The Economics of Soil Health:

Current Knowledge, Open Questions, and Policy Implications*

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Abstract

Soil health plays an important role in agricultural productivity, environmental resiliency, and ecosystem sustainability. However, this hard-to-quantify holistic concept has proven difficult to incorporate into existing economic and policy frameworks. This report summarizes existing knowledge about the economics of soil health, suggests a methodology for studying the economics of soil health, identifies areas with a need for further research, and discusses current and potential policies that address the economics of soil health. Important components of optimal soil health management include search costs for information, private vs. public benefits, land ownership, carbon policy, and the natural dynamics of soil health characteristics. A case study (Berazneva *et al.*, 2014) is highlighted as an application of an economic framework to soil health in Kenya, suggesting the need for similar studies focused on American agricultural systems. The framework developed in this report suggests that soil health policies focus on increasing access to information and internalizing the positive externalities of healthy soils. However, the magnitude of how far the *status quo* is from an economic optimum is unclear.

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1 Introduction

The concept of soil health, sometimes called soil quality, is a broad and multifaceted way of summarizing a soil's productivity, resilience, and sustainability over both short- and long-term time horizons. Over the last several decades, soil health has been successfully incorporated into several fields of study, including soil science, agronomy, plant biology, and ecology. However, since soil health is often defined in different ways by different people, there is no standardized approach to quantifying this concept. As a result, there has been relatively little work done on the economics or public policy of soil health. This report aims to investigate the existing work on the economics of soil health, identify opportunities for future research, and highlight implications for public policy around soil health.

A recent article in Science (Amundson *et al.*, 2015) highlights the current over-reliance on soil resources across the world. If the *status quo* continues, the total amount of soil will continue to drop due to erosion and the health of the remaining soil will be considerably reduced. With the prospect of population growth in the billions over the coming decades, these facts make for a compelling case in favor of public policies to protect soil resources.

In this report, I begin by developing some basic structure for discussing soil health: definitions, benefits, and measurements. I then discuss the fundamental dynamics of soil health in both natural and agronomic dimensions. Next, I lay out an analytic framework for studying the economics of soil health. The framework accounts explicitly for dynamic processes and provides tractable optimality conditions that can be applied to data. I then discuss a case study (Berazneva *et al.*, 2014) that applies a similar framework to agricultural productivity and soil carbon in Kenya. This case study demonstrates the relevance and power of a cohesive analytical framework as I suggest. I finally discuss the current environment of soil health policies in the United States and point out areas for potential policy work and future research.

I find that the most compelling cases for policy intervention in soil health arise in areas of market failures: high information search costs, positive externalities of soil health, and differing incentives between landowners and renters. However, I also note that the economic social optimum may not be largely different from the *status quo*, especially if farmers are truly discounting the future at high rates.[1] Soil health is certainly an important component of agricultural and environmental management, and has some role in large-scale issues like carbon policy, but is also unlikely to be a panacea for such issues.

2 Defining Soil Health

Soil health is simultaneously remarkably easy and remarkably difficult to define. In the abstract, soil health is a straightforward concept: it is a measure of a soil's ability to support life, withstand transient environmental stresses, and endure as a core component of a resilient ecosystem. Doran and Parkin (1994) suggest defining soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health." However, the question of how to measure and quantify this inherently holistic concept has proven exceedingly difficult.

One approach to quantifying soil health has been to develop soil quality indices. These indices collapse multidimensional data about a soil's physical, chemical, and biological characteristics into a single-dimensional measure of soil quality (Mukhergee & Lal, 2014). The benefits of such indices are clear: they provide a single measure of soil health, thus allowing for direct comparison across different soils. However, there are several challenges to this approach. First, there are many ways to construct a single-dimensional index for soil health. As a result, different indices may rank a soil's health differently relative to other soils, leading to conflicting conclusions. Second, single-dimensional indices do not provide helpful information about the most effective ways to improve a particular soil's health. For instance, two separate soils may share the same score on a soil health index, but differ drastically in their

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[1] In economics, we assume that agents "discount" the future, meaning that they put more weight on utility or profits today than on utility or profits in the future. The discount factor – usually denoted by δ or ρ – is often called the rate of pure time preference and quantifies how agents trade off costs and benefits over time. Time discounting has been a canonical economic assumption since before Ramsey (1928).

characteristics.

