Soil Health at the Nexus of Food, Energy, and Water

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Feeding the expected mid-century global population of 9.5 billion people will require the sustainable intensification of agricultural operations, in which farmers produce greater yields within the same footprint [*Garnett et al.*, 2013]. This effort will require the confluence of new technologies, improved management practices, and optimized water and nutrient use efficiencies. Soil – as the medium that provides support and sustenance for crops – acts as a crucial nexus between food, energy and water. In recognition of the importance of soil to sustainable food, water and energy systems, farmers, regulators and scientists have begun working to better understand and manage soil health and productivity. However, many questions remain about how even to best quantify what it means to have "healthy" soils, as well as to what true impacts healthy soils may have on agricultural productivity and environmental preservation.

Soil health – according to definition provided by the U.S. Natural Resources Conservation Service (NRCS) – is "*the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans, [which] speaks to the importance of managing soils so they are sustainable for future generations*." This definition has been interpreted to mean that healthy soils are managed so as to optimize their biological, physical, and chemical characteristics (Figure 1), which, in theory, should help to ensure that their productivity is sustained over both the short and long terms, while at the same time minimizing unintended environmental impacts from agriculture. In other words, a healthy soil should maximize yield (food) while minimizing the inputs of water and energy (in the form of fuel and fertilizers). However, this theory requires much more rigorous exploration and testing, particularly at larger (e.g., watershed, regional, global) scales.

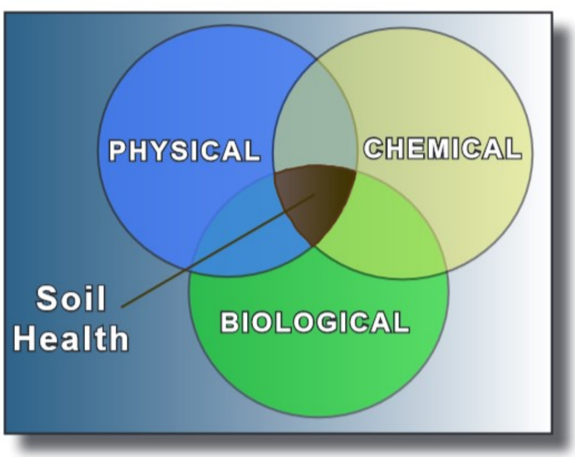

Figure 1: Diagram showing Soil Health at the center of soil physical, chemical and biological properties. Source: http://soilhealth.cals.cornell.edu/about/index.htm; Accessed November 26, 2015.

Until now, most soil health research has focused on plot-scale measurements, in which some combination of tillage and/or cover cropping practices are compared. Given the considerable variety of soil textures, cropping systems, and management practices represented in the literature, it is perhaps not surprising that inconsistent results and variable effects are often noted when multiple studies are compared [*USDA NRCS,* 2015]. As such, there are many critical questions that are yet unanswered about the specific role of soil health at the nexus of energy, food, and water systems. For instance, the use of a "green cover" (i.e., cover crops) has been recommended as a means to improve organic matter content of soil [*Beniston et al.*, 2015] and reduce erosion [*Derpsch et al.*, 1986; *Langdale et al.*, 1991; *Dabney et al.*, 2001]. Nonetheless, little is known about how the usage of cover crops may affect soil water storage, e.g. by altering the timing and magnitude of transpiration in a field, and/or by causing variations in infiltration rates. Other recent research has suggested that managed soils using no-till practices may result in increased subsurface leaching of phosphorus [*Kleinman et al.*, 2009] and nitrogen [*Han et al.*, 2015]. Given the recent proliferation of cyanobacteria blooms and eutrophication in relatively pristine waters such as Lake Erie (*Michalak et al.* [2013]; Figure 2), there is an urgent need to understand if and under what circumstances soil health practices can cause increased nutrient losses from fields. One specific hypothesis holds that increases in soil structure (i.e., the aggregation of primary soil particles into larger secondary aggregates) resulting from soil health management practices may result in more soil macro-porosity and, by extension, greater opportunity for water and nutrients to preferentially move through the soil profile, thus causing increasing loading of nitrogen and dissolved reactive phosphorus in surface waters (Figure 3). Still another relevant area of exploration is how soil health management practices may affect the emissions of greenhouse gases from soils, as well as the storage of carbon within soils [*Mangalassery et al.*, 2014]. Inherent to these processes are even more complex questions about the role of biology and soil ecology in sustaining soil productivity and function [*Bossio et al.*, 2005; *Le Roux et al.*, 2008]. At a basic level, we still understand very little about even what type of micro-organisms inhibit soil [*Fierer et al.*, 2007], much less about any functions that they may provide in the context of sustainable agriculture. Overall, such examples demonstrate that we still understand very little about the mechanisms, incidence, variability, and consequences of soil health management practices, in particular with regard to the interactions between water, gases, soils, micro-organisms and plants.

