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MICHIGAN POTATOES — MICHIGAN POTATO INDUSTRY COMMISSION

Managing Soil Health for Root and Tuber Crops

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I. Soil health – An introduction

Michigan farmers know that some soils are better suited to crop production than others. Differences can be detected through texture, color and odor as farmers take a handful of soil and examine it for tilth. Soil tilth is also referred to as soil quality or soil health. It consists of the soil biological, physical and chemical properties that together support crop growth and determine yield response to agricultural inputs or weather. For example, soil aggregation affects the amount of pore space available in soil for aeration, water infiltration and root growth (Figure 1).

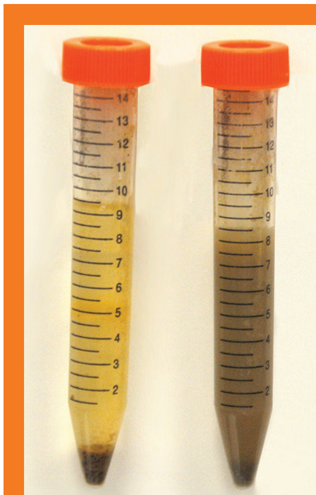

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Figure 1. Field soil with excellent aggregate stability (left) and poor aggregate stability (right).

Soil health influences both yield and quality in root and tuber crops such as potato, sugar beet and carrot. This is not surprising because the harvested portion of these crops is directly connected with the soil environment. Root and tuber producers are among those who invest heavily in soil management. However, there is growing concern that, despite this investment, soils are becoming degraded. About 50 percent of Michigan potato growers surveyed recently indicated that yield has decreased by at least 5 percent over the past decade (N. Rosenzweig, unpublished data). As a result, soil health has become a priority research area for the Michigan potato, sugar beet and vegetable industries (agbioresearch.msu.edu). The focus of this bulletin is on improving Michigan root and tuber crop yields through principles and practices that enhance soil health.

Soil health is determined by the interaction of farmers' management practices and fundamental, unchangeable soil factors such as rock parent material and topography. Identifying the soil series found in a specific field and its associated properties provides a baseline for determining soil health. An excellent source of this information is the U.S. soil survey (www.websoilsurvey.nrcs.usda.gov). Soil type is important, but historical and current management also play key roles in determining soil functioning. Two soils that are described as being from the same soil series and class on a soil survey map may have quite different soil health properties, depending on their management history. This is good news – it means that farm managers can influence soil health and over time build high quality soil across an entire farm. A soil series is the starting point you inherit; soil health is what you shape over your lifetime and pass on to the next generation.

Soil health incorporates the chemical, biological, and physical properties of soil. (The three components of soil health are described in an excellent website resource: http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/.) We consider all three in this bulletin but focus particularly on biophysical aspects that are not necessarily addressed by soil fertility practices.

Michigan agricultural producers widely recognize the importance of soil health and associated biophysical properties. A survey of potato growers in 2013, for example, highlighted soil organism activity as the No. 1 factor contributing to soil health (Figure 2). As a result, the Michigan Potato Industry Commission has supported initiatives including soil health workshops, a soil health white paper (available at http://www.ent.msu.edu/directory/george_bird) and a soil health survey of producers' fields.

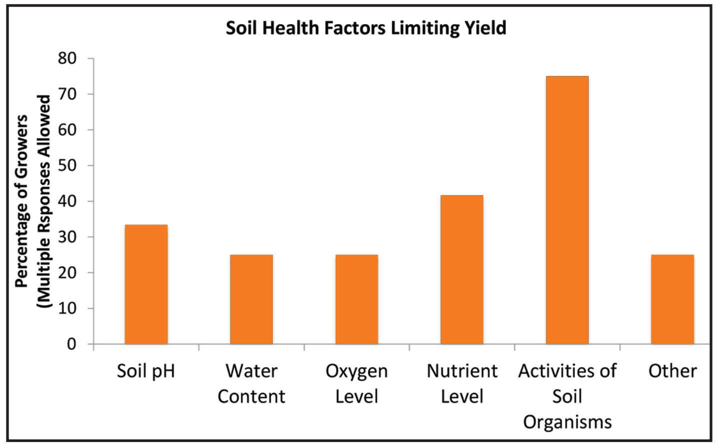


Figure 2. Soil health factors that potato growers reported as being important, where multiple responses were allowed. Source: web-based survey of Michigan potato growers in 2013 (Rosenzweig and Steere, unpublished data).

II. Soil health on Michigan farms

Results from soil monitoring surveys carried out on Michigan fields indicate that soil chemistry is usually very well-managed on Michigan potato and root crop farms. Nutrient requirements of crops are generally well-understood, and potassium status in particular is well-maintained (Po et al., 2010).

Consider, for example, the findings from a study carried out on eight potato farms in Michigan that monitored soil at 96 sites (Table 1). In this study, soil properties of 56 potato fields were considered. We report here on soil properties from fields reported by farmers to have high yield potential and contrast these with fields from the same farms that were reported to have poor yield potential. Measurements included common soil chemical properties as well as soil organic matter (SOM) content and potentially mineralizable nitrogen (PMN), two indicators of soil biological health. The soil chemical property of extractable potassium level was generally adequate and not noticeably higher on fields that produced high tuber yields (Figure 3A). Potassium is very important for plant water relations, and farmers are aware of the need to maintain optimum soil potassium levels to support excellent potato tuber yields. Fields that were rated as high-yielding by growers were frequently associated with higher SOM content and greater potential for nitrogen mineralization than fields with a history of low tuber yields (Figure 3B and C). PMN measures the amount of nitrogen available in organic forms to be mineralized – made plant-available – by soil fungi and bacteria during a growing season. PMN is related to organic matter content and driven by farmer practices such as the amount and quality of residues incorporated into a soil.

