Exploring Opportunities to Advance Soil Health

The Role of Commodity Crop Supply Chains in Maintaining and Improving the Health of Our Nation's Soil

Contributions and Acknowledgments: The primary contributors to this document were Allison Thomson (Field To Market), Cynthia Kallenbach (Colorado State University) and Martin Adkins (USDA Natural Resources Conservation Service), with guidance and assistance from the Field to Market Metrics Working Group and Soil Health Subgroup as well as support from additional expert reviewers. We especially would like to thank Nick Goeser (National Corn Growers Association), Cliff Snyder (International Plant Nutrition Institute, Matt Wallenstein (Colorado State University), Charles Shapiro (University of Nebraska), Bill Berry (National Association of Conservation Districts), Charles Rice (Kansas State University), Dennis Chessman, Diane Stott, Bianca Moebius-Clune and Brandon Smith (USDA Natural Resources Conservation Service) Kate Scow and Deirdre Griffin (University of California - Davis), Stuart Grandy (University of New Hampshire), and others who devoted time to review and comment on earlier versions. Due to limited space we were unable to expand the document to encompass the many nuances of soil science, but we have done our best to represent the overall state of knowledge and ongoing scope of research and other work around the topic of soil health at this point in time. The final document represents solely the views of Field to Market: The Alliance for Sustainable Agriculture.

For comments or questions, contact: Allison Thomson (athomson@fieldtomarket.org; 202-499-4397)

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EXECUTIVE SUMMARY

Over the past decade, Field to Market: The Alliance for Sustainable Agriculture has developed a set of sustainability metrics that focus on environmental outcomes of agricultural management practices, specific to commodity crop production systems in the United States. Responding to a charge from membership to conduct an assessment on how the Alliance can work to further overall maintenance of and improvement to soil health, we have prepared this paper as a resource for member organizations. Here we assess the current situation of the science of soil health and related research and conservation community efforts, and the relationship to Field to Market's ongoing efforts.

Soil health is often defined as "The continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals and humans" and is characterized by a combination of soil characteristics including physical factors such as soil structure and texture, chemical factors such as acidity and nutrient levels, and biological factors such as microbial activity. Many of the key indicators of these soil characteristics that can be measured are described in this paper, highlighting the complex interactions that occur within a soil ecosystem. All of these indicators, separately and in combination, are the subject of ongoing research in the scientific community that continues to improve our understanding while also illuminating many complexities.

Of particular interest for Field to Market is how farm management practices may influence the key soil processes and functions associated with soil health. We discuss a number of practices and their influence on individual physical, chemical and biological indicators, illustrating how many of the complexities in the interactions within a soil necessitate consideration of a range of factors when looking to adopt new practices. While many practices have in some cases been tied to improved soil health indicators, the responses are far from universal. For some conservation practices the relationship to soil properties is relatively well understood, while for others the relationship is known to be highly complex and dependent on many factors, such as weather and land history, that are not within the direct control of a land manager. We also discuss the progress being made in the research community towards standardized soil health testing that will provide an opportunity for land managers to gain a deeper understanding of their specific soils properties and possibilities.

Finally, we review the current sustainability metrics in use by Field to Market and assess how they are related to key soil health measures and indicators. The current Fieldprint® Platform contains soil specific metrics that can be used to begin ac conversation within supply-chain partnerships about the importance of maintaining soil (Soil Conservation Metric) and reducing the potential for soil carbon losses (Soil Carbon Metric); appropriate interpretation and guidance on practices related to these metrics can begin to better understanding of soils in specific fields, and encourage soil health enhancing practices. Additional metrics in the Field to Market program can be expected to respond to improved soil health, providing an additional way by which the Fieldprint Platform can be used to continue to advance the concepts of soil health. In addition, we outline a number of ways for Field to Market members and supporters to engage in efforts to advance soil health research, promote soil health testing efforts, and supporting research on the connections between soil health, conservation practices, and sustainability outcomes.

2
Introduction

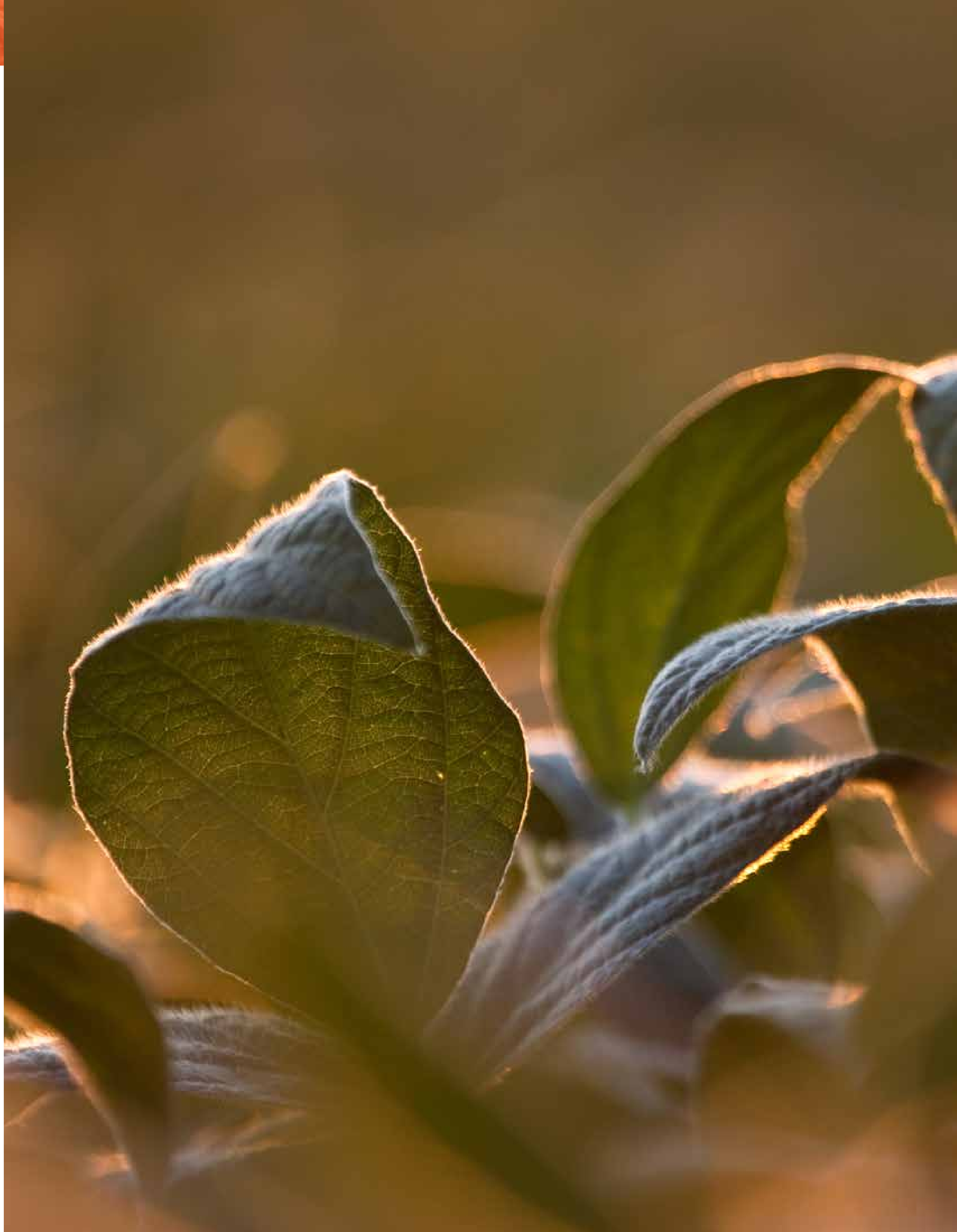
INTRODUCTION

Field to Market: The Alliance for Sustainable Agriculture is a collaborative, multi-stakeholder organization comprised of a diverse group of food and retail companies, agribusinesses, conservation groups, and grower associations with a common goal to define, measure, and promote food, fuel and fiber sustainability for U.S. agriculture. The member organizations share a commitment to maximizing productivity while helping producers improve natural resource management. Field to Market has developed a Fieldprint® Platform that calculates sustainability outcomes at the field scale for eight metrics including land use, greenhouse gas emissions, biodiversity, water quality, irrigation water use, energy use, soil conservation and soil carbon. Recently, there has been increased interest in soil health, a concept that moves beyond the traditional agricultural considerations of soil's chemical and physical properties to also integrate biological communities as key elements important for sustaining soil productivity.

In November 2014, programmatic goals were adopted by Field to Market's membership that directed the Metrics Working Group to conduct an assessment of what the Alliance can do in order to further "overall maintenance and improvements to soil health." A group of members has since engaged with ongoing soil health efforts to identify opportunities for collaboration in development of consistent and complementary efforts to achieve this goal.

