

[xiii] The OMAFRA has been working to develop a soil health assessment protocol by testing the Cornell Soil Health Assessment test and adapting it to the Ontario context. This work is still in progress.

The Potential of Carbon Offsets in Agriculture

The use of carbon offsets to incentivize increases in soil carbon,[163,164] while at first glance attractive, includes some major pitfalls. As discussed above, increases in soil carbon levels are difficult and costly to measure, and perhaps most significantly, these increases can be quickly and easily reversed by abandoning the practices that created them in the first place. This does not mean that as a society we should not find ways to promote, or even reward, soil carbon sequestration;[xiv, 165] rather, it means that direct offset payments to farmers for sequestering carbon may not be the best way to achieve the overall goal of healthier soils.

One useful direction with respect to the use of offsets may involve taking a different focus. Instead of rewarding carbon storage in soils, some organizations are employing a protocol for reduction in fertilizer use. As stated above, 43 per cent of Ontario agriculture's GHGs come from the application of synthetic fertilizers and raw manures. As demonstrated by existing soil-health practitioners, farmers adopting this approach could gradually reduce their need for synthetic nitrogen fertilizer. In fact, several fertilizer protocols have already been developed in the U.S.; three of them are based strictly on reduced application rates,[166] while the other also includes factors such as form, timing, and placement of the fertilizer.[167] They are all used for corn crops in the U.S., but could be adapted to other regions and crops.

The ECO believes that this approach has potential for reducing GHG emissions from soils. The provision of offsets for certain reductions could help farmers who have adopted soil-health practices take that risky but important next step of reducing fertilizer inputs. Even after implementing a number of soil health best management practices, farmers may be understandably worried about reducing the recommended levels of synthetic fertilizers, uncertain whether the increased natural fertility of their soils will be enough to maintain yield. Offsets could help in that regard, especially if they were accompanied by other support mechanisms, such as appropriately modified crop insurance programs.

[xiv] In fact, the USDA recently awarded a U.S. $1,000,000 grant to the National Corn Growers Association to "develop a system for scalable carbon accounting in agriculture, to be developed through its Soil Health Partnership Initiative."

ECO Comment and Recommendations

Comment

The climate change potential in healthy soils is enormous, but if the soil health movement is to fully take hold in a timely manner in Ontario, government must play a substantive and proactive role.

> Soil health is not something that you can just "add on" to an existing system of soil management

The most significant challenge to this initiative arises from the fact that soil health is not something that you can just "add on" to an existing system of soil management. It requires a different approach that puts the primary focus on protecting and enhancing the life in the soil. This approach requires a deep appreciation and technical understanding of soil life, and how largely invisible creatures, in tandem with photosynthesis, pull carbon out of the atmosphere, mitigating climate change, and then use it to build and maintain the resiliency needed for effective adaptation. Soil health, and the soil food web that provides it, cannot be an afterthought; it must be the first thought.

A province-wide conversion to a soil health approach will take time, effort and resources by government. It will require significant efforts in the areas of focused research, targeted technical assistance, appropriate risk-management programs, effective and easily accessible education, and workable incentives.[168] Most of all, however, it will require a profound commitment on the part of government, to understand the nature and value of the changes required and of the challenges involved, and to making the necessary changes happen.

Recommendations

First, the ECO recommends that the province of Ontario sign up to the *4/1000 Initiative*. Encouraging a conversion to a soil health focused approach to agriculture will be easier if we work with other jurisdictions that are on the same path.[169] We also encourage the OMAFRA to recommend membership in this initiative to the various appropriate civil society organizations, such as the Ontario Federation of Agriculture and the Ontario Soil and Crop Improvement Association.

Second, the ECO recommends that the OMAFRA:

- co-ordinate the development of a protocol, with supporting methods and technologies, for reliably estimating soil-carbon levels in Ontario; and
- implement a program for estimating soil-carbon levels across the province every three years, and making these results public.

Third, the ECO recommends that the Ontario government find a way to link the cost of crop insurance to soil-carbon levels in recognition that high-carbon soils reduce risks to crops.

And fourth, the ECO recommends that the province develop a program to provide financial support for up to 10 years for farmers who adopt soil health best management practices, designed to offset any yield loss due to transition issues. This program could potentially employ carbon offsets, such as those that reward reduced fertilizer use, as part of the financial support framework.

