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Economic Theory Provides Insights for Soil Health Policy

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Over the past decade, soil health has become a buzzword among both farmers and environmentalists. Farmers see healthy soils as a key to agricultural productivity, and environmentalists see healthy soils as the foundation of a robust ecosystem. Although so many people seem to want to boost soil health, soils around the world remain in crisis. Erosion is rampant (Wilkinson and McElroy, 2007), nutrient levels are falling (Jones et al., 2013), and microbial ecosystems are collapsing (Tsiafouli et al., 2015). Why is this happening? And what can we do about it?

Three observations help explain the soil health disconnect. First, soil health is hard to define. This makes it difficult for farmers, agronomists, soil scientists, economists, environmentalists, and policy makers to effectively communicate. Second, each group of stakeholders has a relatively narrow understanding of soil health. For instance, farmers tend to oversimplify the concept, reducing it to mere soil fertility or nutrient content. Environmentalists, on the other hand, tend to conflate optimal land management with maximizing soil health, ignoring farmers' need to earn a profit. Finally, soil health is fundamentally dynamic. That is, soils' health evolves slowly over time, responding to agricultural inputs and land management practices. No management technique can magically transform a poor soil into a healthy one; years of steady investment are necessary to see meaningful change.

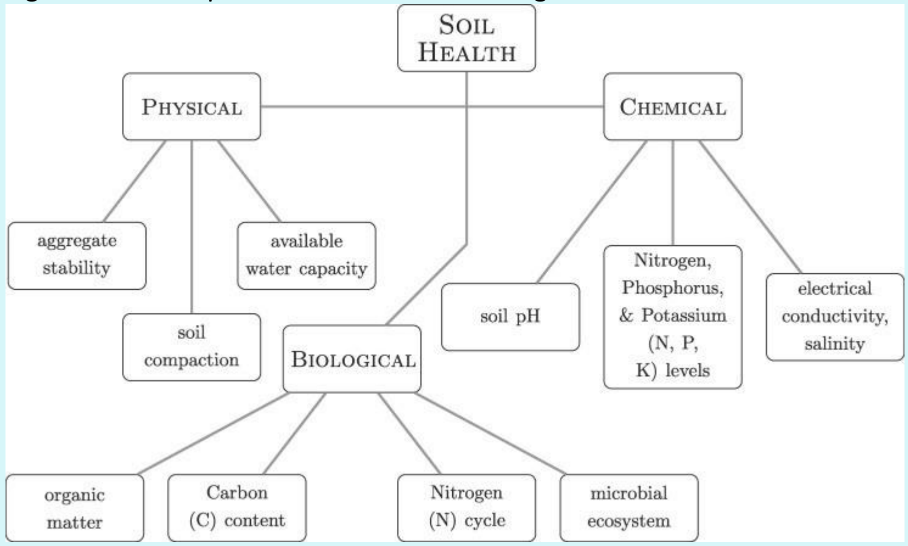
To design effective and efficient soil health policies, stakeholders need to share (i) a common definition of soil health, (ii) an appreciation of the benefits of healthy soils, and (iii) an integrated model of how physical, chemical, biological, and economic processes relate to one another over time. In this article, I advocate for a holistic definition of soil health, discuss the benefits of healthy soils, and outline a dynamic model of soil health in the agricultural setting that can help inform policy. The model suggests that policy should focus most heavily on making information accessible to landowners: the current state of their soil health, how soil health responds to different management techniques, and how soil health affects crop yield. Additionally, policy makers need reliable estimates of how soil health affects environmental outcomes beyond mere agricultural output.

Defining Soil Health

Historically, farmers and agricultural economists have focused on the concept of soil fertility: the capacity of a soil to support agricultural yields. Soil health, however, is broader in scope. It encompasses how a soil affects both agricultural production and environmental sustainability. The Natural Resources Conservation Service of the U.S. Department of Agriculture defines soil health as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Bowman, Wallander, and Lynch, 2016). Although individual definitions of soil health differ, they all divide soils into three primary components: physical, chemical, and biological (Figure 1).

A soil's physical components relate to the structure of individual soil particles. The healthiest soils are sturdy enough to support a plant's roots while not being too dense. They also retain sufficient water between their particles for plants' use while allowing excess water to drain away easily. Soil scientists focus on specific indicators of a soil's physical structure such as aggregate stability (a soil's ability to maintain structure when exposed to stress), soil compaction (the density of soil particles), and available water capacity (how much water is held between soil particles). Although a farmer cannot alter a soil's composition of clay, silt, and sand, the farmer can affect aggregate stability, soil compaction, and available water capacity through practices like tillage, planting cover crops, and the use of heavy machinery.

Figure 1. A Conceptual Framework for Defining Soil Health



Source: Stevens (2018).