Table 1. Soil health indicator values associated with 96 soil samples from Michigan potato, field crop and forest sites in 2012 (G. Bird, unpublished data).

Soil health indicators[1]	Potato field soil	Forest soil
Aggregate stability (%)	39.0	56.6
Available water capacity (g/g)	0.08	0.12
Surface hardness (psi)	87	100
Subsurface hardness (psi)	302	300
Organic matter (%)	1.0	5.3
Active carbon (ppm)	225	737
Mineralizable nitrogen (µgN/g dw soil/wk)	7.1	38
Root health index (1-9)	4.2	5.4
pH (5.0-8.0)	6.1	5.5
Extractable phosphorus (ppm)	11.7	8.4
Extractable potassium (ppm)	116	95
Soil health index (0-100)	57	73

[1]Samples processed at the Cornell University Soil Health Laboratory (Geneva, New York) in accordance with the assessment protocol described in the Cornell Soil Health Assessment Training Manual (2nd edition, 2009).

Awareness of the importance of soil biology to crop health is growing among Michigan potato producers.

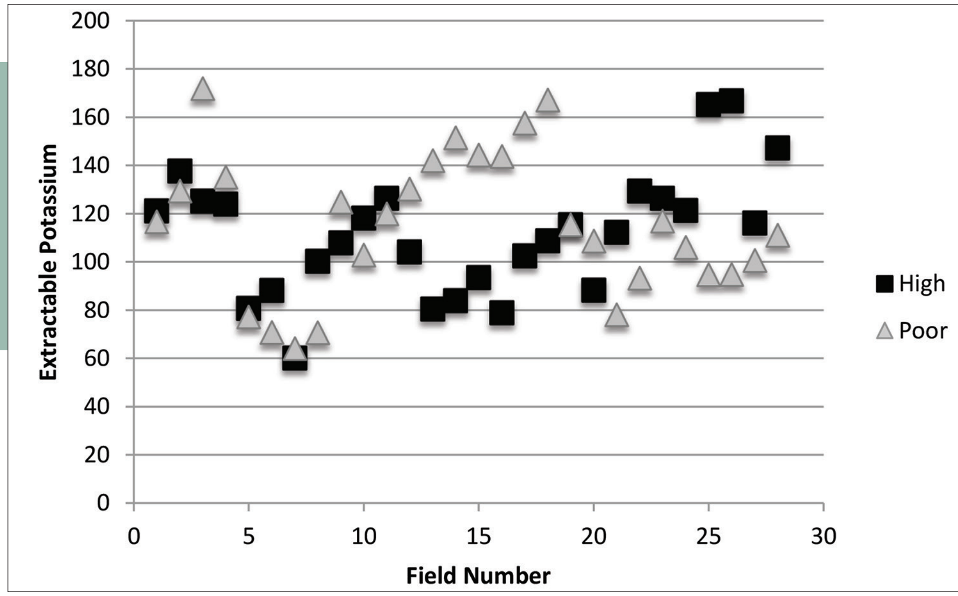


Figure 3A. Soil extractable potassium average for 56 fields rated either high productivity or poor productivity by eight Michigan potato farmers. Fields are presented as pairs from the same farm and organized by region (George Bird, unpublished data, 2013).

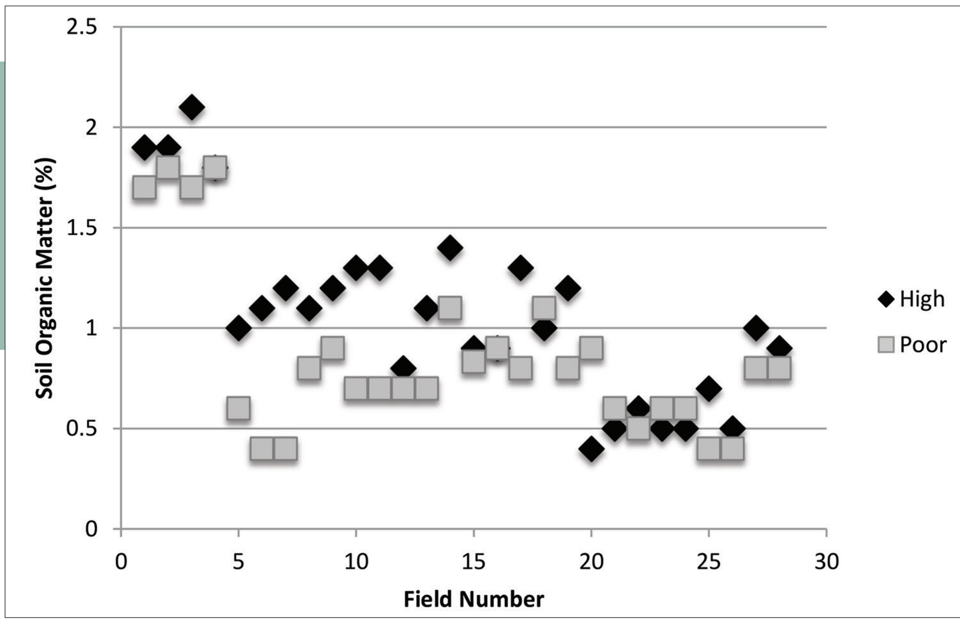


Figure 3B. Soil organic matter average for 56 fields rated either high productivity or poor productivity by eight Michigan potato farmers. Fields are presented as pairs from the same farm and organized by region. (George Bird, unpublished data, 2013).