Endnotes

[1] Simpson, Sarah. Scientific American. Nitrogen Fertilizer: Agricultural Breakthrough – And Environmental Bane. March, 2009.
[2] Health Canada. GM Foods and their Regulation. http://www.hc-sc.gc.ca/fn-an/gmf-agm/fs-if/gm-foods-aliments-gm-eng.php
[3] Statistics Canada. Human Activity and the Environment, Pub. 16-201-X. Section 1: Food in Canada. Chart 1.1.
[4] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Historical Provincial Estimates by Crop, 1981-2014. http://www.omafra.gov.on.ca/english/stats/crops/estimate_hist_imp.htm
[5] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Historical Provincial Estimates by Crop, 1981-2014. http://www.omafra.gov.on.ca/english/stats/crops/estimate_hist_imp.htm
[6] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Estimated Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2011-2015 (Imperial and Metric Units). http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm
[7] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Historical Provincial Estimates by Crop, 1981-2014. http://www.omafra.gov.on.ca/english/stats/crops/estimate_hist_imp.htm
[8] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Estimated Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2011-2015 (Imperial and Metric Units). http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm
[9] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Historical Provincial Estimates by Crop, 1981-2014. http://www.omafra.gov.on.ca/english/stats/crops/estimate_hist_imp.htm
[10] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Estimated Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2011-2015 (Imperial and Metric Units). http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm
[11] Statistics Canada. 2011 Farm and Farm Operator Data: Snapshot of Canadian Agriculture: Chapter 1. http://www.statcan.gc.ca/pub/95-640-x/2011001/p1/p1-01-eng.htm
[12] Environment and Climate Change Canada. Canada's Greenhouse Gas Inventory. March, 2016. https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=83A34A7A-1
[13] As communicated to the ECO by Environment Canada.
[14] Agriculture and Agrifood Canada. Environmental Sustainability of Canadian Agriculture – Agri Environmental Report Series – Report #4. 2016, p. 94.
[15] Environment and Climate Change Canada. Canada's Greenhouse Gas Inventory. March, 2016. https://www.ec.gc.ca/ges-ghg/default.asp?lang=En&n=83A34A7A-1
[16] Food and Agriculture Organization (FAO). Trade Reforms and Food Security. Chapter 2: "Food Security: Concepts and Measurement."
[17] Gunderson, Lance H. Annu. Rev. Ecol. Syst., 31. Ecological Resilience – in Theory and Application, pp. 425-39. 2000.
[18] United States Environmental Protection Association (US EPA). Climate Change Impacts on Agriculture and Food Supply. https://www3.epa.gov/climatechange/impacts/agriculture.html
[19] Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR). Agriculture: in a changing climate. www.climateontario.ca
[20] Schlenker, Wolfram and Michael J. Roberts. PNAS. Vol. 106, no. 37. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. September, 2009.
[21] Ontario Centre for Climate Impacts and Adaptation Resources (OCCIAR). Agriculture: in a changing climate. www.climateontario.ca
[22] Center for American Progress. Agriculture and the Paris Agreement. May 12, 2016.
[23] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Role of Soil Organic Matter.
[24] Bot, Alexandra and Jose Benites. 2005. "The importance of soil organic matter." Food and Agriculture Organization of the United Nations: FAO Soils Bulletin 80.
[25] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Role of Soil Organic Matter. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
[26] United States Environmental Protection Association (US EPA). Climate Change Impacts on Agriculture and Food Supply. https://www3.epa.gov/climatechange/impacts/agriculture.html
[27] Penn State Extension. Managing Phosphorus for Agriculture and the Environment. http://extension.psu.edu/plants/nutrient-management/educational/soil-fertility/managing-phosphorus-for-agriculture-and-the-environment
[28] Dirzo et al. Science 25. Defaunation in the Anthropocene. pp. 401-406. July, 2014.
[29] Schwagerl, Christian. Yale Environment 360. Vanishing Act: Why Insects Are Declining and Why It Matters. 6 Jul, 2016.
[30] For a fairly detailed analysis of the problems associated with intensive or "industrial agriculture," see the following report: International Panel of Experts on Sustainable Food Systems (IPES-Food). From Uniformity to Diversity: a paradigm shift from industrial agriculture to diversified agroecological systems. June, 2016. www.ipes-food.org.