Another approach to quantifying soil health has been to use a collection of soil health "indicators" that each measure particular component of soil health. This approach provides more specific information about a soil's characteristics, but also makes it more difficult to use this information in other contexts. Furthermore, many soil indicators may be difficult to easily observe.

When thinking about how to define soil health, a useful parallel is that of human health. The concept of a "healthy" person is easy to grasp, but difficult to quantify in a single number. Similarly, medical professionals are able to observe myriad components of human health ranging from blood pressure all the way to gastrointestinal bacteria levels. A truly complete list of all health measures is not only overwhelming, but also infeasible.

To balance the inherent complexities of soil health with the pragmatic goal of incorporating soil health measures into an economic or policy context, the most promising strategy is to identify a finite number of soil health indicators that capture the most prominent characteristics of soil health. These indicators can then be analyzed in a manageable multidimensional framework to provide meaningful information to farmers, ranchers, and policymakers.

2.1 Major components of soil health

While different authors have suggested many different ways to systematize soil health measures, they all share a common framework. Soil health can be parsed into three primary components: physical characteristics, chemical characteristics, and biological characteristics. Within each of these three components – physical, chemical, and biological – exist many possible soil health characteristics and indicators. Figure 1 outlines this conception of soil health.

In the following subsections, I explore the three major components of soil health: physical, chemical, and biological. For each, I identify what I argue are the most economically meaningful characteristics in the component. By economically meaningful, I mean the char-