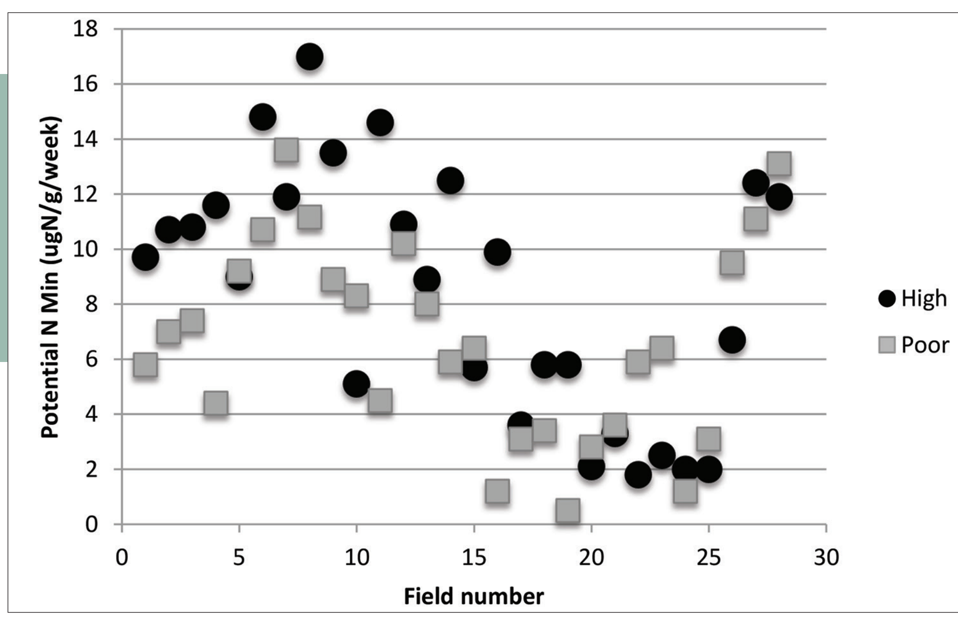


Figure 3C. Potential nitrogen mineralization average measured at the same time as soil organic matter (George Bird, unpublished data, 2013).

Soil nutrition and chemical management is generally well-understood by Michigan farmers, but soil biophysical properties are more challenging to manage. In all, 12 soil health indicators were measured in the 2012 soil health survey of 96 Michigan potato fields and forest sites (Table 1). A few fields were found to have high levels of SOM and potential nitrogen mineralization, but the majority of fields did not. The potato field sites had an average score of 57, based on a soil health index of 0–100. Samples collected from nearby natural areas, which were predominantly forest sites, had an average score of 73. The poor ranking of potato field sites was in the main due to very low SOM status (1 percent compared with 5 percent in nearby forest sites), as well as related deficiencies in available water capacity, active carbon and mineralizable nitrogen.

As in the example above, recommended practices for enhancing soil health vary depending on the specific issue(s) identified. Some soil properties can be managed more directly or immediately than others, so careful consideration should be given to prioritizing soil properties of interest. For example, if the soil nutrient supply is insufficient or not available when crops need nutrients, this type of issue can be addressed within just one or two years through practices such as application of synthetic fertilizer, manure or cover cropping (Nyiraneza and Snapp, 2007; Snapp et al., 2003). However, if soil aggregation is poor and the goal is to improve soil tilth, this will likely require additions of large amounts of organic material over a longer period of time (Snapp and Morrone, 2008). In general, soil management to improve the biophysical properties that limit root crop health usually requires a long-term commitment. Laboratories that provide tools for field monitoring and assess soil for various physical and biological soil health indicators are now available (http://soilhealth.cals.cornell.edu/ and https://solvita.com/fieldtest).

Soil chemistry and nutrient deficiencies are best addressed through frequent soil monitoring and following recommendations for amendment with inorganic and organic sources (Nyiraneza and Snapp, 2007). We suggest that growers monitor soils as described on the website for Michigan soil

Carrot rotation: A strip tillage/cover crop case study

Innovative carrot producers in western Michigan recognize the importance of soil health in determining crop quality and yield, and they have been experimenting with multiple strategies to conserve and improve their soils, including cover crop windbreaks, strip tillage and crop rotation. Because carrots have very slow germination and early growth, one of the key challenges is minimizing erosion from wind and rain during carrot establishment in early spring. To protect carrots during this period, growers often combine strip tillage with a preestablished small grain cover crop such as barley or wheat, which is left between rows as a windbreak until carrots are well-established. Strip tillage is a form of reduced tillage that targets tillage to the zone where crops will be planted, leaving 50 percent to 75 percent of the soil surface undisturbed. This system facilitates retention of surface residue as well as living cover to protect and build soils while saving costs for fuel and equipment, and maintaining or improving carrot yields (Brainard and Noyes, 2012).