[31] Don McCabe, personal communication: buffer strips are ineffective because most P is lost in winter and early spring when the strips are frozen and the P-laden water runs right over them.
[32] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Video on Soil Health Principles, featuring NRCS spokesperson Ray Archuleta. From minute 9:30 on, Archuleta describes how buffers are “diapers” and not a real solution to the problem of nutrient and water loss.
[33] The information in Footnote 4 was provided by Charles Lalonde and Don McCabe of the Ontario Federation of Agriculture (OFA).
[34] Cernansky, Rachel. 2016. Secrets of life in the soil. Nature/News Feature. 13 September, 2016.
[35] Stika, Jon. A Soil Owner’s Manual. Introduction. 2016.
[36] Clapperton, Jill. Rhizoterra Inc. Slide presentation - Soil Health Principles. 2014. www.rhizoterra.com
[37] New research suggests that the flow of carbon through plants to underground ecosystems may be crucial to how the environment responds to climate change – See: Bardgett, Richard D. The Scientist. The Root of the Problem. August 1, 2011.
[38] Clapperton, Jill. Rhizoterra Inc. Healthy Soil is the Foundation of Civilizations. www.rhizoterra.com
[39] Orgiazzi, A., Bardgett, R.D., Barrios, E., Behan-Pelletier, V., Briones, M.J.I., Chotte, J-L., De Deyn, G.B., Eggleton, P., Fierer, N., Fraser, T., Hedlund, K., Jeffery, S., Johnson, N.C., Jones, A., Kandeler, E., Kaneko, N., Lavelle, P., Lemanceau, P., Miko, L., Montanarella, L., Moreira, F.M.S., Ramirez, K.S., Scheu, S., Singh, B.K., Six, J., van der Putten, W.H., Wall, D.H. (Eds.). European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas. 2016. Page 9.
[40] Kibblewhite, M.G., K. Ritz and M.J. Swift. Phil. Trans. R. Soc., 363: 685-701. Soil Health in Agricultural Systems. 2008.
[41] Orgiazzi, et al. European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas, Chapter 1 – the Soil Habitat. 2016.
[42] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Soil Health Nuggets. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
[43] Damrosch, Barbara. Washington Post. ‘Symphony of the Soil’ examines the fascinating world below your feet. October 2, 2013.
[44] Orgiazzi, A. et al. European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas. Page 169. 2016.
[45] Wardle, David et al. 2004. Science, vol. 304. Ecological Linkages between Aboveground and Belowground Biota. June 11, 2004.
[46] Townsend, Lee, Potter, Dan, and Powell, A.J. University of Kentucky Cooperative Extension Service, College of Agriculture. Earthworms: Thatch-Busters.
[47] Wall, Diana H., Uffe N. Nielsen, and Johan Six. Soil biodiversity and human health. Nature, Vol 000. 2015.
[48] Orgiazzi, A. et al. European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas. Page 93. 2016.
[49] Stika, Jon. A Soil Owner’s Manual, p. 26. 2016.
[50] For more detailed discussions of this specific benefit, see: “The Roots of Sustainability: Engaging the Soil Carbon Solution”, Section 6.2 of the ECO’s 2010/2011 Annual Report, entitled Engaging Solutions; and Section 3.2.5 of the ECO’s 2014 Climate Change Report: *Looking for Leadership*
[51] Magdoff, Fred and Harold Van Es. Sustainable Agriculture Research and Education (SARE) Program. Building Soils for Better Crops. 3rd Edition. Handbook Series Book 10, pp. 39-41. 2009.
[52] Penn State Extension. Cooperative Extension, College of Agricultural Sciences. Introduction to Soils. Soil Quality. p. 2.
[53] Nichols, Kris. USDA-ARS-Northern Great Plains Research Lab. Does Glomalin Hold Your Farm Together?
[54] Rillig, Matthias C., Sara F. Wright and Valerie T. Eviner. Plant and Soil 238:325-333. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: comparing effects of five plant species. 2002.
[55] Singh, Pradeep Kumar. 2012. Agricultural Science Research Journal. Vol 2(3). Role of Glomalin Related Soil Protein Produced by Arbuscular Mycorrhizal Fungi: A Review. March, 2012.
[56] Penn State Extension. Cooperative Extension, College of Agricultural Sciences. Introduction to Soils. Soil Quality. Pp. 3-4.
[57] Murphy, B.W. 2014. Department of the Environment, Canberra, Australia. Soil Organic Matter and Soil Function – Review of the Literature and Underlying Data, p. 34.
[58] For a detailed discussion of how SOM holds water, and how much it can increase the water holding capacity of soils, see: Jones, Christine. Managing Wholes.com, May 2. Soil Carbon means WATER to me! 2010.
[59] Clapperton, Jill. Rhizoterra. Inc. Healthy Soil is the Foundation of Civilizations. 2014. www.rhizoterra.com
[60] Orgiazzi, A., et al. (Eds.). European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas, p. 176 2016.
[61] Cornell University. NRCCA Study Resources, Competency Area 2: Basic Concepts of Soil Fertility.
[62] International Plant Nutrition Institute. Enviro-Brief # 01.
[63] International Plant Nutrition Institute. Enviro-Brief # 01.
[64] Ingham, Elaine R. Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Soil Food Web. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/