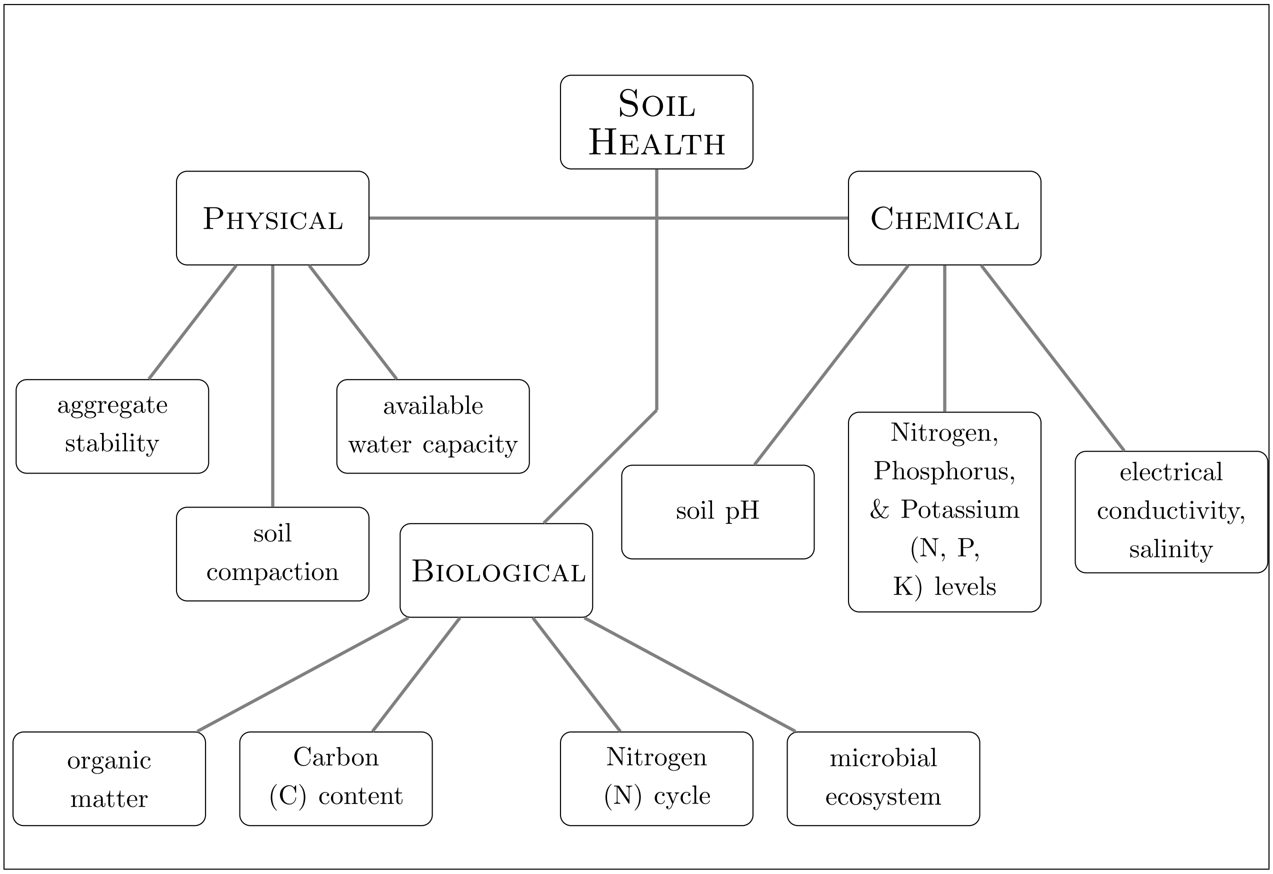

Figure 1: A simplified framework for soil health

acteristics that have the largest and and most easily identifiable impact on a soil's ability to support life, maximize agricultural yields, display environmental resiliency, and further ecosystem sustainability.

2.1.1 Physical characteristics

Many of a soil's physical characteristics are geological in nature and are not alterable by soil management techniques. For instance, a soil's composition of clay, silt, and sand is the result of millions of years of geological history and not changeable by a farmer. However, there are some physical soil characteristics that can be affected by soil management. The three most economically meaningful of these characteristics are aggregate stability, soil compaction, and available water capacity.

Aggregate stability is a measure of a soil's ability to maintain its structure when exposed to different stresses. Soil structure is critical to support plant root systems, provide for air and water movement through the soil, prevent erosion, and provide a stable environment for soil microbiota. A soil that maintains its structure when stressed, specifically by water, is well-suited to supporting robust ecology and agriculture (Amézketa, 1999).

Bulk density is a measure of how closely soil particles are packed together, and is measured by dividing a soil sample's mass by its volume. When soils become more dense (undergo compaction), plants' roots have a more difficult time growing through the soil. Low bulk densities are thus desirable for farmers. A common cause of soil compaction is tractor use where heavy machinery puts pressure on the soil. (Unger & Kaspar, 1994).

Available water capacity is a measure of how much water a soil can hold between its soil particles. This is particularly important in a soil's root zone where water availability is critical to plant growth. Not surprisingly, available water capacity and bulk density are inversely related: as a soil becomes ore compacted, its capacity to hold water decreases (Archer & Smith, 1972).

2.1.2 Chemical characteristics

In addition to physical properties, soils have distinct chemical makeups that can change over time. Plant cover, irrigation, and soil additives such as organic or inorganic fertilizer play a large roll in how soil chemistry evolves over time, and this chemistry can have large effects on plant growth and crop productivity. The most significant chemical characteristics of soil include pH (a measure of acidity), phosphorous levels, potassium levels, presence of micronutrients, and soil salinity. (Nitrogen, while a chemical compound, is discussed as a biological characteristic due to the highly biologic nature of the nitrogen cycle.)

A soil's pH – a measure of acidity – gives information about how available other nutrients are to plants the grow in that soil. Most soils are most productive in neutral to slightly-acidic conditions (pH 6-7). In more acidic soils, there is a low availability of calcium, magnesium, and phosphorus. In more alkaline soils, iron, manganese, copper, zinc, phosphorus, and boron are relatively unavailable. Soil pH can be changed by applying different substances to the soil. For instance, nitrogen fertilizer often acidifies soils, while lime makes soils more basic (NRCS, 1998).

After nitrogen, phosphorus (P) is the most important nutrient limiting crop growth. Phosphorus must be in a particular chemical form to be accessible by a plant, and operates on a long natural chemical cycle. In practice, phosphorus can be added to soils as an inorganic fertilizer. In high-productivity agricultural systems, external sources of phosphorus are often necessary to maintain agricultural yields. (Holford, 1997).

Potassium (K) is another critical macronutrient for agricultural crops. As with phosphorus, potassium is often applied as fertilizer in large agricultural operations. When soils are low in potassium, crops' leaves can turn yellow at their edges and growth is significantly curtailed. Potash is the most common source of potassium fertilizer (Rehm & Schmitt, 2002).