While the potential sustainability outcomes of enhancing soil health are numerous and range from improvements in water quality, increased water use efficiency, reduced erosion and greater resilience of crops to weather extremes, the soil health research and soil measurement communities are still in an active phase of scientific research. These communities are working to develop new tools, indicators and testing protocols as well as conduct experimental work to understand and quantify both the conservation practices associated with soil health and the environmental outcomes that result from building soil health. Scientific evidence is building that supports what early adopters of soil health-enhancing practices have learned: improving soil health may lead to many potential benefits that promote continuous improvement in agricultural sustainability.

Field to Market's sustainability metrics are defined by specific environmental outcomes. As such, consideration of the relationship of soil health to these metrics involves first understanding how the current metric outcomes might be influenced by improved soil health. To determine whether Field to Market should consider adding a soil health metric, an exploration of whether there are additional environmental outcomes related to soil health that should be addressed through the metrics is needed. This paper explores those elements with an overview of the current scientific understanding of soil health, discussion the importance of soil health for agricultural sustainability as well as the Field to Market metrics and identifies opportunities for Field to Market members to engage in efforts to further soil health improvements.



3
Soil Health and Sustainability

SOIL HEALTH AND SUSTAINABILITY

History of Soil Health

While the modern soil health movement may seem to be a relatively new development, in reality some of the basic concepts of soil health have been researched and written about since the time of Plato, under other names. One early American soil health advocate was Thomas Jefferson, third President of the United States, farmer and proponent of crop rotation for rejuvenating depleted soils and protecting them from erosion. Jefferson used a wheat-corn-peas-rye-clover-clover/vetch rotation and penned cattle over poor-producing spots in his fields with the goal of concentrating manure and improving fertility. Across the Atlantic, innovations of the British Agricultural Revolution greatly improved farm productivity and food availability with development of new rotations such as the Norfolk four-course rotation, featuring clover and turnip as forage and cover crops, along with wheat and barley.[1] Later, in the years before the Civil War, Edmund Ruffin, farmer, secessionist, Secretary of the Virginia Board of Agriculture and President of the Virginia State Agricultural Society, was also a proponent of improved soil management and advocated for the use of crop rotations in order to maintain productivity. His book "An Essay on Calcareous Manures" helped him become known as the father of soil chemistry.

The use of cover crops and crop rotations continued into the 1900s, helping to restore and maintain soil fertility and productivity on the small- to medium-sized farms that dominated agriculture before 1950. On many of these farms, cereal grains and forages grown in rotation were used to feed horses and livestock and the manure produced was applied on-site as a source of crop nutrients. While it was observed that these practices were beneficial to overall farm productivity, science was not yet able to characterize the soil's properties, functioning and importance to sustainability. Mechanization and the introduction of manufactured fertilizers changed agriculture during the mid-1900s, enabling farmers to work larger acreages. As farms transitioned, horses disappeared and overall farm population declined. These factors and many others caused cropping patterns to change; specialization increased, as did field and farm sizes, and use of crop rotations declined.

Throughout these transitions, practices to improve and maintain soil health have remained important in our agricultural system, both on farms and in the training of agricultural professionals. Crop rotations

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1 Overton, Mark (1996). Agricultural Revolution in England: The transformation of the agrarian economy 1500-1850. Cambridge University Press. p. 206. ISBN 978-0-521-56859-3

and cover crops were important tools for Soil Conservation Service conservationists in the 1930s and 1940s. College textbooks, including *Soil Management for Conservation and Production*[2], offered sections on soil biology and the role of soil micro- and macro-organisms in building soil aggregate stability, cycling nutrients, and increasing water infiltration and storage.

Combining new scientific knowledge and modern research techniques with insights from historical experience is at the core of the current interest in soil health. We are building a more advanced knowledge of soil through the ability to test chemical, physical and biological properties in greater detail. This knowledge enables a growing scientific understanding of what soil health is, why it is important, and how specific farming practices can improve or restore soil properties over time.

Definitions of Soil Health

The current conversation around soil health has emerged out of the experiences of farmers and land managers and from agricultural research on the effects of conservation tillage, residue management, crop rotations, cover crops, rotational grazing and other practices that have been found to affect several soil functions such as nutrient, soil organic matter and water storage. Soil health involves the capacity of a soil to maintain system stability and resiliency to buffer against stressors (e.g., extreme weather or disease) within the soil ecosystem.

A common definition for soil health adopted by the Soil Health Partnership, the Soil Renaissance and the USDA Natural Resource Conservation Service (NRCS) Soil Health Division is: *The continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals and humans.*[3] The primary U.S.-based scientific society for soils research, the Soil Science Society of America, does not define soil health separately from soil quality, which is defined as: *The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health.*[4]

Soil health functions are typically categorized into biological, chemical and physical processes that, as defined by USDA NRCS, include:

- Regulating water flow into and through the soils
- Sustaining diverse and productive plant and animal life
- Filtering and buffering potential organic and inorganic pollutants
- Cycling of carbon, nitrogen, phosphorus and other nutrients
- Physical stability that provides resistance to erosive effects of wind and water and support for plant roots

These processes interact with each other to determine a soil's potential to deliver key goods and services such as food, fiber, feed and bioenergy; erosion and pest control; maintenance of water quality and supply; and habitat. To evaluate the capacity of a soil to carry out and sustain these functions, a number of measurable indicators have been employed to characterize soil chemical, physical and biological properties.

2 © 1962, John Wiley and Sons
3 http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/
4 https://www.soils.org/publications/soils-glossary

4 The Science of Soil Health and Sustainability

THE SCIENCE OF SOIL HEALTH AND SUSTAINABILITY

A soil health assessment involves the integration of soil biological, chemical and physical indicators on the basis of soil function and how soil functions change in response to management. Evaluating soil health is a sequential process where first, the soil function of concern is determined based on the use of and goals for the land being assessed; secondly, the specific soil processes associated with a function are identified; and lastly, soil properties that are sensitive to changes in management and which regulate the process(es) are measured. Many of the functions associated with soil health align directly (*e.g.*, greenhouse gas emissions reduction) or indirectly (*e.g.*, pest control) with the sustainability outcomes in existing Field to Market metrics (Fig. 1). Functions relate to what the soil does, or the outcome of a specific process, such as improving water quality. Soil processes describe how these outcomes are achieved (e.g., soils can filter environmental pollutants out of water percolating through). Soil properties refer to specific characteristics of the soil required for the process to be carried out (e.g., soil biological activity, soil texture and structure influence the soil filtering process).