[65] Magdoff, Fred and Harold Van Es. Sustainable Agriculture Research and Education (SARE) Program. Building Soils for Better Crops. 3rd Edition. Handbook Series Book 10, pp. 38-39. 2009.
[66] Jill Clapperton. Video - Soil Health Principles. https://www.youtube.com/watch?v=-z-r30mKP3c
[67] Bais et al. Annu. Rev. Plant Biol. 57. The Role of Root Exudates in Rhizosphere Interactions with Plants and Other Organisms. pp. 233-266. 2006.
[68] Walker, Travis S., Harsh Pal Bais, Erich Grotewold, and Jorge M. Vivanco. Plant Physiol. Vol 132. Root Exudation and Rhizosphere Biology. pp. 44-51. 2003.
[69] Clapperton, Jill. Rhizoterra Inc. Healthy Soil is the Foundation of Civilizations. www.rhizoterra.com
[70] Nguyen, C. Agronomie 23, as referenced by Patrick Lavelle on p. 11 of Chapter 1.1 of Soil Ecology and Ecosystem Services, Diana Wall, ed. Oxford University Press. 2003.
[71] Bais et al. Annu. Rev. Plant Biol. 57:233-266. The Role of Root Exudates in Rhizosphere Interactions with Plants and Other Organisms, p. 251. 2006.
[72] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). Soil Biology Primer, Chapter on Soil Fungi. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
[73] Magdoff, Fred and Harold Van Es. Building Soils for Better Crops. Handbook Series Book 10. Sustainable Agriculture Research and Education (SARE) Program, 3rd Edition. pp. 39-41. 2009.
[74] For a good explanation of the entire C cycle, as it pertains to soil-carbon sequestration, see: Kane, Daniel. National Sustainable Agriculture Coalition. Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices. 2015.
[75] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). The Food Web and Carbon Sequestration. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
[76] A very important paper on soil carbon sequestration argues that new models are needed to predict levels of soil carbon sequestration because it is what the authors call "an ecosystem property", rather than simply a biological, chemical or physical property. See: Schmidt et al. Nature, Vol 478. Persistence of soil organic matter as an ecosystem property. October, 2011. pp. 49-56.
[77] Mycorrhizal fungi are particularly important to soil-carbon sequestration. See: Wilson et al. Ecology Letters, vol. 12: 452-461. Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments. 2009.
[78] These principles are described in detail on the NRCS Webpage on Soil Health Management. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
[79] Davis, Adam S., Jason D. Hill, Craig A. Chase, Ann M. Johanns, and Matt Liebman. PLOS|One, Vol 7, Issue 10. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. October, 2012.
[80] Vukicevich, Eric, Tom Lowery, Pat Bowen, Jose Ramon Orbez-Torres, and Miranda Hart. Agron. Sustain. Dev. 36:48. Cover crops to increase soil microbial diversity and mitigate decline in perennial agriculture. A review. 2016.
[81] Jill Clapperton. Video - Soil Health Principles. https://www.youtube.com/watch?v=-z-r30mKP3c
[82] Lancaster University. Science Daily, 27. Mix up plant species to keep soil healthy. July, 2016.
[83] Mulhollem, Jeff. Penn State. First-of-kind study suggests cover crop mixtures increase agroecosystem services. September 7, 2016.
[84] American Society of Agronomy. Science Daily. More for less in pastures. July 20, 2016.
[85] For example, see: Basche et al. Agriculture Water Management. 172: 40-50. Soil water improvements with the long term use of a winter rye cover crop. 2016.
[86] Rillig, Matthias C. Can. J. Soil Sci. 84: 355-363. Arbuscular mycorrhizae, glomalin, and soil aggregation. 2004.
[87] In fact, mycorrhizal fungi may be a key factor in the amount of carbon that a soil sequesters. Dr. Christine Jones, an Australian soil ecologist, has held this view for several years and the latest science seems to support her position. See: Jones, Christine. Evergreen Farming Newsletter. Mycorrhizal fungi – powerhouse of the soil. September, 2009.
[88] Jones, Dr. Christine. From light to life: restoring farmland soils. 2016. www.amazingcarbon.com
[89] Stika, Jon. A Soil Owner's Manual. See Chapter 4.
[90] Magdoff, Fred and Harold Van Es. Sustainable Agriculture Research and Education (SARE) Program. Building Soils for Better Crops. 3rd Edition. Handbook Series Book 10. p. 213. 2009.
[91] Magdoff, Fred and Harold Van Es. Sustainable Agriculture Research and Education (SARE) Program. Building Soils for Better Crops. 3rd Edition. Handbook Series Book 10. p. 235. 2009.
[92] Russel, Ann E., Cynthia A. Cambardella, David A. Laird, Dan B. Jaynes, and David W. Meek. Ecological Applications, 19(5). Nitrogen fertilizer effects on soil carbon balances in Midwestern U.S. agricultural systems. 2009.
[93] Hepperly, Paul. Pesticides and You, Vol. 27 (1). The Organic Farming Response to Climate Change. 2007.
[94] Orgiazzi, A., et al. (Eds.). European Commission, Publications Office of the European Union, Luxembourg. Global Soil Biodiversity Atlas, pp. 122-3. 2016.