Crop rotation is another critical tool used by carrot growers to address soil and pest issues. In particular, several growers have adjusted their crop rotation to include winter wheat before carrots. Although the short-term returns to wheat are low, many growers see sufficient economic benefits for subsequent high-value vegetables to justify wheat as a rotational crop. In addition to building and protecting soils, small grains such as winter wheat can reduce the incidence of certain key pests that are often problematic in carrots, including the northern root-knot nematode (Belair et al., 1996) and Powell amaranth (Brainard et al., 2008). In addition, volunteer wheat emerging following wheat harvest can serve as both a winter cover crop and subsequent windbreak for carrot production the following spring, allowing growers to forgo the costs associated with cover crop seed and establishment. Finally, since winter wheat is harvested in early July, its inclusion as a rotational crop opens up opportunities to grow cover crops in late summer that may also be beneficial for carrots the following spring. For example, research has demonstrated that certain varieties of sorghum-Sudangrass grown during this window can suppress northern root-knot nematodes and improve carrot yields the following year (Widmer and Abawi, 2000). However, care must be taken to select cover crop varieties that do not inadvertently exacerbate pest issues or suppress crop growth. An important example is *Brassica napus* (var. 'dwarf Essex rape'). This cover crop can be grown in the postwheat window, but it has been observed to suppress carrot emergence and increase the incidence of forked carrots the following spring (D. Brainard, unpublished, 2015).

fertility management in row crops (http://www.soil.msu.edu). Comprehensive information is provided on nutrient requirements for Michigan row crop production. Soil samples can be sent to MSU and commercial soil labs, which will provide excellent guidance on the requirement for N-P-K fertilizer. As a result, these crops are generally not deficit in macronutrients or micronutrients.

III. Improving soil physical properties

The physical properties associated with soil health interact with soil chemistry and biology and are often overlooked aspects of farm management. This is illustrated by an on-farm study of commercial potato fields in Michigan that found that potato tuber weight from geo-referenced yield monitors was related strongly to SOM, aggregation and water-holding capacity, desirable physical properties that were lacking in the majority of fields (Po et al., 2010). Soil texture partially determines physical properties such as available pore space and water infiltration rates. Gains in SOM can enhance soil aggregation and improve structure in contrasting soil textures such as sandy and clay-textured soils (Snapp and Grandy, 2011). The primary means of building SOM are additions of high-quality organic material from amendments or crop residues and judicious tillage to prevent organic matter degradation. Organic matter helps form microaggregates that hold water and support good drainage. They are also stable and resistant to breakdown during routine cultivation.

One of the challenges to maintaining and building soil physical structure in root and tuber production systems is neglect of soil-restorative crops such as wheat and hay. A grower survey conducted in Michigan during 2013 suggested that winter wheat and alfalfa are included in less than a quarter of respondents' rotation sequences (see Figure 2 on page 2). Potato, carrot and sugar beet fields are also frequently tilled, sometimes during less than ideal soil moisture conditions when aggregates are susceptible to degradation. The adoption of long, diverse crop rotation sequences can help address these issues. Some crops can be grown with minimum tillage, others produce large amounts of residues, and a diversity of root architecture, soil cover and residue biochemistry can be maintained. This diversity counteracts the intensive production of root and tuber crops, which necessitates soil disturbance at multiple times during the year and alone results in minimal residue production.

Profit potential and markets influence crop choice, and sometimes winter cereals and forage are not economically competitive or feasible to grow. However, it is important to factor in the soil-restorative role of these crops when evaluating your bottom line. A crop such as winter wheat may not produce a large profit immediately, but it contributes to farm profits over the long term by rehabilitating SOM and soil aggregation. Still, a farmer may face economic pressure to grow crops that require intensive tillage and do not return abundant residues to the soil. In this case, alternative sources of vegetative cover and organic matter should be pursued, such as cover crops and manure (Snapp and Grandy, 2011).

IV. Improving soil biology

The soil habitat or home available for microorganisms is extremely diverse and heterogeneous. It is not surprising that the soil biological community is amazingly diverse as well. In a single ounce of soil there are likely to be over 10,000 species of bacteria and thousands of species of fungi. All this diversity is important for maintaining critical soil functions such as nutrient cycling. This section discusses the importance and process of maintaining soil biodiversity and the activity of the soil biota in the complex soil habitat.

The primary source of energy and elements that soil bacteria and fungi need to grow is SOM. In addition to acting as a nutrient reservoir for biology, SOM influences soil structure, water-holding capacity, pH and ion exchange capacity. All of these factors in turn help determine soil fertility, or the ability of soils to provide water and nutrients in support of plant growth.

How is SOM formed from crop residue or other biomass? Traditional views of SOM formation rely heavily on the humification theory, in which organic, primarily plant-derived compounds are converted into humus that cannot be broken down any further by soil microbes. The rate of SOM formation was largely attributed to plant tissue quality – i.e., how much lignin tissues contain to resist microbial breakdown. More recent research has emphasized another set of mechanisms controlling SOM formation: processes related to microbe activity and growth rates (Nin et al., 2015). The abundance and diversity of soil biota itself is now known to also influence SOM formation.

Microbial biomass has been described as the "eye of the needle through which all the natural organic material that enters the soil must pass" (Jenkinson, 1977, page 213). Polysaccharides and other chemical byproducts are excreted by soil microorganisms as they digest residues and other dead microbes. These microbial byproducts act as a sort of glue, aggregating mineral and organic soil compounds. There is, therefore, a strong positive relationship between soil microbial biomass and SOM content in agricultural fields, as shown in Figure 4 (next page).