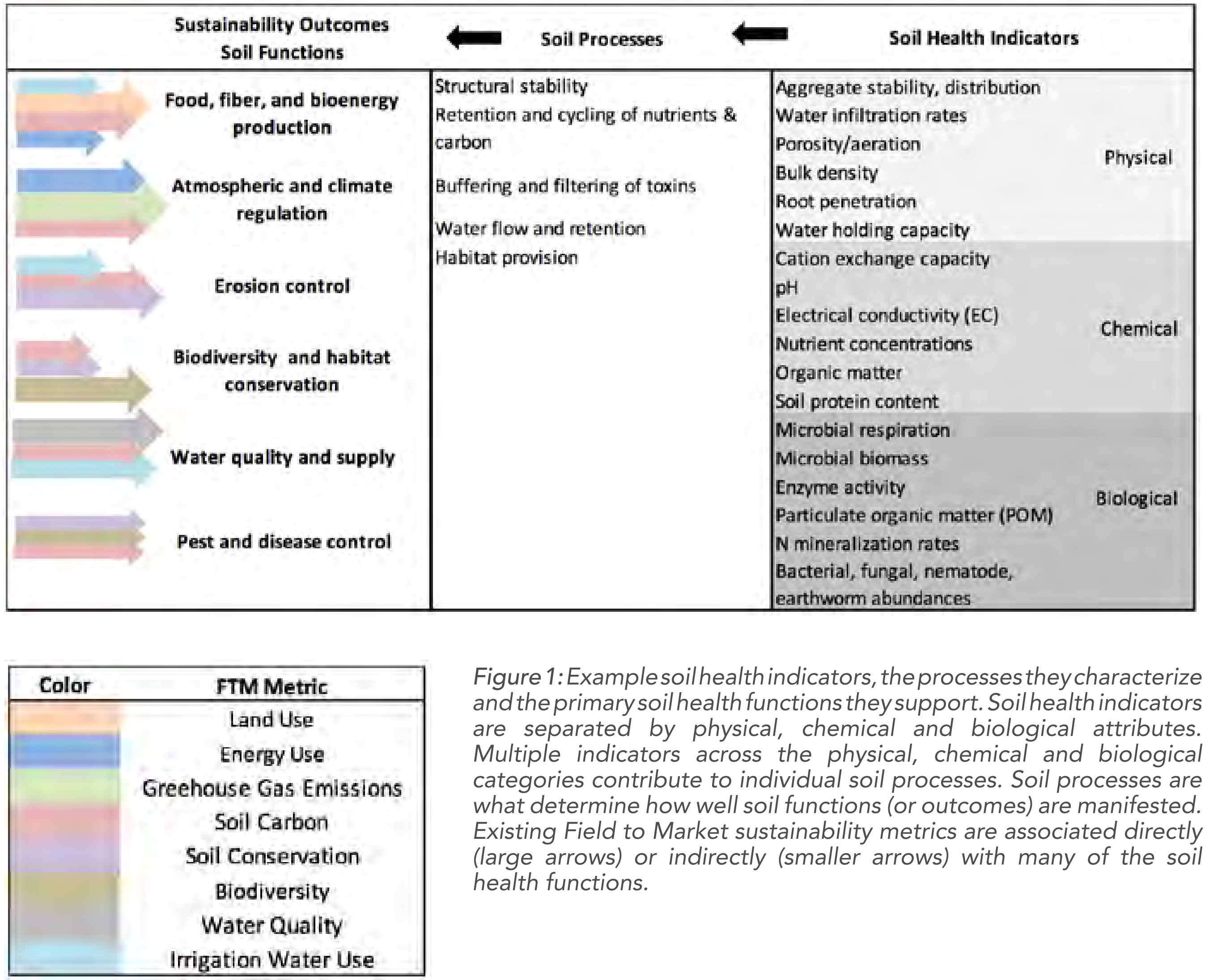

Figure 1: Example soil health indicators, the processes they characterize and the primary soil health functions they support. Soil health indicators are separated by physical, chemical and biological attributes. Multiple indicators across the physical, chemical and biological categories contribute to individual soil processes. Soil processes are what determine how well soil functions (or outcomes) are manifested. Existing Field to Market sustainability metrics are associated directly (large arrows) or indirectly (smaller arrows) with many of the soil health functions.

When assessing soil health, it is important to recognize that each soil has certain **inherent** properties that are determined by the climate, parent material of the soil, topography and age of the soil. These properties, such as soil texture and mineralogy, change little in response to management. Other soil properties, like nutrient concentrations, are more sensitive to land-use practices and are referred to as **dynamic**. The response of these dynamic properties to management is constrained by the inherent soil properties; thus, soil health is always relative to inherent soil characteristics and site-specific.

Soil Health Indicators

To measure soil health, a number of different physical, chemical and biological properties can be used as indicators. Many of these indicators will affect more than one soil process and can influence more than one soil function. It is important to bear in mind that interpretations of soil health indicators are not universally equivalent and depend on how soil and management practices interact with local ecosystems; the inherent limitations of a soil; and the desired soil function. In addition, soil health assessments typically do not measure all of the indicators discussed here. Specific soil health testing protocols, discussed later, include subsets of these indicators to guide the overall soil health assessment of a field or farm.

Soil Physical Processes

Soil physical processes regulate the movement of water, air and roots through the soil as well as provide stability and anchoring for plant roots. Soil physical properties can be thought of as providing the structural framework for soil biology and chemistry, influencing the space and fluxes of the soil's biological and chemical components. In turn, biological and chemical soil properties can also have feedbacks to physical soil characteristics. When physical processes are supported there is a positive impact on the key soil functions of plant available water supply; achievable crop yield potential; greenhouse gas regulation; environmental pollutant buffering and filtering; and erosion control. Soil texture and mineralogy are key primary inherent soil properties influencing physical processes. These soil properties can influence processes in a way that is interactive and results in both positive and negative feedback loops. Therefore, understanding cause and effect in a specific soil requires careful analysis of the measured indicators. For example, soils with higher clay content tend to aggregate more easily; provide greater stability for crop roots; increase soil water retention; and reduce leaching of pollutants into ground water. However, under certain conditions, clay soils can lead to reduced root penetration and compaction, with subsequent water, nutrient and sediment runoff from overland flow. By contrast, sandy soils have higher infiltration rates; tend to be more porous; and are typically less susceptible to compaction. Soil bulk density (i.e., the weight of soil in a given volume) is an important indicator that is closely related to aggregate formation and stability as well as soil organic matter content. For example, adopting management practices to increase soil organic matter can improve soil aggregate formation, which in turn helps protect the carbon in the organic matter from decomposition. This improves bulk density, which can provide additional protection against erosion. Thus, measurements of bulk density can indicate opportunities for improvement in several soil functions.

Physical Indicators

Soil Structure: How particles in the soil are arranged, such as the distribution of space (porosity) between soil particles and aggregates, with defined shape, grade and size of structural units.

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Soil Texture: The relative amount of clay (<0.002 mm diameter), silt (0.05-0.002 mm) and sand (2-0.05 mm) particles in a soil, which is illustrated in Fig. 2. Texture is an inherent soil property that influences aggregation; retention of nutrients and carbon; soil structure; and cation exchange capacity. This is a key defining feature separating different layers, or horizons, in a soil. In an eroded soil, or soil with a thin layer of topsoil, tillage may mix horizons, thus changing the texture of the uppermost soil layer.

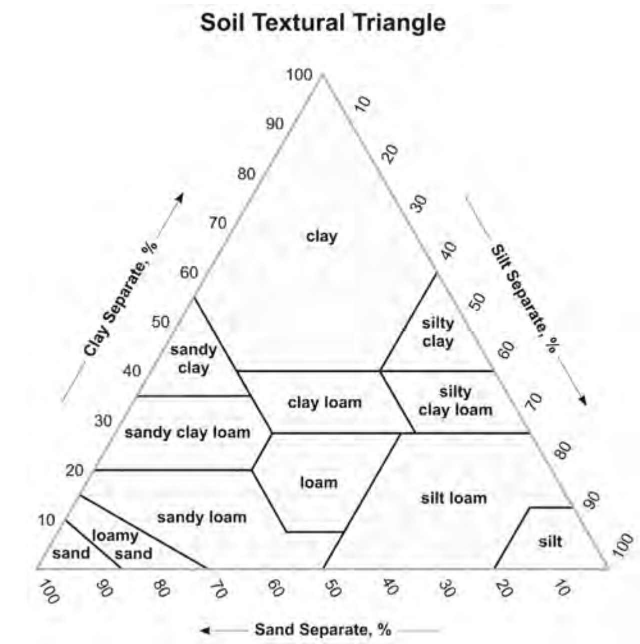

Figure 2: Soil texture triangle (source: USDA NRCS) illustrating common soil types and their relative concentrations of sand, silt and clay.

Aggregate Stability and Distribution: Soil aggregates are formed from groups of soil particles that bind to each other more strongly than adjacent soil particles. Aggregates can form and be destroyed at different rates and they vary in their size, binding strength and structure. Aggregate stability refers to how well an aggregate can withstand collapse following disruptive forces, usually related to water and cultivation. Aggregation is a mix of inherent and dynamic processes and some aggregates can collapse and reform within a growing season.

Soil Porosity: Related to soil structure and texture, porosity refers to the distribution and amount of pore space between soil aggregates or particles and thus affects the movement of soil water, gases, organisms and roots within the soil.

Soil Aeration: The amount of air-filled pore space.

Bulk Density: The weight of soil relative to its volume; bulk density is dependent on soil texture and aggregation. Higher bulk density indicates that soil particles are packed more closely. When bulk density is too high there is less available pore space, reflecting greater soil compaction, which can result in restricted root penetration, water infiltration and permeability.

Infiltration Rate: A measure of how quickly water enters the soil. This is dependent on surface soil stability, texture, porosity, aggregate strength and initial water content.

Water Holding Capacity (WHC): The amount of water a soil holds following water inputs (e.g., rain or irrigation). Soils with low WHC dry out more quickly and are more susceptible to leaching. A higher WHC helps to keep soil moisture more constant in between rain or irrigation events. It is primarily a function of soil texture and soil organic matter, with sandier soils typically exhibiting lower WHC than clay soils.

Available Water Capacity: The amount of water available to plant roots.

Soil Chemical Processes

Chemical processes in soils are closely related to the physical properties and biological indicators in a soil and indicators of specific chemical processes provide important information about the regulation of transformations and concentrations of chemical elements in a soil. These processes relate to primary soil health functions of crop yield potential, water quality, pollutant filtering, soil carbon storage and greenhouse gas regulation. The right balance of plant nutrients and other elements is important for maintaining these functions, which are also dependent on biological processes in the soil. Elemental concentrations and availability depend in part on inputs to the soil from fertilizers, manures, pesticides, crop residues, and industrial and human waste. The balance of elements from these inputs is then under the influence of crop nutrient needs, nutrient status and a variety of physical and biological processes that influence element retention, transformation and movement. For example, soil microbial activity affects the transformation rate of organic nitrogen to plant available inorganic nitrate, while clay content and mineralogy affects elemental retention. Chemical processes and their interaction with the soil ecology and soil physical properties should facilitate the provision of necessary elements required for crop growth (e.g., macro and secondary nutrients), but not at levels that would be toxic to soil organisms, the crops themselves or in such excess that they result in the accelerated release of greenhouse gases (e.g., nitrous oxide or carbon dioxide) or adversely affect water quality. In addition to regulating important plant nutrients, many chemical processes affect the breakdown and storage of soil carbon.