[95] Townsend, Lee and Dan Potter. University of Kentucky – College of Agriculture. Entfact-402. Earthworms: Thatch-Busters.
[96] Tsiafouli et al. Global Change Biology 21: 973-985. Intensive agriculture reduces soil biodiversity across Europe. 2015.
[97] Beck, Dwayne. Dakota Lakes Reseach Farm, South Dakota State University. Managing Agricultural Ecosystems.
[98] Top Crop Manager. Use integrated fertilizer and cropping systems to help manage weeds. Nov. 29, 1999. http://www.topcropmanager.com/
[99] Doornbos, Roger F., LeendertCornelis van Loon, and Peter A. H. M. Bakker. Agron. Sustain. Dev.32: 227-243. Impact of root exudates and plant defense signaling on bacterial communities in the rhizosphere. A review. 2012.
[100] Stika, Jon. A Soil Owner's Manual. See p. 30.
[101] Townsend, Lee and Dan Potter. University of Kentucky – College of Agriculture. Entfact-402. Earthworms: Thatch-Busters.
[102] Sullivan, Preston. 2004. "Sustainable Management of Soil-Borne Plant Diseases." National Centre for Appropriate Technology: National Sustainable Agriculture Information Service (ATTRA).
[103] Karlsson, Ida, Hanna Friberg, Christian Steinberg, and Paula Persson. 2014. "Fungicide Effects on Fungal Community Composition in the Wheat Phyllosphere". PLOS|one. November.
[104] Kelley, Emily C. 2014. "NMSU researcher's carbon sequestration work highlighted in 'The Soil Will Save Us'". New Mexico State Newsletter, 07/08/14.
[105] Wilson et al. 2009. "Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: results from long-term field experiments". Ecology Letters, 12: 452-461.
[106] Read, David J., Jonathon R. Leake, and Jesus Perez-Moreno. 2004. "Mycorrhizal fungi as drivers of ecosystem processes in heathland and boreal forest biomes". Can. J. Bot. 82: 1243-1263.
[107] Johnson, David, Joe Ellington and Wesley Eaton. 2015. "Development of soil microbial communities for promoting sustainability in agriculture and a global carbon fix." PeerJ Preprints. | http://dx.doi.org/10.7287/peerj.preprints.789v1 | CC-BY 4.0 Open Access | rec: 13 Jan 2015, publ: 13 Jan 2015
[108] Leifheit, Eva F. 2014. "Soil sustainability and arbuscular mycorrhizal fungi". Inaugural-Dissertation. Freie Universitat Berlin.
[109] Rinaudo, Valeria, Paolo Barberi, Manuela Giovannetti, Marcel G.A. van der Heijden. 2009. "Mycorrhizal fungi suppress aggressive agricultural weeds". Plant Soil, 333:7-20.
[110] USDA. NRCS. Farming in the 21st Century.
[111] USDA. NRCS. Grower checklist
[112] Conant, Richard T., Mark Easter, Keith Paustain, Amy Swan, and Stephen Williams. Soil & Tillage Research 95. Impacts of periodic tillage on soil C stocks: A synthesis. pp. 1-10. 2007.
[113] Fisher, Madeline. Crops & Soils Magazine, American Society of Agronomy. Sod-based rotations. Sept-Oct, 2011.
[114] Syngenta. 2016. Improving Soil Health and Choosing the Right Cover Crops Can Reduce Soybean Cyst Nematode.
[115] Davis, Adam S., Jason D. Hill, Craig A. Chase, Ann M. Johanns, and Matt Liebman. PLOS|ONE 7(10). Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental Health. e47149. Doi:10.1371/journal.pone.0047149 . 2012.
[116] Thierfelder, Christian and Patrick C. Wall. International maize and Wheat Improvement Centre (CIMMYT). The Importance of Crop Rotations.
[117] Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Cover Crops: Adaptation and Use of Cover Crops. http://www.omafra.gov.on.ca/english/crops/facts/cover_crops01/cover.htm
[118] International Plant Nutrition Institute (IPNI). 4Rs of Nutrient Stewardship. http://www.nutrientstewardship.org/4rs
[119] Hepperly, Paul, Don Lotter, Christine Ziegler Ulsh, Rita Seidel and Carolyn Reider. Compost Science & Utilization, Vol 17, No. 2, 117-126. Compost, Manure and Synthetic Fertilizer Influences Crop Yields, Soil Properties, Nitrate Leaching and Crop Nutrient Content. 2009.
[120] Leu, Andre. Organics and Soil Carbon: Increasing soil carbon, crop productivity and farm profitability. Presentation to Katanning Workshop, March, 2007. www.amazingcarbon.com
[121] "Once plants and animals were raised together on the same farm — which therefore neither produced unmanageable surpluses of manure, to be wasted and to pollute the water supply, nor depended on such quantities of commercial fertilizer. The genius of America's farm experts is very well demonstrated here: they can take a solution and divide it neatly into two problems". Berry, Wendell. The Unsettling of America: Culture & Agriculture (1996), p. 62.
[122] Agriculture and Agri-Food Canada, Victoria McPhail, Ontario Ministry of Agriculture, Food and Rural Affairs, and Jack Kyle. Rotational Grazing in Extensive Pastures. A Best Management Practice (BMP) Guide. 2012.
[123] Hamilton, Lisa S. The Atlantic. The Brown Revolution: Increasing Agricultural Productivity Naturally. September 29, 2011.
[124] For a dramatic Ontario example of this statement, consider this case study: Islam, Rafiq, Dean C. Glenney, and George Lazarovits. Agron. Sustain. Dev. 35: 837-846. No-till strip row farming using yearly maize-soybean rotation increases yield of maize by 75%. 2015.
[125] Brown, Gabe. Keys to Building a Healthy Soil. One-hour presentation by Gabe Brown at a the Idaho Center for Sustainable Agriculture's annual symposium. 2014. https://www.youtube.com/watch?v=9yPjoh9YJMk