In any soil system, most microbes are dormant, waiting for conditions favorable for their growth. Outside of the rhizosphere (the area immediately adjacent to roots) soil is a virtual desert for microbes. As a result, microbial boom-and-bust cycles are common. Microbes in the soil experience a boom in growth and activity when they are provided with high-quality organic matter, whether this is from crop residues, organic amendments, dying roots or root exudates. Such high-quality material is finite, however, leading to a bust when most microorganisms starve and cells break apart. Some of this cellular material is recycled, but much of the resulting dead microbial tissue is glued together with minerals by polysaccharides and fungal hyphae as described above. This means that the microbial biomass becomes associated with mineral surfaces, where it is protected from further decomposition, and starts to build up stable SOM. It is this long-lived SOM that is the key to maintaining good soil structure, water-holding capacity and cation exchange capacity (Nin et al., 2015).

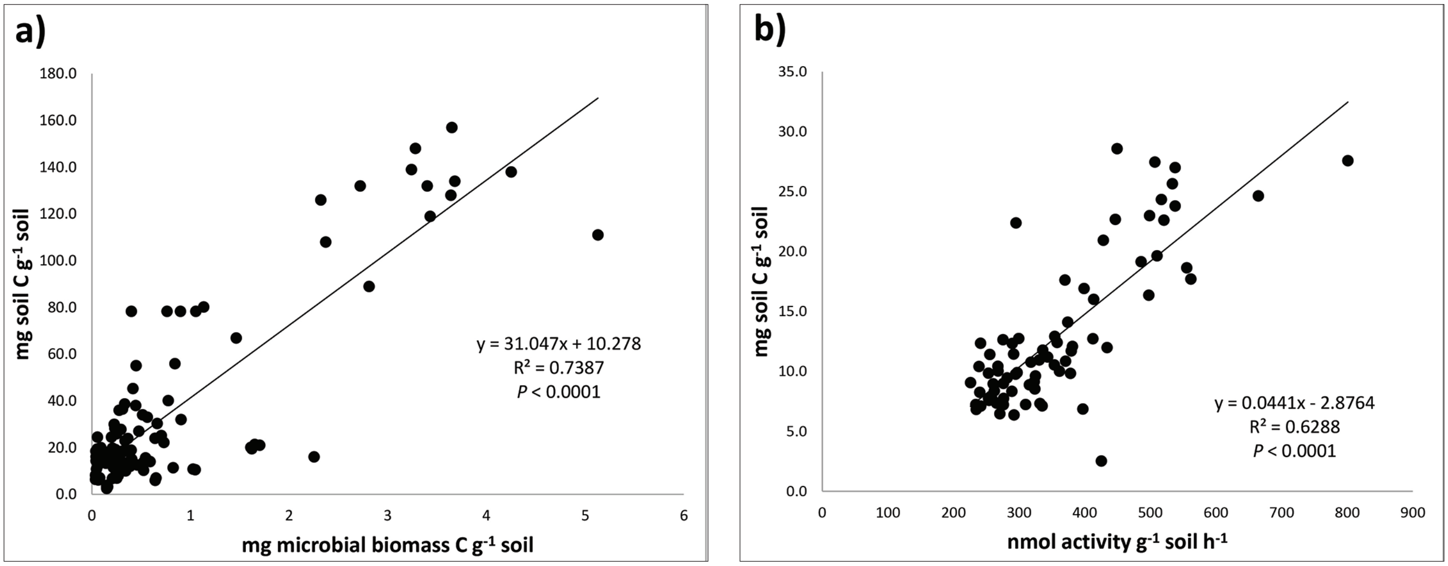


Figure 4. Microbial biomass versus soil organic C (a) and microbial enzyme activity versus soil organic C (b) across multiple agricultural systems. As microbial biomass and activity increase, so does soil C, which is closely related to soil organic matter (L. Tiemann, unpublished data).

How can you "wake up" soil microbes so that they are active to help build SOM? The addition of high-quality organic materials (those that have a nitrogen concentration above 2 percent and a C:N ratio < 25) such as legume cover crops, young cereals, and poultry or slurry manures can increase microbial biomass by roughly 36 percent within just a year or two of addition (Kallenbach and Grandy, 2011). This is the most direct way to stimulate microbial activity and growth rates. However, it is complicated to predict the effects of adding high-quality residues because increased microbial activity can either increase organic matter loss from the system through mineralization to CO_2, or do the opposite if the activity helps improve SOM status over the long term through microbial contributions. In many cases, microbial activity is positively related to soil organic carbon accumulation (Figure 4). Yet, the net outcome depends on the efficiency of microbes as they use organic materials for both energy and growth. That is, the balance of carbon retained as microbial biomass versus that lost as respired CO_2 determines the contribution of microbes to building SOM (Tiemann and Billings, 2011). Though exciting new research findings are emerging, there is still limited information available on how farmers can manage this trade-off and harness soil biology for sustained soil health. Initial research suggests that adding a diverse mix of organic materials to soil is a practical way to enhance soil biological health and encourage microbial contributions to SOM.

Widely available sources of high- and medium-quality materials that farmers can use to feed soil biology are shown in Table 2. These organic amendments include

Table 2. Organic amendments that can be used as sources of residues to improve soil health in root and tuber crop production systems. These supply a source of available nitrogen and energy to microbes.