Chemical Indicators

Soil pH: The degree of soil acidity or alkalinity, which is measured by the hydrogen ion (H+) activity of a soil solution. Plant nutrient availability, microorganism activity and soil mineral weathering are all influenced by pH. While pH is partly an inherent soil property driven by soil weathering, temperature, parent material, moisture and vegetation, it is also dynamic in that it is influenced by management factors such as irrigation, crop rotation, fertilization and liming.

Cation Exchange Capacity (CEC): The total amount of positively charged nutrients a soil can hold. When CEC is high, the soil has an increased capacity to store important plant nutrients. CEC is an inherent property of the soil, primarily determined by parent material, clay content and mineralogy. Soil organic matter, a dynamic soil property, also affects CEC.

Salinity: The concentration of salts (e.g., sodium, calcium, magnesium, chloride) present in a soil, which is measured by electrical conductivity (EC). Some level of soluble salts is required for plant growth, but an excess can be toxic for plant and microbial growth, restrict nutrient uptake and negatively affect soil water dynamics. Salt-affected soils, which are more common in arid and semiarid environments, can lead to surface sealing and crusting as well as decreased water infiltration and seedling emergence. They can also develop from excessive manure inputs and under certain irrigation conditions. For sodic soils (i.e., soils with high sodium levels), the Sodium Adsorption Ratio (SAR) or Exchangeable Sodium Percentage indices may be needed to appropriately measure EC.

Soil Nutrient Status: The concentration of total and plant available macro-, secondary- and micronutrients essential for plant growth and development. Nitrogen (N), phosphorus (P) and potassium (K) are the primary considerations when assessing soil fertility related to plant growth because they are taken up in largest amounts by plant roots. Secondary nutrients (e.g., calcium, magnesium and sulfur) and micronutrients (e.g., iron, manganese, molybdenum, copper, boron, zinc, chloride and nickel) are also important contributors to plant growth. Nutrient status can change rapidly over the course of a season and can differ over very small areas. Thus, predicting or measuring soil nutrient status throughout the year and across the field, although ideal, is typically not practical.

Soil Organic Matter (SOM): The make up of plant, animal and microbial materials at various stages of decomposition. SOM is often regarded as a master variable in soil health due to its ubiquitous influence on many soil indicators and processes. Traditionally, SOM has been separated into fast, slow and passive pools that relate to the longevity (i.e., turnover time) of SOM. However, in reality there is feedback and flow among these pools, which are often operationally defined by chemistry, size class or density.[5] The age of SOM can range from newly added crop residues, to organic matter thousands of years old and resistant to further decay. There are four major SOM pools that differ in their degree physio-chemical protection and microbial decomposition potential:[6,7] (1) living plant roots and organisms; (2) dissolved organic matter, which includes microbial materials, root exudates and decomposed or leached plant materials; (3) particulate organic matter (POM), which is largely made up of plant residues across different stages of decomposition; and (4) long-lived stable SOM often closely associated with soil minerals and within stable aggregates, thought to consist mainly of microbial byproducts or highly decomposed plant residue compounds. These pools differ in both their proportion in the soil as well as how they influence soil function and processes. Moreover, soil organic matter can be a significant source of nutrients for plants;[8] for example, a soil with 1 percent SOM concentration can release 20-50 lbs of nitrogen/acre/year,[9,10] much of which comes from amino acids and proteins. Soil organic matter also impacts soil structure, cation exchange capacity, pH, water holding capacity, aggregation, plant available nutrients, water quality, greenhouse gas emissions and the activity and structure of the soil ecology. SOM is highly influenced by both environmental variables (e.g., moisture and temperature) and management practices.

Soil Organic Carbon (SOC): The amount of carbon concentrated in soil. Soil organic matter is about 58% organic carbon, which provides energy for many active soil organisms and thus is important for many biological soil health indicators (Fig. 3). The concentration of carbon in the soil is strongly influenced by plant growth and land management. Soil organic matter is often used as a proxy for SOC concentrations, as it can be more accurately measured.

5 Lehmann, J. and Kleber, M., 2015. The contentious nature of soil organic matter. Nature, 528:60–68 doi:10.1038/nature16069
6 Grandy, A.S. and J.C. Neff. 2008. Molecular soil C dynamics downstream: The biochemical decomposition sequence and its effects on soil organic matter structure and function. Science of the Total Environment, 404:297-307.
7 Plaza, C., et al., 2013. Physical, chemical, and biochemical mechanisms of soil organic matter stabilization under conservation tillage systems: A central role for microbes and microbial by-products in C sequestration. Soil Biology and Biochemistry, 57:124-134.
8 Gardner, J.B. and Drinkwater, L.E., 2009. The fate of nitrogen in grain cropping systems: a meta-analysis of 15N field experiments. Ecological Applications, 19(8):2167-2184.
9 Cassman, K.G. et al. 2002. Agroecosystems, nitrogen-use efficiency, and nitrogen management. Ambio 31:132-140
10 Grandy, A.S. et al. 2012. The biological basis for nitrogen management in agroecosystems. In: T. Cheeke, D. Wall, D. Coleman, eds. Microbial Ecology in Sustainable Agroecosystems. Taylor and Francis LLC.

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Soil Biological Processes

Soil biological processes are carried out by organisms living in the soil, ranging from microscopic bacteria to earthworms. Soil has greater biodiversity than any other environment on Earth[11] and a healthy soil supports a complex food web of soil micro- and meso-fauna that includes bacteria, archaea, fungi, protozoa, nematodes, earthworms and arthropods. These organisms drive many of the dynamic properties related to soil health and thus have critical influences on and are influenced by the dynamic chemical and physical properties discussed above. For example, many of the organisms themselves affect soil aggregation and therefore erosion, water supply and carbon storage. Some soil food webs can protect crops from pest and disease pressures, resulting in increased crop productivity and yield stability. Alternatively, soil borne diseases can be pervasive in some soil biological communities, which may harm crop productivity and require management intervention.

The activity and abundance of different soil organisms are essential to the decomposition of organic material as well as the transformation and availability of both pollutants and essential crop nutrients, thus impacting environmental pollution, crop nutrition, greenhouse gas regulation and water quality. A number of organisms are directly beneficial for plant growth, such as nitrogen fixing *Rhizobia*, which form a symbiotic relationship with legume roots, and mycorrhizal fungi, which colonize root systems of almost all plant species and can facilitate plant nutrient uptake and enhance tolerance to drought and disease. The soil food web is highly sensitive to shifts in pH, soil organic matter and nutrient supply. Moisture and temperature can alter not only soil biological activity but also which organisms are present to carry out these important biological processes. Most of the biological indicators are technically difficult to measure and development of appropriate, easily applicable indicators, which link back to soil health outcomes, is a very active area of research.

Biological Indicators

Soil Respiration: Soil respiration is the production of carbon dioxide (CO2) in the soil by microorganisms, plant roots and soil fauna (e.g., earthworms, nematodes) (Fig. 3). Soil organisms that break down or mineralize SOC to grow and carry out basic metabolic functions produce CO2 as "waste". While CO2 production from soils is influenced by environment and management (e.g., crop type, tillage and soil moisture), high respiration rates generally indicate abundant and/or highly active soil organisms. Active soil organisms can enhance soil aggregation and increase the rate of nutrient and soil organic matter cycling, particularly transformations of nitrogen. However, if respiration rates exceed organic matter inputs to the soil, soil carbon stocks can be depleted. Soil respiration is a major part of the global carbon cycle (Fig. 3), which affects soil carbon storage and impacts atmospheric CO2 concentrations. Respiration rates are greater under moist, warm conditions and where microbial-available carbon levels are high. Soil respiration is a highly dynamic soil property that is temporally and spatially variable, influenced by available carbon and nutrients, pH, disturbances such as tillage, and the aboveground plant community.

[11] Bardgett RD, van der Putten WH. 2014. Belowground biodiversity and ecosystem functioning. Nature 515:505–11

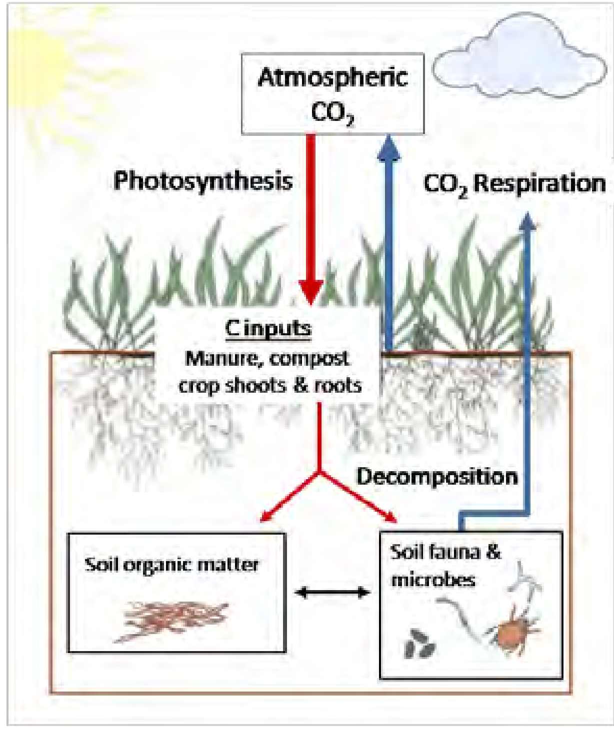

Figure 3: A diagram of the carbon cycle in cropping systems illustrating how SOC/SOM connect to soil biology, greenhouse gas emissions and other factors involved in plant productivity and soil health.