After nitrogen, phosphorus, and potassium (the "big three" macronutrients N, P, and K), many other chemical micronutrients are important for soil health. Although micronutrients such as boron, copper, iron, chloride, manganese, molybdenum, and zinc are needed in much smaller quantities than nitrogen, phosphorus, and potassium, a deficiency of these nutrients can have as significant an impact on plant growth. Micronutrient deficiencies are highly soil- and crop-specific, meaning that farmers need to be particularly aware of the risks for their particular crops (White & Zasoski, 1999). For instance, many corn farmers know to look for the signs of boron deficiencies in their soils.

Salinity, or the amount of salt in a soil, is another important chemical characteristic of soil health. As a soil becomes more saline, it becomes significantly less productive and can even become infertile in extreme cases (Parida & Das, 2005). Most soil salinity can be attributed to salt deposited by water. Efficient irrigation methods, such as drip irrigation, can increase soil salinity while flood irrigation can "flush" salt out of the soil. Thus, there is a tension between efficient water use and soil salinity.

2.1.3 Biological characteristics

Far from being an inert or passive substance, healthy soil is home to a wide variety of life. The biologic characteristics of soil health are some of the most complex and relatively least understood of all. Among the most important biological characteristics are the amount of organic matter, the amount of active carbon, the mineralizable nitrogen, and the microbial ecosystem found in the soil. Of these, nitrogen is the most well understood, and arguably the most important component of soil productivity in agricultural settings.

Organic matter is all material in a soil that is or was at one time alive. This includes plant residues, microbial life, active soil organic matter called detritus, and stabilized soil organic matter called humus. Organic matter provides an environment and sustenance for microbes, while also increasing the soil's resistance to compaction and erosion. Organic matter can be built up over time by adopting no- or low-till soil management practices, planting cover crops, or using compost. The importance of organic matter to agricultural productivity varies greatly with soil type (Lewandowski, 2000).

Active carbon is a subset of the organic matter described above. In particular, active carbon is easily available to microbes and plants in the soil and reacts much more quickly to land management strategies than inactive carbon (e.g. humus). Active soil carbon is beneficial to soil health and simultaneously keeps that carbon out of the atmosphere, thereby presenting a possible mitigation strategy to carbon emissions.

Mineralizable nitrogen is the nitrogen in soil that can be used by plants. Since plants cannot access atmospheric nitrogen, nitrates are critical nutrients for plant growth, and mineralizable nitrogen is often the most important nutrient limiting plant growth. Nitrogen can be considered a biological characteristic of soil because one of the primary natural ways for soils to build mineralizable nitrogen is through nitrogen-fixing bacterial processes. In practice today, however, many farmers use inorganic nitrogen fertilizers to augment soil nitrogen. Another approach is to rotate crops between nitrogen-leaching and nitrogen-fixing species (e.g. corn/soybeans). Nitrogen is a critical contributor to the agricultural productivity of a particular soil, and its dual nature of being both chemical and biological characteristic of soil health makes it particularly notable (Lamb *et al.*, 2014).

The microbial ecosystem within a soil is one of the least understood characteristics of soil health. Nonetheless, a diverse and thriving microbial ecosystem is associated with increased plant growth, increased agricultural production, and higher resiliency to pests and disease (Van Der Heijden *et al.*, 2008). When other components of soil health are performing well, especially pH, salinity, bulk density, and active carbon, soil microbes are more likely to thrive.

3 Benefits of Soil Health

Healthy soils increase plant growth, reduce erosion, prevent against pest and disease outbreak, and can serve as a carbon sink. Physically, healthy soils have high aggregate stability, low bulk density, and high available water capacity. Chemically, healthy soils have neutral to slightly acidic pH, abundant and stable levels of phosphorus and potassium, adequate levels of micronutrients, and low salinity. Biologically, healthy soils have large amounts of organic matter, high levels of active carbon, adequate and stable levels of mineralizable nitrogen (having too-high levels of nitrates can decrease soil health), and a thriving microbial ecosystem.

One of the most challenging aspects of studying soil health is that the benefits of any one soil characteristic are highly dependent on the status of the other characteristics. For instance, micronutrient levels are meaningless in a soil with extremely low aggregate stability. Similarly, compaction may not be a very important issue when a soil is extremely saline. On top of that, any agronomic benefits of soil health will also be highly crop-dependent. A nitrogen-fixing crop like soybeans requires much less mineralizable nitrogen than does a nitrogen-leaching crop like corn.