Organic material	High quality nitrogen sources*	Medium quality nitrogen sources**
Manure	Swine slurry	Beef cattle, dried
Compost	Poultry compost, dried	Dairy compost, dried
Winter cover crop	Red clover Alfalfa Mixtures with legumes such as hairy vetch/rye	Rye Wheat
Short-season cover crop (45 to 60 days)	Buckwheat, mustard	Pearl millet, oil-seed radish
Crop rotation	Soybean, hay crop, pasture	Wheat

*High quality residues are those with nitrogen contents above ~2 percent.
**Medium quality residues for root and tuber crops have N content from ~1 percent to 2 percent.

manure, compost and cover crop residues, which generally have high nitrogen content and carbon that is readily available to supply energy (in contrast to complex polysaccharides and recalcitrant carbon sources such as lignins, which are difficult for microoganisms to digest). Medium-quality materials are not as readily available to soil biology but rather offer a slow and steady supply of nutrients and energy that provides support for growth over a longer period. High-quality materials are used by microbes as an energy source to power their initial growth after dormancy, which prepares them to eventually decompose these lower quality organic materials. The subsequent decomposition of lower quality materials is thus inherently more efficient (i.e., there is less CO_2 loss) and therefore likely to result in gains of SOM.

Minimizing tillage can also be effective as a means to build SOM if minimal tillage is used in combination with growing cover crops or rotation with a small grain crop that provides cover throughout the winter and large amounts of fine roots. It is important to grow soil-restoring crops at high seeding rates and to allow time for extended growth. In an on-farm study of potato growers in Michigan, the size of the cereal rye cover crop root system depended on seeding rate – 120 pounds/acre or more of seed produced the best cover crop stands – and length of time the cover was allowed to grow in the spring. Crops grown through late April gave the best results (Morrone and Snapp, 2011).

Farmer practices that generate a mixture of high- and lower quality organic inputs help to ensure that SOM building processes are occurring alongside maintenance of other soil biology functions such as nitrogen mineralization for crop growth. One effective strategy to supply mixed-quality residues is growing a high-quality legume crop along with a lower quality cereal crop. An example is a red clover cover crop sown beneath a wheat crop (Mutch and Snapp, 2003). This combination provides a source of mixed residues from decomposing wheat stubble and red clover biomass (Table 2). Another option is to grow a winter cereal cover crop, such as rye or wheat, and then spread manure or compost just before incorporating the cover crop residue (Rector et al., 2009). Incorporating cover crops before flowering, while they are still succulent and green, is yet another way to increase the amount of nitrogen and energy available to soil microbes. However, this often means that much less biomass is ultimately produced because less time is allowed for growth. If a farmer's goal is to maximize the volume of organic material incorporated into the soil, then a cover crop should be allowed to grow longer. Though this produces a larger amount of biomass, it is lower quality material because the cover crop stems and leaves lignify as they mature, and the percentage of leaf nitrogen content generally declines.

These and other benefits of cropping systems diversity have been investigated in a long-term ecological field study at Kellogg Biological Station in southwestern Michigan. Crops planted as continuous monocultures were compared with crops in rotation, with the highest diversity being a corn-soy-wheat rotation with two cover crops, rye and red clover. This study revealed strong, positive relationships between rotational diversity and microbial activity/diversity in the soil. Rotational diversity also had positive effects on SOM accumulation, aggregate formation and ultimately corn yields (Tiemann et al., 2015). A literature review of the effects of mixed-quality residues across a wide range of cropping systems and climates revealed an average increase in soil microbial biomass of 21 percent and an average increase in SOM of 9 percent (McDaniel et al., 2014). These increases in microbial biomass and SOM were accompanied by a 13 percent increase in soil nitrogen. In a soil with 2 percent organic matter, this 13 percent increase in total soil N would translate into an increase of about 4 pounds of plant-available N per acre.

In summary, farm management practices that increase the amount and diversity of organic soil amendments support microbial diversity. Over time, the balance of microbes with high- and low-efficiency growth strategies becomes more even, thus there is greater potential for SOM accumulation and nutrient cycling. A further benefit of a diverse microbial community is increased activity of soil predators, including bacterial- or fungal-feeding organisms such as nematodes, flagellates, ciliates and amoebae. These organisms feed on bacteria or fungi and in doing so release excess nitrogen, often directly on the root surface or in the adjacent rhizosphere, making it readily available for the growth and development of plants. The process is very similar to digestion in humans, requiring elimination of excess nitrogen through the process of urination. Increased diversity and abundance of predatory soil organisms can result in increased plant biomass yield (Nehr, 2010) It can also help control soil-borne pathogens, which is discussed in greater detail in the next section.

V. Soil-borne disease management

Soil-borne diseases are the second most important limiting factor on crop yield after water insufficiency, accounting for approximately half of all U.S. crop losses – $4 billion annually. Potato (*Solanum tuberosum* L.) production systems in particular are plagued by many intractable soil-borne diseases, including Rhizoctonia canker and black scurf (*Rhizoctonia solani*), common scab (*Streptomyces* spp.), powdery scab (*Spongospora subterranea* f. sp. *Subterranean*), white mold (*Sclerotinia sclerotiorum*), silver scurf (*Helminthosporium solani*), pink rot (*Phytophthora erythroseptica*) and Verticillium wilt (*Verticillium dahliae*), and the potato early-die disease complex caused by an interaction between *Pratylenchus penetrans* (Nematoda) and *V. dahlia*. Typically, these diseases affect growth, vigor, tuber quality and, at times, harvestable yield. Most are difficult to manage and have often resulted in the use of soil fumigants, which have potential to be detrimental to beneficial soil-borne organisms. Therefore, the development of sustainable, biologically based disease management strategies in root and tuber production is more urgent than ever.