Microbial Biomass Carbon (MBC): The component of soil carbon that comes from living microorganisms, mostly bacteria, archaea and fungi. This pool of carbon is relatively short lived (i.e., days to months) and is highly dynamic, responding rapidly to changes in management. Though MBC makes up only a small portion of total carbon (e.g., less than 4 to 5 percent), it has a major role in the mineralization of organic nutrients. Moreover, the turnover of the living microbial biomass is thought to be a major input to the stable SOC pool,[12] where dead microbial cellular materials are stabilized via their interactions with soil aggregates and clay minerals. Relatively higher MBC indicates a greater abundance of bacteria and fungi that break down organic matter such as crop residues, which release plant available nutrients.

Particulate Organic Matter (POM): The amount of decomposed crop residues and roots, which is either defined by size (0.053 to 2 mm) or density. Younger POM that is not physically protected in aggregates tends to be easily decomposed and is a significant source of energy and nutrients for microorganisms and a habitat for soil fauna. POM can also increase soil aeration, aggregate stability, water holding capacity, and the cation exchange capacity of soil. The size of the POM pool is related to the amount of plant residue inputs and how quickly they are decomposed by microorganisms and fauna, in part a function of management practices such as tillage.

[12] Kallenbach, C.M. et al.. 2015. Microbial physiology and necromass regulate agricultural soil carbon accumulation. Soil Biology and Biochemistry. 91:279-290.

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Soil Enzyme Activity: The amount of enzymes released into the soil by microbes and plant roots. Enzymes act to catalyze the decomposition of organic matter and release of nutrients, with different enzymes carrying out specific reactions. While living microbes make enzymes, once enzymes are excreted into the soil environment they can stabilize and remain active long after the death of the microbe. Consequently, enzyme activity is not necessarily correlated with microbial activity, but it can be an indicator of the decomposition capacity of a soil. Particularly important for soil organic matter decomposition are the oxidative enzymes that breakdown complex carbon and peptidase enzymes that break down organic nitrogen.

Potentially Mineralizable Nitrogen (PMN): The estimate of crop available nitrogen (i.e., ammonium/ NH4+ and nitrate/NO3-) released from organic sources via microbial activity under favorable soil conditions (e.g., adequate moisture and warmth). Soil organic matter is rich in organic nitrogen, but soil microbes will not mineralize most of it within a year. Typically, less than 1 to 2 percent of the total soil organic nitrogen is mineralized each year. The nitrogen in PMN is from the more easily decomposed fractions of soil organic matter, such as the microbial biomass and particulate organic matter pools. The amount of PMN relies heavily on the activity of microorganisms and the amount and stability of soil organic matter in the soil.

Abundance of Fungi, Actinobacteria, Bacteria, Archaea, Nematodes, Earthworms: The abundance and distribution of different organisms reflects the habitat nature and the potential biodiversity of a soil and has an important influence on nutrient cycling, decomposition, pest control, disease, pollutant degradation, soil structure, water infiltration and root growth. Different organisms perform different functions. For example, fungi, fungi bacteria and archaea are the primary drivers of nutrient and carbon cycling. Non-parasitic nematodes can release nutrients from organic matter, increase nitrogen mineralization and prey on disease-causing microbes. Actinobacteria is a group of bacteria that includes species that can produce antibiotics, fix atmospheric nitrogen and breakdown complex carbon, such as tough plant tissues. Earthworms increase soil aeration and improve soil aggregation and structural stability as they ingest partially decomposed plant matter and move it into the soil. The interaction of these organisms with each other, with the soil environment and their response to disturbances will affect their abundance and diversity. Understanding which organisms are desirable for soil health is complicated by the multiple functions, both beneficial and detrimental, that they perform; the complexity of the food web made up by many individual species; and depends, in part, on the desired soil function being promoted.

Influence of Conservation Practices on Soil Health Indicators

The physical, chemical and biological indicators described above relate to the key functions of a healthy soil that can be impacted by conservation practices and are important for sustainability outcomes. Improvements in these soil health processes can often be achieved by adoption of certain conservation and restoration practices.[13] Thus, numerous soil health indicators can be affected by the adoption of even a single agronomic conservation practice. One common, although not universal, soil health indicator that is influenced by the adoption of conservation practices is soil organic matter.

13 http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/health/mgnt/?cid=stelprdb1257753

Development of a universal approach for soil health assessments that can be widely adopted is spurring active research to address challenges including: reconciling the spatial and temporal variability of indicators not only within a field but between geographic regions; the site-specific interactions of management practices and soil characteristics; identifying the appropriate indicators for a specific field and soil health function; and translating those indicators into meaningful guidance for farmers and land managers. Moreover, there are often trade-offs associated with adopting certain management practices or targeting specific soil health indicators; some management approaches may enhance one soil property at the expense of another. For example, under certain conditions, increasing available water holding capacity may have the unintended consequence of increasing nitrous oxide emissions. Therefore, it is important to simultaneously monitor changes across biological, chemical and physical soil properties. The following sections summarize some of the key relationships between conservation practices, soil health indicators and the sustainability metrics of Field to Market.

Soil Tillage and Residue Management

Tillage is the mechanical disturbance or cultivation of the soil and typically modifies soil physical structural characteristics such as bulk density, aggregation, aeration, water infiltration and also the distribution of soil carbon and crop residues and weed population dynamics. Such modifications can impact soil biological activity and nutrient cycling. Various degrees of soil tillage can be applied, ranging from deep moldboard plowing and reduced tillage methods such as zonal or strip shallow tillage to zero or no-till. The effects of the degree and type of tillage on soil health is contingent on a host of local and regional factors including climate, soil texture, crop rotation decisions and length of time a level of tillage has been practiced.

When reduced- or no-tillage systems are adopted, two things occur: mechanical disturbance of the soil is reduced and more crop residues remain on the soil surface. With time, these are often positively related to improved water infiltration, increased aggregation and stability, higher available water content, reduced soil compaction, increases in soil carbon, reduced erosion and higher soil fungal populations. Reduced mechanical disturbance also minimizes the breakage of important mycorrhizal fungal networks that help form soil aggregates, enhance plant nutrient acquisition and help confer improved drought and disease tolerance. These soil improvements can have positive feedbacks on crop productivity in systems with soil structural limitations. Outcomes, however, are tightly linked to how tillage interacts with other management practices such as rotational diversity, cover cropping and the time since adoption of a tillage practice change. For example, soil bulk density may initially increase following adoption of reduced or no-tillage, but be followed by decreases over the long-term.

Increases in crop residue inputs, which can be associated with limited tillage, result in more carbon and nutrients returned to the soil. Crop residue can also alter soil temperature and moisture fluctuations and provide habitat for soil fauna, especially arthropods and earthworms. Understanding of increases in soil carbon with limited tillage is incomplete and a better characterization of soil carbon changes at all soil depths is needed. Changes in total carbon may not always be observable within the first few years of after a practice is adopted.[14] However, increases in the microbial biomass carbon (MBC) and particulate organic matter (POM) pools and some enzyme activities, can sometimes be detected within a year.

14 http://www.fao.org/docrep/t1696e/t1696e09.htm

Exploring Opportunities to Advance Soil Health 4 The Science

Increases in soil carbon associated with limited tillage are partially attributed to crop residue inputs which make more carbon and nutrients available to support an active microbial community. Increased bacterial and fungal activity in turn enhance the mineralization of key crop nutrients and influence aggregation from the carbohydrate "glues" microbes (especially mycorrhizal fungi) exude that help bind soil particles together. These enhancements to soil structure and carbon can have positive benefits on irrigation water use efficiency and water quality, crop yields and reductions in greenhouse gas emissions and soil erosion. Higher soil carbon can lead to beneficial structural changes and with higher aggregation, infiltration and reduced bulk density, more water enters and remains in the soil profile. This allows for greater resilience to water stress in times of both shortage and excess. Decreased water stress, greater microbial mineralization of organic nutrients and more mycorrhizal fungi also benefit crop growth and yield stability.