One can, however, categorize the various benefits of soil health into several distinct groups: in one dimension, ecological/environmental benefits vs. agronomic benefits, and in another dimension, private benefits vs. external benefits. Ecological/environmental benefits are those that contribute to the resiliency of the area without directly increasing agricultural yield, while agronomic benefits are those that manifest specifically in increased yield. Private benefits are those that are realized by a farmer, while external benefits are realized by others. Table 1 illustrates these distinctions.

	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

Table 1: Soil health benefit categories

It is impossible to quantify these benefits in the abstract, but progress could be made on a case-by-case basis.

4 Measuring Soil Health

Once one has identified which soil health indicators are most useful for summarizing a soil's overall health, one must next measure these indicators. A persistent challenge of soil health analysis is the relative complexity of measuring all the indicators we think are important. While some soil indicators are more or less easy to observe by sight and touch, others require specialized equipment or analytical skills. To again invoke the human health metaphor: it is relatively easy to take your own temperature at home to see if you have a fever, but you need to visit the doctor to determine whether or not your sore throat is viral or bacterial.

The Department of Crop and Soil Sciences at Cornell University has developed several benchmark soil health assessments that balances the complexities of soil health with the challenges of measurement (Gugino *et al.*, 2009). In these assessments, a farmer collects soil samples from her fields and sends the samples to Cornell for lab analysis. The lab then sends the farmer test results along with contextual information about which soil indicators are most constraining, and which direction they must move to improve soil health moving forward. Soil assessments such as Cornell's are much more comprehensive than traditional "N-P-K" tests that measure macronutrients and have been promoted by fertilizer companies for decades.

There are several characteristics of soil tests like the one from Cornell that can impede usage. First, it takes time to receive test results. Second, tests must be repeated often (annually) to properly track how a soil responds to different management techniques. Third, tests must occur at the right time in the year so they can be useful information for that year's production; late tests may prove interesting, but they are not practically helpful in most cases. Lastly, tests like the Cornell test are costly, running somewhere between $45 and $75 per test. While this is not a large number in the context of a large farm operation, this cost must be paid annually for annual tests, and often may not provide any new or surprising information that would change a farmer's thinking.

It is possible – even likely – that the real and perceived costs of measuring soil health are an effective detriment to many farmers who might otherwise be interested in the information. Soil health indicators, especially the biological components of soil health, are likely not the most highly salient factors for many farmers when they make farm management plans. In economic terms, this is often described as a "search cost," where obtaining and observing information is itself costly either financially or behaviorally (Stigler, 1961). This provides an avenue for public policy that reduces search costs or highlights the high expected benefits of observing soil health measurements.

5 Soil Health Dynamics

Unlike many production processes, agriculture is particularly dynamic in that future production is highly dependent on past production. Much of this temporal dependency comes from soil health dynamics where future soil health is dependent on past soil health. The nitrogen cycle and carbon cycle are just two examples of complex dynamic systems affecting soils. In addition to natural system dynamics, agricultural practices are also dynamic. Crop rotations, tillage practices, and irrigation all are long-term processes that cannot be reduced to a single-year decision. In this section, I discuss some of the most prominent dynamic considerations affecting soil health.

5.1 Natural Processes and Cycles

I discuss two biogeochemical cycles that are particularly relevant for agriculture and soil health: the nitrogen cycle and the carbon cycle. I also discuss pest and weed cycles.

5.1.1 Nitrogen Cycle

As discussed earlier, nitrogen is a particularly important chemical nutrient for many agricultural crops. While atmospheric nitrogen (N_2) is abundant, it is not accessible to plants. In order to become a useful nutrient for plant life, atmospheric nitrogen must be "fixed." The process by which atmospheric nitrogen is fixed into ammonia, then to nitrates, and back to atmospheric nitrogen is called the nitrogen cycle.

Most atmospheric nitrogen is converted to ammonia (NH_3) by either lightning strikes or nitrogen-fixing bacteria. These bacteria are found primarily in root nodules of legumes.[2] Different bacteria in soil then convert ammonia to nitrates (NO_2- and NO_3-) which are consumed by plants. Crops such as corn are particularly nitrogen-sensitive and respond well to plentiful levels of nitrate in the soil. However, once nitrates are leeched from soils by crops, they must be replaced either through natural processes or the application of additional fertilizer. Since natural nitrogen-fixing is performed by bacteria, it follows that soils with healthy biologic ecosystems will be more effective at self-producing nitrogen.