A soil's chemical components relate to the chemical makeup of the soil environment. These include the soil's acidity (pH), salinity, and chemical nutrients. Farmers will easily recognize the "big three" soil nutrients: nitrogen (N), phosphorus (P), and potassium (K). These elements are so important to agricultural productivity that fertilizers are identified by their N–P–K mix. But a soil's overall chemical health is more than just its nitrogen or phosphorus levels. The combination of pH, salinity, and nutrient levels helps determine what nutrients are actually available to plants and also affects the soil's biological characteristics. Heavy metals are another component of a soil's chemical makeup that can affect its agricultural suitability.

Biological characteristics comprise the third major component of soil health. Healthy soils have high levels of organic matter and carbon content while also maintaining a stable nitrogen cycle and microbial ecosystem. Biological soil health supports the formation of mineralizable nitrogen, the form of nitrogen actually accessible to plants. Organic matter also helps prevent soil compaction and erosion. Finally, soils with vibrant microbial ecosystems have proven especially productive and resilient, although the specific mechanisms are still poorly understood.

Historically, researchers have sought to explain a soil's health with a single number: a soil health index. Using an index is attractive because it allows direct comparisons across different locations and over time. However, an index can greatly oversimplify reality. Two soils could share the same value on a soil health index, for example, but have very different underlying characteristics. One could have great physical properties and poor chemical properties, while the other could have good chemistry and bad water capacity.

Instead of using soil health indices, researchers are turning toward using a set of multiple soil health indicators that each measure a different component of overall soil health. For instance, a researcher may measure and track a soil's aggregate stability, N–P–K levels, and organic matter over time. These individual indicators each contribute different information to the overall picture of soil healthy.

Benefits of Healthy Soils

Farmers and ranchers care about soil health because healthy soils support high agricultural yields. But there are other benefits, too. For example, healthy soils can have positive spillover effects on other agricultural producers. Healthy soils also have a positive impact on their surrounding environment, irrespective of their agronomic effects. For example, to summarize all these different benefits, it is possible to think of soil health benefits along two dimensions: agronomic versus environmental and private versus public (Figure 2).

Figure 2. Soil Health Benefit Categories

	Ecological/Environmental	Agronomic
Private	• erosion control • local biodiversity, natural beauty, etc. • flood control	• increased yields (direct effects) • pest control • reduced fertilizer expenditures • less necessary irrigation
External	• erosion control • cleaner water (fewer nitrates, etc.) • flood control • carbon sequestration	• lower risk for pest outbreaks • lower risk for disease outbreaks • fewer unwanted nitrates from runoff

Source: Stevens (2018).

On the agronomic side, healthy soils increase yields, control pests, and reduce fertilizer and irrigation needs. They also lower the risk of pest and disease outbreaks on neighboring lands and cut down on nitrate runoff. On the environmental side, healthy soils prevent erosion, control flooding, increase biodiversity, clean water, and sequester carbon, among other things (Moebius-Clune et al., 2017).

Looking at Figure 2, it is clear that healthy soils provide some positive externalities—that is, they provide some benefits that aren't directly enjoyed by the private producer. Externalities like carbon sequestration and flood control are neither excludable nor rival, making them public goods (Ostrom, 2015). However, it is not clear whether these positive externalities are large enough to justify expensive policies aimed at increasing soil health. The model presented below is flexible enough to include the external benefits of healthy soils and help answer this question.

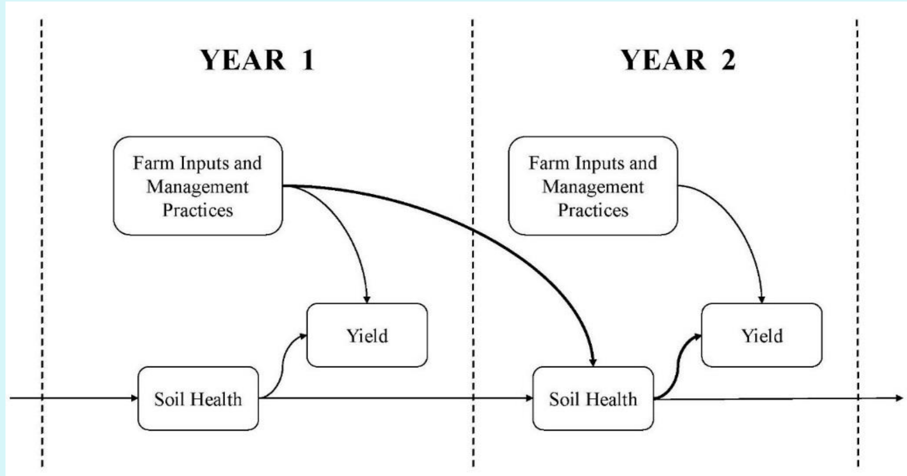
A Dynamic Model of Soil Health

To combine the physical, chemical, and biological components of soil health with a model of human decision making, we need a dynamic framework. In other words, we need a model that explicitly accounts for how actions in one period affect outcomes in future periods, constrained by the natural processes governing how a soil's health changes in response to different management practices. What we need is an optimal control model (Weitzman, 2003). Here, I describe the model in words and figures. For a more detailed exposition, see Stevens (2018). The main components of the model are as follows:

- **A set of soil health indicators**: N–P–K levels, soil organic matter, compaction, etc.;
- **A set of farm inputs or land management practices**: fertilizer, pesticides, cover-cropping, tillage, etc.;
- **An agricultural production function** that describes how soil health indicators and farm inputs/practices come together to create a certain expected crop yield;
- **A function of soil health transition** that describes how previous values of the soil health indicators and previous farm inputs/practices combine to generate future values of the soil health indicators.