[126]Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Estimated Area, Yield, Production and Farm Value of Specified Field Crops, Ontario, 2011-2015 (Imperial and Metric Units). http://www.omafra.gov.on.ca/english/stats/crops/estimate_new.htm

[127] USDA/NASS 2015 State Agriculture Overview for New York State.

[128] The information on the Martens' farm is from a recorded webinar conducted by the Natural Resources Conservation Service (NRCS), United States Department of Agriculture. The webinar can be found here: http://www.conservationwebinars.net/webinars/managing-for-soil-health-on-an-organic-farm/?searchterm=None

[129] Data provided by the St. Clair Conservation Authority.

[130] St. Clair Region Soil and Crop News, Vol 2, Issue 1. Crops and Conservation. March, 2016.

[131] Davis, Adam S., Jason D. Hill, Craig A. Chase, Ann M. Johanns, and Matt Liebman. PLOS|One, Vol 7, Issue 10. Increasing Cropping System Diversity Balances Productivity, Profitability and Environmental health. October, 2012.

[132] Knapp, Alex. Forbes. These Two Scientists Just Raised $4 Million to Test Soil Health For Farmers. July 13, 2016.

[133] Biological controls use microbes to prevent disease or inhibit pests. Here is another example: Narisawa et al. Plant Dis. 89: 285-290. Effects of Pathogen Density, Soil Moisture, and Soil pH on Biological Control of Clubroot in Chinese Cabbage by Heteroconium chaetospira. 2005.