Like any management change, adopting new tillage or residue management practices can introduce trade-offs. For example, reductions in greenhouse gas emissions (carbon dioxide/CO_2 and nitrous oxide/N_2O) following reduced and no-till adoption depend on many environmental and management conditions. The balance between the plant roots and soil microbes producing CO_2 and the plants that take up atmospheric CO_2 during photosynthesis determines the amount of carbon that can be stored in the soil (Fig. 3). Reduced and no-till systems can increase stable soil aggregates that physically protect soil carbon from microbial processes that emit CO_2, thus enhancing soil carbon storage. The majority of soil N_2O emissions occur under very moist conditions (e.g., greater than 80 percent water filled pore space) and when there is an ample supply of mineral nitrogen and carbon for the microbes to transform nitrogen into its gaseous N_2O phase. In some cases, if limited tillage increases both the soil carbon and moisture, higher N_2O emissions may occur. A collection of studies, however, found that after 10 years of no-till practices, N_2O emissions were reduced.[15] Rapid changes in N_2O emissions with fluctuations in soil moisture, temperature, carbon and nitrogen availability across space and time make it challenging to adequately characterize and predict the potential for certain management practices to reduce N_2O emissions. These complex interactions are the subject of much ongoing scientific research.

Crop Rotations and Cover Crops

Increasing the diversity of crops in rotation—including additions of a cover crop—alters the timing, type and quantity of above- and below-ground crop roots and residue that enter the soil. Changes in plant inputs to the soil directly impact the soil microbial and faunal communities, nutrient cycling and soil structure. Specific impacts of increasing diversity in a crop rotation are active areas of research, and, like other practices, the response of soils will be dependent on diverse inherent and dynamic properties and environmental and management variables. A diversified crop rotation, especially when it includes a crop with relatively high root biomass, or a legume cover crop, may have a greater potential to support higher biodiversity of soil organisms, increase soil carbon, decrease the loss of nutrients from the soil and improve disease and pest resistance. Plants with high root biomass or deep rooting systems may improve soil aeration and aggregation and can capture nitrates, helping to reduce nitrogen leaching. A diversified rotation also may support a more diverse soil biological community, which may enhance disease suppression.[16] This is due in part to crop rotation's ability to break pest life cycles as well as support natural pest enemies. Plant root exudates are an important nutrient and energy source for soil microbes.

15 Van Kessel et al. 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Global Change Biology 19, 33-44.
16 Larkin, R.P., 2015. Soil Health Paradigms and Implications for Disease Management. Annual Review of Phytopathology, 53:199-221.

Thus, including cultivars or crops with higher root exudation rates into a rotation, or maintaining a plant cover throughout the year, can have a positive impact on microbial activity and nutrient availability. Organic acids from roots also help free up mineral-bound nutrients such as phosphorus.[17] Due to these diverse impacts on soil function, one of the potential benefits of rotational diversity is increased nutrient availability.

One component of rotational diversity is a cover crop—planting a grass, legume or other crop for the specific purpose of seasonal cover between plantings of commercial crops. Cover crops are often planted in species mixtures customized to specific regions and management objectives. Depending on the rotation and growing season for a farm, they can sometimes be interplanted with the main crop, or —more commonly—planted after harvest of the main crop. Cover crops, as part of a well-managed cropping system, can help improve many of the indicators associated with soil health. Like all management practices, outcomes of using cover crops are situationally dependent upon cover crop species, inherent soil properties and other management decisions. Well-established cover crops can provide ground cover when soil might be otherwise bare, thereby reducing soil erosion and providing additional inputs of carbon which may help increase soil organic matter. Legume cover crop species have an additional benefit of supporting microbes (*Rhizobia*) that biologically "fix" nitrogen (N), which can then be made available for the main crop as the cover crop residues decompose. Non-legume cover crops can be used to take up excess nutrients (especially nitrate-N) in a field, thereby improving water quality outcomes.

While cover crops can play a role in supplying nutrients to future crops, the amount and timing of nutrient availability will depend in part on the cover crop species. Success will also depend on the main crop species (e.g., cover crops can interfere with seedling emergence and some have effects that can inhibit crop growth). Careful planning and understanding of objectives will help in gaining the greatest benefit from a cover crop. For example, adding cover crops with a high tissue carbon (C) concentration relative to nitrogen (N) concentration (a high C:N ratio) can result in early season nitrogen limitations if other fertilizers, manures, or other available-N containing amendments are not added. With a high C:N input, microbes will immobilize most of the nitrogen in their biomass rather than mineralize it during decomposition. The nitrogen may then only be made available late in the major crop-growing season, after the microbial community has met its own nitrogen demands and the biomass has turned over in the soil. By contrast, legume cover crops tend to have a lower C:N ratio and tend to supply more nitrogen early on in the main crop growing season. Therefore, selection of a cover crop should take into account what desired functions of soil health are being targeted. Multiple challenges have been associated with cover crops and are the subject of ongoing research. However, continued use of cover crops in combination with no-till, where possible, can improve soil organic matter and subsequently improve water infiltration rates, offsetting some moisture limitations related to their use.

Nutrient Management

How nutrients are managed is an important and complex component of soil health. If nutrients are deficient, crop yields can suffer and soil biological activity may be inhibited. If nutrients inputs are excessive, water quality can be threatened from increased nitrogen leaching or field runoff of phosphorus.

17 Lu and Cao, 2001. Mobilization of soil phosphorus by low-molecular-weight organic acids. Plant Nutrition 92: 554-555.

Greenhouse gas emissions (mainly nitrous oxide) may increase if soil nitrogen levels are not judiciously managed. The rate, source, timing and placement of fertilizer applications will affect when nutrients are available for plant uptake and the potential loss of nutrients from the field. For summer crops, mineral nitrogen applied at the beginning of rapid crop uptake rather than applied in fall or early spring will more likely be utilized by the plant and may be less susceptible to leaching, runoff, volatilization (if containing urea forms of nitrogen), denitrification and nitrous oxide emissions. The appropriate timing for organic-based fertilizers is more complicated—the timing of nutrient release will depend on the soil biological activity as well as the input nutrient concentrations and environmental conditions, particularly rainfall. Fertilizer application methods such as knifing or mixing with drip irrigation water (i.e., fertigation) may also minimize leaching and gaseous nitrogen losses. Nutrient composition data and mineralization rates of organic-based inputs are available from sources such as local cooperative extension offices, the USDA Agricultural Research Service (ARS) and qualified professional agronomic specialists.

Along with timing, matching the amount of available nutrients with crop needs is an important component of soil health. Frequent soil and tissue tests are often required to adjust rates based on contributions from the soil organic matter, crop residues and cover crops. The supply and loss of soil nitrogen will depend on many factors, including the levels of soil organic matter, the soil biological community, soil texture, the ratio of evapo-transpiration to rainfall plus irrigation and soil drainage. Diverse sources of nutrient inputs (e.g., animal manure resources) can help ensure the supply of important secondary and micronutrients and enhance soil physical properties. This can enhance the soil nutrient supply for crop yields while improving soil biological activity and physical properties through increases in soil organic matter.

Research has found that many of the practices that promote soil health can also positively benefit nutrient retention, recycling and plant uptake.[18,19] Because some soil nutrient cycles are carried out by soil organisms and are highly regulated by soil physical processes, maintaining these processes via practices such as diversified crop rotations, cover crops, or no-till may have positive feedbacks on nutrient retention and plant nutrient uptake. Nutrient management that considers the timing, rate, placement and source of the nutrient supply will better align plant available nutrients with plant nutrient uptake. This optimizes crop yields and can help maintain water quality and reduce nitrous oxide emissions into the atmosphere.

Measuring Soil Health in the Field

Most agricultural producers are accustomed to testing their soils for nutrient and acidity levels and using the information to adjust their fertilizer, manure and other amendment applications. Only recently has a wider array of testing become available that includes the biological and structural qualities of soil health, discussed above. The most widely used comprehensive tests to date include the Cornell Comprehensive Assessment of Soil Health (CASH), developed from earlier versions of the Soil Management Assessment Framework (SMAF), as well as the Soil Health Nutrient Tool (SHNT), which is often called the Haney Test. While specifics are slightly different, one common element is the integration of soil biological indicators into the assessments. CASH and SMAF also include physical indicators of soil health, while SHNT does not. These tests have primarily been applied regionally: CASH in the Northeast; SMAF as a research tool

18 German, R.N., et al., 2016. Relationships among multiple aspects of agriculture's environmental impact and productivity: a meta-analysis to guide sustainable agriculture. Biological Reviews. doi: 10.1111/brv.12251

19 Drinkwater, L.E., et al. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature, 396:262-265.

on croplands within the U.S. and internationally; and SHNT in the South and Midwest. There is ongoing work to validate these tests across a larger geographic area to determine whether adjustments to the indicators, scoring process and associated practice recommendations are needed for diverse regions, crop systems and soil types.

The CASH test is fully documented online[20] and has been available to the public since 2006 to provide field specific information on the constraints in physical and biological processes in soil, in addition to soil nutrient analyses. The tool is under continued development as new indicators are identified as important to determining management practices to improve soil health and functioning with a specific focus on crop productivity. Each indicator provides information about the field-level as well as the level required for proper functioning of key soil processes. The test analyzes soil samples and provides results that include interpretation and management suggestions for improving functioning for each indicator: soil texture, aggregate stability, available water capacity, surface and subsurface hardness, organic matter, active carbon, soil protein index, soil respiration, root pathogen pressure and standard fertility tests. Soils are scored on each indicator and an overall quality score is averaged from the individual indicators.