The nitrogen cycle is a primary driver of several agricultural behaviors including fertilizer application and crop rotations. The more a farmer relies on natural sources of nitrogen (optimized crop rotations, etc.), the fewer additional inputs are necessary to maintain yields without taxing long-term soil health.

5.1.2 Carbon Cycle

The carbon cycle is a global-scale process by which carbon moves between soils, oceans, biomass, and the atmosphere. Much of the earth's carbon exists in "sinks" such as soil and the deep ocean, but incremental increases in atmospheric carbon are having significant impacts on planetary heat retention.

All plant matter acts as a carbon stock while it is alive, and this includes agricultural crops. However, when plant matter is burned, consumed, or otherwise decomposes, much of its carbon is released to the atmosphere. Over long periods of time, soils with high levels of organic matter can successfully incorporate that carbon into the long-term soil carbon stock, but this process takes decades or centuries rather than months or years.

An important distinction must be highlighted: land use practices that capture carbon in the short-term (growing forests, cover crops, etc.) will only have long-term soil capture impacts if such practices continue or are improved over time. Growing a forest for 20 years and then cutting it down to grow crops will only effectively capture carbon for the 20 years

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[2] A common misconception is that legumes (such as soy) are directly responsible for fixing nitrogen. This is not true. These plants merely provide the environment necessary for nitrogen-fixing bacteria to thrive.

the forest stands. This is not to say there are not benefits too the 20 years of storage; the impacts of atmospheric carbon likely increase nonlinearly with the stock of atmospheric carbon today. It may be optimal to adopt short-term carbon sequestration policies even if long-term carbon sequestration is not achieved. However, determining the "optimal" strategy depends on myriad additional factors beyond the scope of this report.

While the long-term net effect of soil health on total soil carbon stocks is uncertain, we do know that soil practices that support soil carbon, organic matter, and overall soil health will *at least weakly* increase long-term soil sequestration over practices that fail to build soil organic matter. The unanswered question is whether the societal net-present-benefits of carbon-sequestering practices outweigh the societal net-present-costs.

5.1.3 Pest and Weed Cycles

In modern agricultural systems, especially monoculture systems, pest and weed populations are important dynamic processes. Pests and weeds both require favorable conditions to thrive. Monoculture systems are particularly susceptible to pests and weeds since these systems provide large homogeneous environments with scant support for natural predators in the case of pests. Historically (over the past century or so, at least), the traditional way for farmers to prevent weeds was to till their fields before planting. While this is an effective strategy against weeds, it exacerbates erosion concerns. Cover crops are seen as one possible management strategy to address weed concerns without engaging in the same amount of tillage.

By multi-cropping, farmers limit the opportunities for pests or weeds to gain a foothold in an agricultural field. Similarly, by physically rotating the placements of different crops each year, farmers can prevent a second-generation pest population from emerging in a field with that pest's preferred environment. These sorts of agricultural management behaviors are a component of "integrated pest management" (IPM) and recognize the important dynamics of both pests and weeds.

5.2 Agricultural and Other Land Use Practices

Many agricultural and land use practices are inherently dynamic. In particular, crop rotations, tillage, and irrigation are all highly dependent on previous behavior. Agricultural dynamics can be directly related to the underlying natural dynamics addressed above. For instance, the reason crop rotations are so agronomically and economically relevant is mostly due to their effects on nitrogen and pest cycles.

In permanent agricultural systems, crop rotations are probably the single most important dynamic management decision a farmer faces. Rotating crops allows for natural replenishment of nutrients (especially nitrogen), reduces the opportunity for large-scale pest outbreak, and allows farm systems to benefit from biological diversity over time. In the United States, the most ubiquitous crop rotation is the corn-soy rotation in the Corn Belt where farmers grow corn and soy successively. These rotations are highly relevant to agronomic and economic outcomes. Livingston *et al.* (2015) illustrate this point particularly well for corn-soy rotations. They argue that a Corn Belt farmer who blindly follows the rule-of-thumb "corn-after-soy" will perform nearly as well as a farmer making "optimal" dynamic rotation decisions. The agronomic benefits of rotations almost always outweighs their opportunity costs.

Tillage is another dynamic management decision for farmers. Practices such as no-till or low-till increase soil organic matter and reduce erosion, but also can allow for increased weed growth and soil compaction. The academic and extension literatures highlight the wide heterogeneity of benefits and costs of different tillage practices across the country and world. In any optimized tillage practice, there is likely to be a multi-year strategy where a farmer tills more in some years than in others.