When managed for biofumigation, residues of about 40 plant species in four genera of the family Brassicacea that contain stable plant metabolites known as glucosinolates (GSLs) can be used for soil-borne disease control. GSLs are degraded by plant enzymes and converted to toxins with fumigant properties, such as isothiocyanates (ITCs). There are about 132 known GSLs that vary in nature and concentration and are specific to each plant species and variety. The biofumigation process is mediated by timing of plant destruction, as well as soil moisture potential, sulfur and nitrogen fertility.

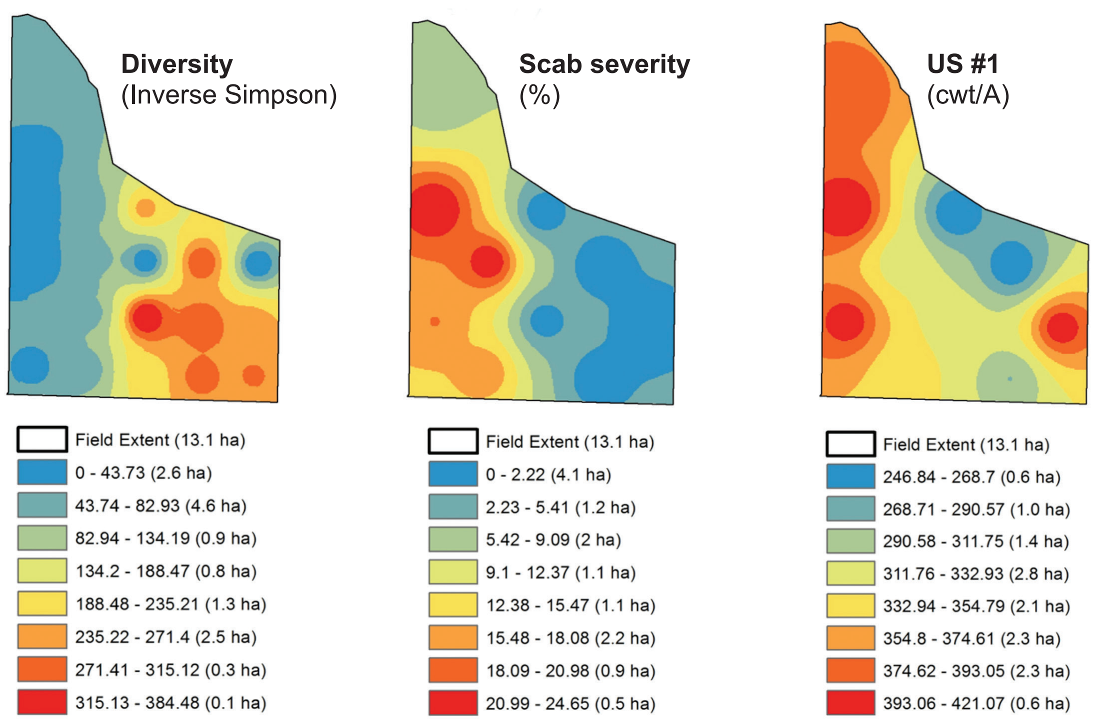
Initial results from Michigan research indicate that Oriental mustard varieties such as ‘Pacific Gold’ can be used as a cover crop to improve potato root and tuber health. The growth of *Rhizoctonia* was slowed by 90 percent in soil amended with Oriental mustard cover crop tissue compared with bare soil (Snapp et al., 2006). Additionally, a field experiment indicated that tubers of the tablestock variety Onaway had no observable signs of *Rhizoctonia* when grown after a spring cover crop of Oriental mustard.

Incorporation of biofumigant crops provides energy to support the complex web of soil organisms that compete with soil-borne pathogens. Thus mustards and related brassica plant species such as oil-seed radish are important means to diversify cover crops and rotation sequences. Growing these soil amendments can enhance the soil biology, and, unlike a chemical fumigant, they do not leave the soil void of organisms (Larkin, 2015). Moreover, these cover crops tend to provide resources that enhance beneficial organisms and suppress soil-borne pathogens. Further research is required to optimize biofumigation practices, but initial results are promising, and farmers are encouraged to experiment with brassica cover crops such as Oriental and white mustard or oilseed radish to improve soil health (Wharton et al., 2007).

Use of cover crops is one of the most cost-effective tools to improve soil biophysical properties and soil health while also reducing pathogens. However, it is important to consider carefully the primary goal in growing a cover crop to minimize potential problems, such as providing a host for new pests. Successful use of cover crops for disease management requires three things: having a disease-specific objective for using the cover crop, selecting the right cover crop variety and managing the cover crop in a manner designed to achieve the objective. Although certain varieties and species of Brassica cover crops may be beneficial for suppression of soil-borne pathogens, recent evidence suggests that others may be ineffective or even exacerbate important diseases of crops often grown in rotation with root crops, such as *Phytophthora capsici* (Krasnow and Hausbeck, 2015). For example, oil-seed radish is a very effective cover crop for improving soil physical structure and suppressing some disease organisms, but it may also serve as a host for root-lesion nematodes and the northern root-knot nematode, depending on the variety. It is recommended that growers consult MSU Extension educators and the Midwest Cover Crop Council decision tool, which can provide important insights into the benefits and challenges associated with various cover crops (see www.mccc.msu.edu/selectorintro.html).