The final component of the model—the soil health transition function—is the most important: It ties together different time periods and makes the model dynamic. Figure 3 summarizes the model over two representative years, ignoring other determinants of yield (such as weather). In year 1, the only factors that affect yield are that year's soil health and farm inputs. Again, in year 2, the only factors that affect yield are that year's soil health and farm inputs. However, year 2's soil health is impacted by year 1's soil health and farm inputs. This is the core dynamic point: Farm input decisions in year 1 indirectly affect yield in year 2 through the soil health in year 2 (see the thick arrows in Figure 3). Therefore, a forward-looking farmer should think about future years' yields when making present-year input decisions. For examples of this sort of approach, see Burt (1981) and McConnell (1983).

Figure 3. A Dynamic Model of Soil Health



To include the external benefits of healthy soils to this model, we can include a fifth model component, not shown in Figure 3: a function of soil health's external benefits. Like the agricultural production function, this function describes how current-year levels of soil health indicators produce current-year external benefits like erosion control and carbon sequestration. By comparing the model's solutions with and without the function of soil health's external benefits, we can quantify how much policy intervention is justified to address the externality problem with respect to soil health.

Policy Implications

The model described above highlights some important insights for guiding soil health policy. Here, I discuss the model's main implications for policy makers:

- **Farmers who rent their land are likely to behave differently than farmers who own their land.** Because soil health is dynamic, a farmer will only invest in their soils today if they expect to reap the reward of that investment in the future. When a farmer rents their land, they are not sure they will benefit from practices that build up future soil health since they may not be farming the same land in the future. Indeed, empirical data suggest that renters are less likely to adopt site-specific conservation practices than owners (Deaton, Lawley, and Nadella, 2018). Further, to the extent that healthy soils get capitalized into land rents—that is, that rents could reflect underlying soil health—renters face a disincentive from improving the soils they farm.
- **Current soil health policy may crowd-out privately optimal behavior.** Today, most soil health policy in the United States is administered through the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture. The NRCS often offers cost-sharing (a subsidy) for various land management practices that promote soil health. But as the model outlined earlier highlights, farmers already have much to gain from healthy soils through their effects on crop yield. Additionally, evidence suggests that soil health is at least somewhat capitalized into land prices, giving landowners an additional reason to invest in healthy soil (Miranowski and Hammes, 1984). If the government pays farmers to implement practices that they would have implemented anyway, those subsidies are an inefficient use of public resources.
- **Optimal policy depends on whether society and landowners value the future differently.** Hidden in the model outlined above is a trade-off between benefits today and benefits tomorrow. Each farmer has to make that trade-off for themselves, and economists describe this decision using a variable called the "discount rate." It is possible that society has a different discount rate than individual farmers and values

the future more highly than producers do. If that is the case (and it is unclear whether it is), this difference in discount rates may justify increased policy intervention in soil health.

- **Farmers probably don't know enough their own soil health.** In order for a farmer to behave as described by the model in this article, they need to be able to observe the value of relevant soil health indicators each year. This is reasonable for some indicators like N–P–K levels; simple soil tests are common. But it is much rarer for farmers to test their soils for things like aggregate stability, soil organic matter, or microbial diversity. There is a clear opportunity for policy to make more-detailed soil testing cheaper and more readily available to farmers (Idowu et al., 2008). Doing so will lower transaction costs and allow individual producers to make more optimal production decisions over time and (privately) increase their soils' health.
- **We still do not know much about how soil health evolves over time in response to production practices.** The model above highlights the importance of the soil health transition function: how past soil health and past production practices combine to determine current soil health. Unfortunately, this transition function can be very complicated, especially as the number of soil health indicators and production practices increase. Here, there is a clear justification for increased public investment in research on precisely this topic: estimating accurate soil health transition functions. The United States already has an excellent system of co-operative extension throughout the states that can facilitate new research getting into farmers' hands.

Soil health continues to be an important issue for producers and policy makers throughout the United States and the world. If current trends do not change, erosion and current production practices threaten to devastate soil health in coming years (Amundson et al., 2015). To meet this challenge, producers, policy makers, soil scientists, and economists must renew efforts to study and understand soil health in the context of our global agricultural system. Models of optimal control—like the one outlined here and in more detail in Stevens (2018)—provide a good baseline of how to think about soil health policy. Most immediately, policy makers would be wise to invest in subsidized soil testing and increased scientific research on how soil health evolves over time.

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