Finally, irrigation is yet another dynamic farming practice. While much of the United States is rain-fed, many areas rely on irrigation in agriculture. Recent advances in precision irrigation (such as the adoption of drip irrigation systems) have allowed farmers to use more water more effectively. The trade-off has been an increase in soil salinity since flood irrigation is often required to "flush out" salts from the soil. Also, in multi-year cycles of drought, management of irrigation water and soil moisture content is a long-term management problem rather than a current-growing-year problem.

6 An Analytic Framework

In section 7, I highlight an existing case study that applies a bioeconomic model to agricultural soil health. Before doing so, however, I build a more general structure into which the case study fits. In this section, I develop a general framework to analyze soil health through an economic lens. This framework is more technical than the material so far in this document, and may not be accessible to all audiences. However, this approach makes a meaningful step towards systematizing the economics of soil health in a well-defined model. The goal is for this framework to serve as a concrete starting point for future economic analyses and case studies of soil health issues.[3]

6.1 The General Model

In general, we can think of a farmer maximizing expected profits from a fixed area of land over some discounted time horizon. In particular, consider a discrete-time model where each year is indexed by t. Let $f(\cdot)$ represent a general agricultural yield function,[4] p represent output price, $\mathbf{v} = \{v_1, v_2, ..., v_i, ..., v_n\}$ represent an n-dimensional vector of variable inputs indexed by i, and $\mathbf{z} = \{z_1, z_2, ..., z_i, ..., z_n\}$ represent an n-dimensional vector of input prices also indexed by i. Next, let $\boldsymbol{\Theta} = \{\theta_1, \theta_2, ..., \theta_j, ..., \theta_m\}$ represent an m-dimensional vector of soil health characteristics indexed by j, $\mathbf{g}(\mathbf{v}, \boldsymbol{\Theta}) : \mathbb{R}^{n+m} \rightarrow \mathbb{R}^m$ represent a vector function for soil health transition, and δ represent the farmer's discount rate. Then, the infinite-horizon

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[3] The model developed here is a special case of a canonical class of economic models known as "optimal control" or "maximum principle" models. For reference on such models, please refer to Weitzman (2003).

[4] In this model, $f(\cdot)$ represents a yield function for some agronomic regime or rotation, rather than a yield function for a particular crop. This interpretation is appropriate for sufficiently diversified farms: farms with many independent fields cultivated over a sufficiently long time horizon.

farmer's problem can be expressed as:

$$\max_{\{\mathbf{v}_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \delta^{-t} \left[p_t f(\mathbf{v}_t, \boldsymbol{\Theta}_t) - \mathbf{z}_t \cdot \mathbf{v}_t\right]$$

$$\text{subject to} \quad \boldsymbol{\Theta}_{t+1} = \mathbf{g}(\mathbf{v}_t, \boldsymbol{\Theta}_t) \quad \forall t, \quad \boldsymbol{\Theta}_0 \text{ given}$$

We can write express this problem in Lagrangian form:[5]

$$\max_{\{\mathbf{v}_t, \boldsymbol{\Theta}_t, \boldsymbol{\mu}_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \delta^{-t} \left[p_t f(\mathbf{v}_t, \boldsymbol{\Theta}_t) - \mathbf{z}_t \cdot \mathbf{v}_t\right] + \sum_{t=0}^{\infty} \boldsymbol{\mu}_t \cdot \left[\mathbf{g}(\mathbf{v}_t, \boldsymbol{\Theta}_t) - \boldsymbol{\Theta}_{t+1}\right] \tag{1}$$

where $\boldsymbol{\mu} = \{\mu_1, \mu_2, ..., \mu_j, ..., \mu_m\}$ is an m-dimensional vector of Lagrange multipliers indexed by j. This gives us the following first-order conditions:

$$\delta^{-t} \left(p_t \frac{\partial f}{\partial v_{i,t}} - z_{i,t}\right) = -\boldsymbol{\mu}_t \cdot \frac{\partial \mathbf{g}}{\partial v_{i,t}} \quad \forall\ i, t \tag{2}$$

$$\delta^{-t} p_t \frac{\partial f}{\partial \theta_{j,t}} = \mu_{j,t-1} - \boldsymbol{\mu}_t \cdot \frac{\partial \mathbf{g}}{\partial \theta_{j,t}} \quad \forall\ j, t \tag{3}$$

$$\boldsymbol{\Theta}_{t+1} = \mathbf{g}(\mathbf{v}_t, \boldsymbol{\Theta}_t) \quad \forall\ t \tag{4}$$