Other organic amendments – e.g., compost, animal manure, seed meal and non-brassica cover crops – have also been evaluated as alternatives to fumigation for control of soil-borne pathogens. Use of such organic amendments has provided mixed results, increasing yield in most studies, reducing Verticillium wilt incidence (Molina et al., 2014) and scab (Nin et al., 2015), but potentially increasing pathogenic nematode populations (Kimpinski et al., 2003). Likewise, several cover crops have been shown to increase soil microbial biomass (Collins et al., 2006), suppress Verticillium wilt (Wiggins and Kinkel, 2005) and reduce populations of pathogenic nematodes (Al-Rehiayani et al., 1999) while increasing the populations of beneficial nematodes (Collins et al., 2006).

Figure 5. The geospatial relationship of diversity of soil bacteria documented through DNA sequencing, scab tuber ratings and tuber yields for a typical GIS field map of selected soil properties measured. Community analysis and sequence identity were determined by next-generation sequencing on the MiSeq Illumina platform using the mother v.1.33.0 software package. The inverse of the Simpson Index is shown as a measure of total diversity (Rosenzweig and Steere, unpublished data, 2015).



Finally, by avoiding fungicides, farmers can harness some of the natural soil microbial communities' interactions that help keep soil-borne diseases in check through natural soil biology. Overall, there is growing evidence that biodiversity of soil microorganisms is often associated with some level of disease suppression and yield of clean tubers, but this doesn't always hold up. In Michigan, a soil health study conducted on potato farms in 2012 found some data to support this relationship – areas of fields where soil microbial diversity was high generally had less severe scab on tubers (Figure 5). However, this relationship was not apparent in many fields, illustrating the need for further research in this area.

VI. The long term: building soil organic matter

Soil organic matter is the foundation for soil health. It supports plant health and crop productivity. The SOM status of many Michigan agricultural fields is poor, but this can be remedied with a plan that aims to both increase the input of organic materials and also prevent loss of SOM beyond sustainable limits. Soil organic matter is continually being depleted through processes such as tillage and erosion by wind and water. Paying attention to preventing erosion, reducing the exposure of bare soil and minimizing tillage intensity will keep losses at a moderate level. Soil conservation and soil health practices should be part of every farm management plan. Advice on how to optimize erosion prevention and protection of precious soil resources can be tailored for each farm. Check out the planning resources that are available from the Michigan chapter of the Soil and Water Conservation Society (http://miswcs.org/), your local USDA-NRCS staff and MSUE educators located at offices throughout the state.

Enhancing SOM requires attention to replenishing and enhancing the amount of crop residues and organic materials added to soil, as well as conservation measures. Practices that enhance the presence of root systems and mixed-quality organic materials have been a key focus of this bulletin. If a soil is degraded, then a substantial investment in cover crops and rotational sequences that include hay crops and pastures may be required to improve SOM. Forage options suited to Michigan are available at the MSU Forage Connection (www.forage.msu.edu). An example of the benefits from alfalfa is its extensive root system, which permeates as much as 6 feet deep in soil and can produce over 5 tons per acre of root material to build soil aggregates and organic matter. Cover crops do not commonly produce as much root material, but a rye cover crop has been shown to consistently add from 1/2 to 2 tons per acre of fibrous root material on Michigan potato fields (Morrone and Snapp, 2011).

Monitoring SOM is critical to evaluating the effectiveness of your efforts to enhance soil health. Soil organic matter consists of various soil carbon types/pools and can be measured in various ways. Most laboratories use the "loss on ignition" approach to measuring total SOM. This is not an exact measure, but if repeated multiple times over a long period (such as a decade), it is a reliable way to see if SOM is increasing or decreasing. Some labs offer analysis of total organic matter by combustion, which is more

accurate for single measurements. There have also been recent efforts to develop measures of the active or biologically available SOM fraction that can be carried out in the field (Snapp and Morrone, 2008). Measures of active carbon, such as permanganate oxidizable carbon (POXC), can respond to changes in management within a couple of years (much faster than total organic matter) and thus provide a good short-term indicator of long-term SOM trends (Culman et al., 2012). Field tests measuring active carbon and soil respiration are growing in popularity and are recommended as a place to start, with several labs providing options for monitoring: soilhealth.cals.cornell.edu and solvita.com/fieldtest.

VII. Conclusion

Farmers who grow root and tuber crops rely on good soil health for productive, profitable crops. Practices that build SOM and appropriate microbial diversity have been shown to improve soil structure, increase nutrient availability and suppress soil-borne diseases, resulting in higher crop yields and improved quality. To summarize, here are five fundamental management practices to ensure these benefits for crops such as potatoes, carrots and sugar beets:

1. Grow cash crops within an extended and diverse rotation sequence that includes soil-building crops such as wheat and alfalfa.

2. Supplement rotational diversity with a robust cover crop management strategy, including frequent and diverse cover crop applications grown using high seeding rates sown as early as possible.

3. Use organic matter amendments such as manure or compost.

4. Employ a system of reduced tillage whenever feasible.

5. Protect beneficial microorganisms and suppress disease by relying on biological practices where feasible, and use chemical toxicants only when they are absolutely essential.

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