CASH evolved out of the Soil Management Assessment Framework (SMAF)[21], which combines indicator scores to produce overall soil quality assessments for agricultural lands. SMAF, documented in the research literature, consists of a set of scoring curves to evaluate individual indicators of soil health and combine them into one rating. The scoring curves have been developed based on extensive research and account for soil type, landscape characteristics, climate regimes and other environmental factors. Currently, scoring curves exist for aggregate stability, bulk density, pH, salinity, sodium adsorption ratio, extractable phosphorus and potassium, soil organic carbon, microbial biomass carbon, potentially mineralizable nitrogen and β-glucosidase activity. SMAF produces a combined Soil Quality Index, which can be subdivided into physical, chemical, nutrient and biological indices. Use of SMAF results involves determining management goals and resource concerns, selecting indicators that best represent those needs, measuring those specific indicators, and then scoring those using a spreadsheet framework where the functions are pre-set.

The Haney Soil Health Nutrient Tool (SHNT)[22,23] is available from the USDA ARS in Temple, TX and several commercial labs as an enhanced nutrient test that provides chemical and biological data to integrate the biological effects of soils on nutrient availability to crops. According to its developer, its key element is a nutrient extractant designed to mimic plant root exudates that make nutrients available to plants and microbes, in addition to tests of microbial activity and available organic substrates. Specific indicators include: respiration (for microbial activity), water extractable organic carbon and nitrogen, and inorganic nutrients. These indicators are used to calculate a soil health measure based on activity and food sources for the soil microbial community. In turn, the results are used to provide recommendations on nutrient management and cover crops to address identified constraints on the microbial community. SHNT is considered only a partial soil health test, as it does not include soil physical indicators.

Work is under way in the scientific community[24] to develop a two-tiered soil health testing protocol that can be adopted more broadly. A number of considerations, including affordability to producers and soil testing labs, standardized protocols and development of appropriate interpretation and

20 http://soilhealth.cals.cornell.edu/

21 Karlen et al. 2014. Journal of Soil and Water Conservation September/October 2014 vol. 69 no. 5 393-401 doi: 10.2489/jswc.69.5.393

22 http://practicalfarmers.org/blog/2014/05/15/scoring-soil-health/

23 Haney et al., 2001. A rapid procedure for estimating nitrogen mineralization in manured soil. Biology and Fertility of Soils 33(2) pp 100-104

24 http://www.soilrenaissance.org/measurement

recommendations, are under discussion. The objective is to develop a simple soil health test in the near term that includes at least one biological indicator and one structural indicator, along with standard nutrient testing, to enable wider adoption and consideration of soil health. Additional test development is occurring at research labs through universities, and the Soil Health Institute, together with USDA-NRCS and members of the broader soil health research community, is currently planning a National Soil Health Assessment. This assessment will measure a number of soil health indicators and use both CASH and SMAF assessments for a wide range of locations. These efforts will provide additional information that can be used in improving both soil health tests and our understanding of soil health interactions with conservation practices and outcomes.

5 Soil Health and the Fieldprint® Platform Metrics

SOIL HEALTH AND THE FIELDPRINT® PLATFORM METRICS

The current version of Field to Market's Fieldprint Platform (2.0)[25] generates seven metrics from one set of producer supplied inputs and has an eighth metric on biodiversity that can be run through an additional module. All of the existing metrics have the potential to be influenced by changes in soil health and are dependent upon the key functions of healthy soil identified earlier. Figure 1, presented earlier in this paper, provides an overview of how the sustainability outcomes measured by Field to Market's metrics relate to specific soil health processes. Here we expand on the relationship between existing metrics and soil health to gain a better understanding of how improving soil health on a field would influence a producers' Fieldprint result, both directly (e.g., adopting practices that change data inputs) and indirectly (e.g., effects of improved soil health on productivity).

Soil Specific Metrics

Two of the metrics are directly related to soil properties and influenced by many of the same practices that are identified above as important for soil health. The Soil Conservation Metric is a estimation of soil loss from a field due to erosion based on the NRCS models RUSLE2 (Revised Universal Soil Loss Equation 2) and WEPS (Wind Erosion Prediction System). The metric takes in data on farm management, soil properties and producer inputs specific to each field and returns an estimate of the amount of soil, measured in tons, that could be eroded each year due to wind and water erosion. Physical processes, such as structural stability, which are measured by the soil health physical indicators discussed earlier, also affect soil erosion. While the current metric is not as sensitive to many of the structural changes discussed above as soil health indicators, erosion will negatively impact efforts to improve soil health and this metric can be an important indicator to producers to begin to understand

25 https://www.fieldtomarket.org/fieldprint-calculator/directions.php

the state of their soil resource.

The Soil Carbon Metric, represented by the NRCS Soil Conditioning Index (SCI), is a qualitative, directional indicator of soil carbon change. The SCI does not provide a value for soil carbon, but rather provides information on whether a field is likely to gain or lose carbon (i.e., soil organic matter), based on producer inputs and soil databases. As discussed above, soil organic matter is considered a key indicator for soil health across many of the physical, chemical and biological processes that sustain soil functions. While the current metric does not capture the full range of responses of soil carbon, it can highlight whether management practices on a specific field are providing an environment conducive to or destructive to soil carbon and organic matter, which are important soil health indicators.

Both of these metrics reflect soil properties that are important for soil health and can be considered indirect indicators. For example, a Fieldprint result with high levels of erosion or high likelihood of carbon loss would indicate significant room for improvement in soil health and the associated field would likely benefit from conducting a soil health assessment to develop targeted management changes. The conservation practices discussed above, which research has shown can lead to improved soil health, could also positively influence these metrics. Changes in management in order to address soil health concerns, including tillage changes, cover crop adoption and residue management that result in more stable soil structure, increased water infiltration and holding capacity as well as increased carbon inputs to the soil would be reflected by positive improvements in the Soil Carbon and Soil Conservation Metric outcomes.

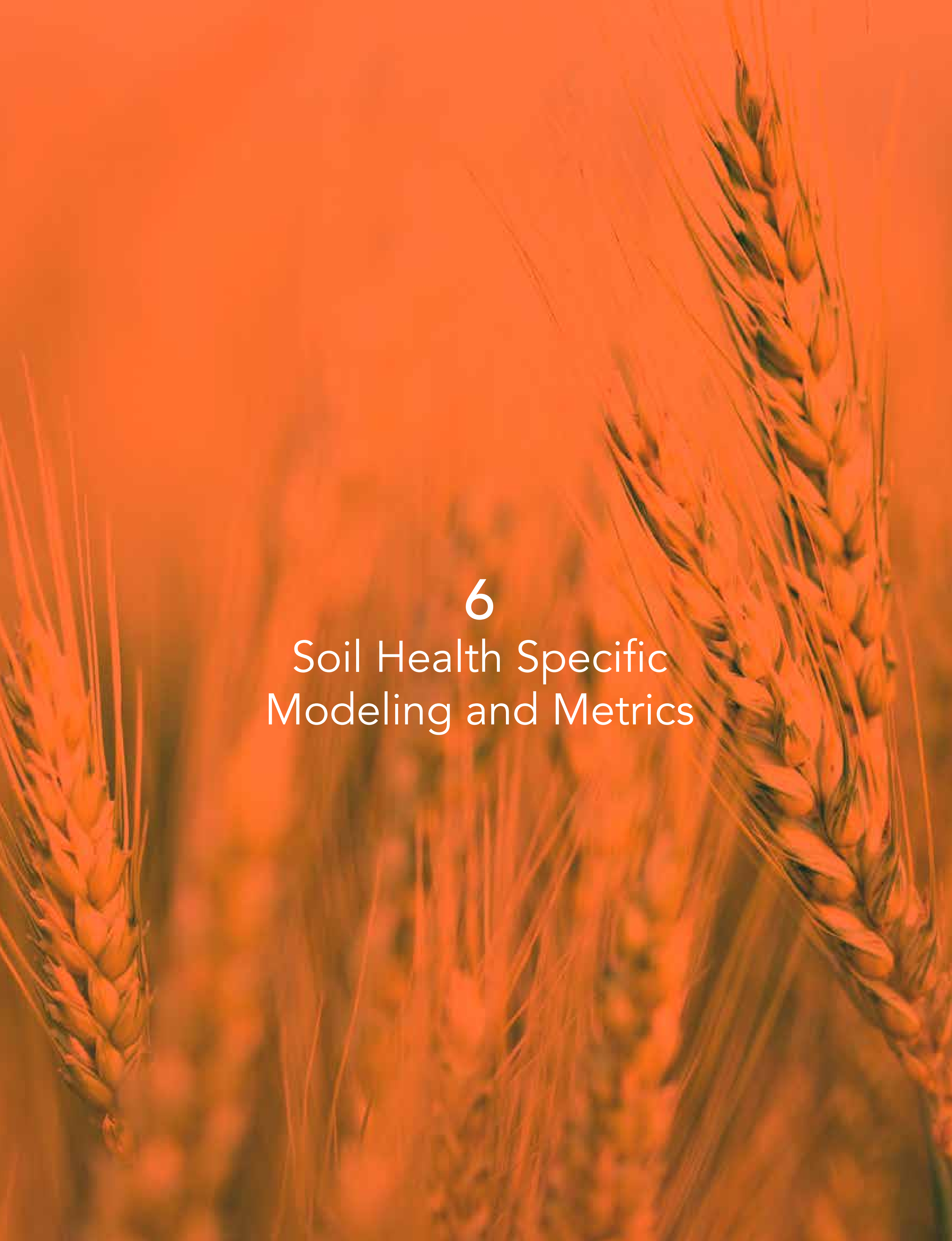
In addition, there is a near-term opportunity for revision of the Soil Carbon Metric. Quantitative modeling approaches produce soil carbon estimates and incorporate additional information such as soil nutrients, multi-year rotation effects and long term tillage effects can be explored for adoption. Use of such a tool would advance the utility of the metric for more comprehensive treatment of soil properties and would align Field to Market's metrics with advanced, biological process-based models of agricultural systems and could be an initial first step toward a more comprehensive soil health metric.