[134] Krotz, Dan. Berkley Lab Newsletter. It Takes a Community of Soil Microbes to Protect Plants From Disease. May 5, 2011.

[135] Pearce, Ralph. Country Guide. Enhancing the biotechnology of crops with microbials. Nov. 12, 2015.

[136] Zhang, Sarah. Genetic Literacy Project. Pesticides, fertilizers derived from microbes offer new frontier in agriculture. March 22, 2016.

[137] Agricultural companies are also partnering with environmental organizations to support soil health initiatives. See: Enoch, Daniel. Agri-Pulse. Companies, green groups partner for soil health. August 31, 2016.

[138] Natural Resources Conservation Service (NRCS), United States Department of Agriculture (USDA). 80 Years Helping People Help the Land: A Brief History of NRCS. http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/

[139] United States Department of Agriculture (USDA). News Release # 0112.16. Agriculture Secretary Vilsack Announces Climate Smart Agriculture and Forestry Results, Additional $72.3 Million Soil Health Investment to Support Paris Agreement. May 12, 2016.

[140] Ministere de L'agriculture de L'Agroalimentaire et de la Foret. Join the 4/1000 initiative, p. 2. 2015. http://newsroom.unfccc.int/media/408539/4-per-1000-initiative.pdf

[141] Ministere de L'agriculture de L'Agroalimentaire et de la Foret. Join the 4/1000 initiative, p. 2. 2015. http://newsroom.unfccc.int/media/408539/4-per-1000-initiative.pdf

[142] Ministere de L'agriculture de L'Agroalimentaire et de la Foret. Join the 4/1000 initiative, p. 2. 2015. http://newsroom.unfccc.int/media/408539/4-per-1000-initiative.pdf

[143] For a good discussion as to how this initiative is supposed to work and whether it is possible, see: Koch, Andrea et al. Global Policy Journal. 4/1000 – Soil Carbon to Mitigate Climate Change.

[144] See also: Gustin, Georgina. Inside Climate News. Looking to the Earth Itself as a Climate Solution. September, 2016.

[145] Ministere de L'agriculture de L'Agroalimentaire et de la Foret. Join the 4/1000 initiative, p. 3. 2015. http://newsroom.unfccc.int/media/408539/4-per-1000-initiative.pdf

[146] Ministere de L'agriculture de L'Agroalimentaire et de la Foret. Join the 4/1000 initiative, pp. 3-5. 2015. http://newsroom.unfccc.int/media/408539/4-per-1000-initiative.pdf

[147] See list of 4/1000 partners at this site: http://4p1000.org/partners

[148] Basche, Andrea D. et al. Agricultural Water Management 172: 40-50. Soil water improvements with the long-term use of a winter rye cover crop. 2016.

[149] Congreves, K. A., A. Hayes, E.A. Verhallen, L.L. Van Eerd. Soil & Tillage research, 152: 17-28. Long-term impact of tillage and crop rotation on soil health at four temperate agroecosystems. 2015.

[150] Van Eerd, Laura L, Katelyn A. Congreves, Adam Hayes, Anne Verhallen, and David. C. Hooker. Can. J. Soil Sci. 94: 303-315. Long-term tillage and crop rotation effects on soil quality, organic carbon, and total nitrogen. 2014.

[151] Ontario Soil and Crop Improvement Association (OSCIA). Healthy Soil Research First of Kind in North America. 2016. http://www.ontariosoilcrop.org/blog/2016/07/26/healthy-soil-research-first-of-kind-in-north-america/

[152] The rate at which agricultural soils can sequester carbon is an important factor. The estimates developed by the International Panel on Climate Change (IPCC) are in the range of 1.1 to 1.8 tonnes of CO_{2e} per hectare per year. A study done in 2007 on the potential for Canadian agriculture put the figures for central Canada somewhat lower: 0.36 tCO_{2e}/ha/yr (for change from conventional tillage to no-till); and 1.1 tCO_{2e}/ha/yr (for decreasing the use of summer fallow). Do these figures imply that the higher rates of soil-carbon acquisition measured by soil-health practitioners like Mike Belan and Gabe Brown (4.5 tCO_{2e}/ha/yr and up) are inaccurate, or are they outliers? This is a matter of some debate and the ECO cannot state a definitive answer at this point in time. However, recent scientific evidence seems to support the view that the established estimates of potential are too low and the higher numbers for soil carbon

sequestration found increasingly in the literature and the media may indeed represent a better expression of the potential of soil to capture carbon. The key to this discussion is an understanding of how the existing models for estimating carbon sequestration are designed. see: Kane, Daniel. National Sustainable Agriculture Coalition. Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices. November, 2015.