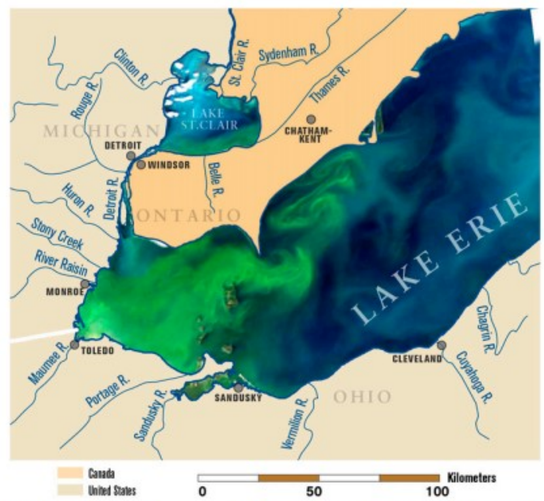

Figure 2: MODIS satellite image of Lake Erie on September 3, 2011, overlaid over map of Lake Erie tributaries. Source: *Michalak et al.* [2013].

Beyond focusing on specific processes and mechanisms, there are a number of large-scale, systems-based questions about soil health that could be relevant to the National Science Foundation (NSF). For instance, if we know how different soil types respond to various management practices, could we optimize the location of certain crops within a watershed or region so as to most sustainably intensify agricultural productivity? Such exercises could be constructed to consider energy usage (e.g., which arrangements could minimize heavy machinery use and/or transportation costs), irrigation efficiencies, resulting effects on surface/ground-water quality and quantity, along with social and economic considerations. Indeed, much of the current interest in precision agriculture is focused on how to best apply nutrients and water in response to real time indications of soil and plant condition, both of which are directly related to soil health/function. Soil health concepts may therefore be used to help scale up and enact precision agriculture across regions, geologies, and climates.

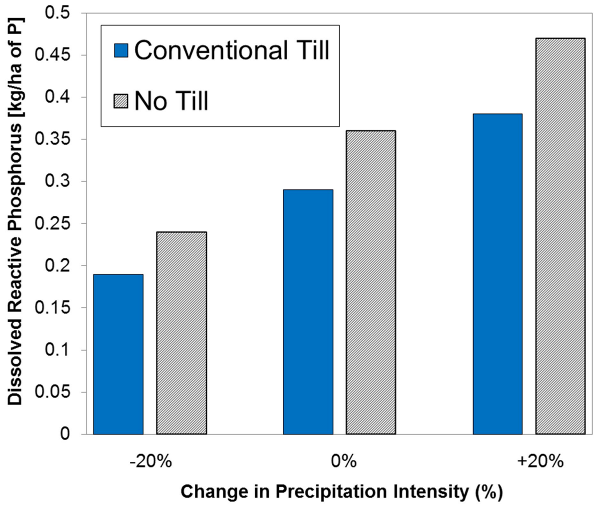

Figure 3: Modeled Dissolved Reactive Phosphorus yields in the Maumee (Ohio) watershed if the watershed is managed with conventional tillage (blue) versus no-till (gray). Three different changes in precipitation intensity (-20%, 0%, +20%) were compared. Modified from *Michalak et al.* [2013].

In the past, the science of soil "health" has been considered to fall within the purview of the U.S. Department of Agriculture and the NRCS. However, given that in order to meet future needs for food, fuel and fiber we must radically transform our agricultural systems [*Godfray et al.*, 2010], and given our current limited understanding of the role of soil at the nexus of energy, food, and water, NSF should consider investing in scientific research focused on soil health processes and implications. In order to meet the challenges of the present and future, it is imperative that we develop better understanding of how soil health affects the fluxes and states of matter and energy within the food-energy-water nexus, as well as how societal and environmental benefits of soil health can be realized at scales with global relevance.

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