Additional Metrics

Efforts to improve soil health in a field would also influence the other metrics currently included in Field to Market's Fieldprint Platform. A soil with healthy physical structure, measured as aggregate stability, may have a higher water-holding capacity and a more porous surface. This means that water infiltrates well to depth in the soil, becoming available to plant roots and that soil moisture may remain higher after a rainfall or irrigation event. This improved moisture retention would be expected to reduce irrigation requirements—and hence would be reflected in the results of the Irrigated Water Use Metric. Additionally, the Water Quality Metric considers sediment erosion potential, which would be positively influenced in a similar manner to the Soil Conservation Metric.

The interaction of efforts to improve soil health with soil nutrient management would also be expected to positively influence the Greenhouse Gas Emissions (GHG) Metric. The current metric accounts for nitrogen rate applied and revisions are underway that will account for additional nutrient management practices. Changes in these practices for purposes of improving soil health would therefore also be reflected in the nitrous oxide emissions component of the GHG Metric. Changes in management practices adopted for soil health that involve alterations to tillage, nutrient and chemical applications to the field would also directly impact the on farm energy use component of both the Energy Use and GHG Metrics.

In some cases, practices to improve soil health, such as buffer strips and other features, can alter the landscape of a farm. These changes in management would be captured in the Biodiversity Metric, which accounts for the habitat potential of these structures. Finally, the Land Use Metric would be influenced indirectly by any changes to productivity of a field resulting from changes in management or improvements in soil health.



6
Soil Health Specific Modeling and Metrics

SOIL HEALTH SPECIFIC MODELING AND METRICS

When considering how to further integrate soil health concepts into Field to Market's metrics, there are several complexities that need to be understood. First of all, the Field to Market metrics are defined and named by the conservation and sustainability outcomes that they represent. As scientific understanding of soil health improves, it is important to consider whether there are important environmental outcomes that are not appropriately considered within the current metrics.

As described above, many of the previously identified outcomes targeted by current metrics are closely tied to soil health and will reflect, to varying degrees, effects of practices adopted for improving soil health. If, in the future "healthy soil" is included as a specific environmental outcome, then there are a number of research, testing and modeling gaps where progress is needed to inform a metric. It is worth noting that all metrics currently in the Field to Market program rely on some level of simulation modeling and at present, none of the metrics require field specific measurements.

Three considerations are key when considering whether a representation of soil health could be applied broadly as a metric in the Fieldprint Platform. First, we must have a clear way to determine key soil health indicators both qualitatively and quantitatively at the field scale. This is currently only possible through soil tests, where the farmer or a soil testing professional gathers samples from the field and sends them for laboratory analyses. To gather enough information for a large field, multiple tests may be necessary and to measure for continuous improvement, the tests would need to be conducted periodically.

As noted earlier, standard soil health tests are still under development and there is active work underway to evaluate and calibrate these tests across broader geographies and crop systems. In addition, the specific practices that are related to such soil health indicators would need to be identified by region and cropping system in order to make it possible to provide guidance to users based on the metric outcomes. To fill this gap, greater scientific understanding of the operation of soil processes at pore to field scale will be needed. A number of these gaps are the subject of active research efforts. In particular, efforts to conduct a National Soil Health Assessment (scheduled for 2018) and create standard protocols for soil health testing provide opportunities for nearer term engagement by Field to Market members.

7
Opportunities for Field to Market

OPPORTUNITIES FOR FIELD TO MARKET

The environmental sustainability outcomes at the core of the Field to Market metrics are closely linked to both soil health processes and to conservation practices designed to improve soil health. While the interlinkages between these components are not fully understood, soil health may be considered as a superseding set of practices that support improvements in several existing metrics. As the science advances, Field to Market can continue to evaluate the need and appropriateness of both current and additional metrics. In the meantime, there are a number of ways for Field to Market members and supporters to engage in efforts to advance soil health concepts, promote soil health enhancing practices and connect these concepts and practices to the current metrics.

Advancing Soil Health Research

A number of efforts are underway to assess the status of soil health science, determine research priorities and establish research programs to advance our understanding of soil health. These include efforts to better understand the functioning of healthy soils and how it is influenced by actions of farmers and land managers, and by natural variability in soil types and climates. Research needs also include better understanding of the short and long term influence of changes in soil health on crop productivity as well as the overall economic sustainability of a farm. Groups aligned with Field to Market are working to set the research agenda and support the science, including the Soil Health Partnership, Soil Renaissance, the USDA-NRCS Soil Health Division and the Soil Health Institute.[26] Field to Market will stay informed on the progress of these efforts and encourages members and supporters to consider engaging in a range of capacities.

26 http://soilhealthinstitute.org

Promoting Soil Health Testing

One active area of work by the organizations mentioned above is the development and calibration of soil health testing protocols and standardizing test result interpretation for specific farmer guidance. One major gap is a baseline assessment of current soil health across the U.S. Developing a database and network of testing sites required to conduct such an assessment will require significant willingness to form partnerships across the public and private sectors. All of these efforts present opportunities for farmers and organizations to engage as participants and supporters.

Connecting Soil Health Enhancing Practices to Sustainability Outcomes

Field to Market members are working directly with growers on 2 million acres of commodity cropland, engaging in discussions around sustainability and measuring outcomes. Many of these outcomes would be positively influenced by practices that are also beneficial to soil health. Consequently, there may be opportunities within Fieldprint Projects to align existing work with soil health efforts and measure progress against the current sustainability metrics as soil health practices are adopted.

Next Steps

Progress in the area of soil health in terms of scientific advances, public support and engagement and policy has grown rapidly in the last decade, culminating with the International Year of the Soil in 2015.[27] Still, there remains much work to do to advance research and scientific understanding in order to address the constraints that continue to limit the measurement, assessment and interpretation of soil health. Important advances that would assist in further developing the Field to Market metrics toward full characterization of the sustainability outcomes of soil health improvements include:

- Defining the key, measurable sustainability outcomes of improved soil health for all stakeholders;
- Resolving issues of spatial and temporal variability in assessing soil health across different cropping systems in different climatic regions;
- Advancing calibration of soil health testing protocols to ensure accuracy across all states and commodity crop systems;
- Identifying biological indicator(s) of soil health that is cost effective, accessible and interpretable across a range of systems;
- Enhancing soil testing lab capabilities to conduct the soil health protocols and provide standardized, practical guidance based on field results; and
- Supporting research on how conservation practices affect key soil health indicators across varied climates, soil types and cropping systems.

27 http://www.fao.org/soils-2015/en/

CONCLUSION

The science of soil health and sustainability is a vibrant area of research that holds great promise for changes in agricultural land management that can improve, restore and protect our nation's soil resources for long-term sustainable agricultural production. The opportunity presented by improved soil health is a promising development for advancing sustainable agriculture, and we are in a dynamic time of exploration and understanding of how to develop the science and testing of soil health that can lead to practical recommendations for agricultural management. What is clear is that recommendations need to be carefully constructed, taking into account scientific understanding of inherent soil properties, field-specific characteristics and soil health goals.

For Field to Market, the existing set of sustainability metrics can be applied with a focus toward soil health by building better interpretation of the outcomes and guidance on how specific soil health improving practices may be manifested in Fieldprint results. In addition, we can explore further development of the Soil Carbon Metric to reflect the best available science and modeling approaches for measuring this key soil health indicator. Field to Market will continue to engage with the soil health research, testing and implementation efforts underway and monitor scientific developments for opportunities to improve existing metrics and develop new metrics. Field to Market is committed to working to advance our understanding of soil health and sustainability interactions, while also collaborating with aligned efforts where our program can assist in furthering the science, measurement and understanding of soil health.

9
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