[153] Li, Xiaomei and Yongsheng Feng. Alberta Research Council. Carbon Sequestration Potentials in Agricultural Soils. www.arc.ab.ca

[154] For an interesting discussion of farming attitudes, read: Pearce, Ralph. Country Guide. Learning from organic agriculture. May 9, 2016.

[155] For an interesting discussion on the topic of changing cultures and risk, see: Wilson, Mike. Farm Futures. Soil health just needs one first step. June 1, 2016.

[156] See the following document for an example of how one group of land managers in Australia have formed a cooperative to "better understand and manage for soil biological health": Mudgee Microscope Group. Beyond the Rhetoric. A Case Study: A cooperative approach by land managers to better understand and manage for soil health. www.watershedlandcare.com.au.

[157] There have been a number of tests developed in recent years to provide the farmer with at least a general idea of soil health. See this article in Country Guide for a general discussion of one of these tests: Pearce, Ralph. 2016. "A healthier soil test". In Country Guide, Sept. 8.

[158] For a good example of soil-health testing and assessment methods, see: Al-Kaisi, Mahdi and David Kwaw-Mensah. Iowa Soil Health Management Manual. Iowa State University, Extension and Outreach, with funding from NRCS. pp. 29-32. 2016.

[159] A new soil health test is being offered in Ontario, as of 2016. It is called the "SoilOne Report". See: Pearce, Ralph. Country Guide. Getting down to biology. August 22, 2016.

[160] De Vries, Jop. Science, Vol. 349, Issue 6249. The Littlest Farmhands. pp. 680-683. 2015.

[161] Province of Ontario. Ontario's Five Year Climate Change Action Plan 2016-2020.

[162] Van Eerd, Laura. Cornell Soil Health Assessment as a possible soil quality standard for Ontario. Project report submitted to Farm and Food Care Ontario, Jan 31, 2015.

[163] Australia already has a well-developed program of carbon credits and offsets. See this article for a description and discussion of the 4/1000 initiative: Koch, Andrea et al. Global Policy Journal. 4/1000 initiative– Soil Carbon to Mitigate Climate Change.

[164] No-Till Farmer. Carbon Trading Pays for Alberta Farmers.

[165] Farm and Dairy. Will it work to pay farmers to sequester carbon? Sept 26, 2016.

[166] American Carbon Registry. Reduced Use of Nitrogen Fertilizer on Agricultural Crops. See: http://americancarbonregistry.org/carbon-accounting/standards-methodologies/emissions-reductions-through-reduced-use-of-nitrogen-fertilizer-on-agricultural-crops ; Climate Action Reserve. Nitrogen Management Project Protocol Vol. 1.1 See: http://www.climateactionreserve.org/how/protocols/nitrogen-management/ ; and, Verified Carbon Standard. "Quantifying N2O Emissions Reductions in Agricultural Crops through Nitrogen Fertilizer rate reduction – Vol. 1.1". – see http://database.v-c-s.org/methodologies/quantifying-n2o-emissions-reductions-agricultural-crops-through-nitrogen-fertilizer .

[167] American Carbon Registry. "Changes in Fertilizer Management" See: http://americancarbonregistry.org/carbon-accounting/standards-methodologies/emissions-reductions-through-changes-in-fertilizer-management .

[168] For a good discussion of the potential of incentives, see; Lovell, Angela. Counting the full value of farming. Country Guide, Oct. 14, 2016.

[169] For a good analysis of what needs to be done to implement the 4/1000 Initiative, see: Chambers, Lal, and Paustian. Journal of Soil and Water Conservation. May/June, 2016. Soil carbon sequestration potential of US croplands and grasslands: Implementing the 4 per Thousand Initiative, pp. 68A-74A.

Environmental Commissioner of Ontario

1075 Bay Street, Suite 605
Toronto, ON M5S 2B1

T: 416-325-3377
F: 416-325-3370
1-800-701-6454

www.eco.on.ca
commissioner@eco.on.ca

ISBN 978-1-4606-8763-5 (Print)
ISBN 978-1-4606-8764-2 (PDF)