This is the classic result for optimal management of a dynamic resource, in our case, soil health. This framework is quite flexible and allows for both computer simulation and steady-state analytical analysis under additional assumptions. However, the most important insight is that optimal behavior depends on $\frac{\partial f}{\partial \mathbf{v}}$, $\frac{\partial f}{\partial \boldsymbol{\Theta}}$, $\frac{\partial \mathbf{g}}{\partial \mathbf{v}}$, and $\frac{\partial \mathbf{g}}{\partial \boldsymbol{\Theta}}$: how the farmer's yield function changes with input use and soil health, and how the soil transition function changes with input use and soil health.

In the case of soil health, unlike in the classic optimal management problem, both $\boldsymbol{\Theta}$

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[5] Using a Lagrangian equation allows me to collapse a constrained maximization problem into an unconstrained maximization problem by including the Lagrangian multiplier terms $\boldsymbol{\mu}$ as choice variables. This allows me to take first-order conditions of the Lagrangian and derive optimality conditions for the constrained maximization problem in which I am interested. Additionally, the $\boldsymbol{\mu}$ terms have a meaningful economic interpretation: they represent the trade-off over time of soil quality today versus soil quality tomorrow. In the language of optimal control problems, $\boldsymbol{\mu}$ are "user costs."

itself and the above relationships $\left(\frac{\partial f}{\partial \mathbf{v}}, \frac{\partial f}{\partial \mathbf{\Theta}}, \frac{\partial \mathbf{g}}{\partial \mathbf{v}}, \text{ and } \frac{\partial \mathbf{g}}{\partial \mathbf{\Theta}}\right)$ are likely costly to observe. The interesting economic question then becomes determining the likely size of $\frac{\partial f}{\partial \mathbf{v}}$, $\frac{\partial f}{\partial \mathbf{\Theta}}$, $\frac{\partial \mathbf{g}}{\partial \mathbf{v}}$, and $\frac{\partial \mathbf{g}}{\partial \mathbf{\Theta}}$, as well as determining the costs of observing $\mathbf{\Theta}$.

As an example, consider a simple case where a farmer grows corn, the only input is nitrogen fertilizer, and the only component of soil health is soil organic matter. In the language of this model, $\frac{\partial f}{\partial \mathbf{v}}$ is how corn yields respond to increased levels of nitrogen fertilizer, $\frac{\partial f}{\partial \mathbf{\Theta}}$ is how corn yields respond to increased levels of soil organic matter, $\frac{\partial g}{\partial \mathbf{v}}$ is how soil organic matter tomorrow responds to nitrogen fertilizer use today, and $\frac{\partial g}{\partial \mathbf{\Theta}}$ is how soil organic matter tomorrow responds to the level of soil organic matter today. If we have credible analytic estimates of these four relationships, we can use data to determine the optimal management behavior a forward-looking farmer would employ.

Clearly, as the set of inputs $\mathbf{v}$ and soil health characteristics $\mathbf{\Theta}$ increase, the number of analytic relationships we need to estimate increase even more quickly. In many practical applications of this framework, researchers will be wise to focus on those inputs and soil health characteristics about which we have the most information.

6.2 Externalities

The framework developed above naturally focuses on the internalized benefits and costs of soil health management. However, soil health also has important external effects as well. To the extent that healthy soils increase biodiversity, prevent erosion, improve water quality, reduce flood risk, sequester carbon, and reduce pest and disease outbreaks, they provide public benefits not captured by a single farmer. In economics, we refer to such benefits as positive externalities. Under market failure, individuals will under-provide these benefits if they are unpriced. The three major traditional approaches to internalizing positive externalities are (1) Pigouvian subsidies, (2) quota-based policies (cap-and-trade), and (3) Coase theorem-inspired bargaining.

The most straightforward way for societies to internalize positive externalities is for society to subsidize them with a Pigouvian subsidy. Pigouvian taxes/subsidies are named for Arthur Pigou, an English economist who developed much of the theory around market externalities. In short, a Pigouvian tax would reflect the public cost of an action that is not otherwise internalized in market transactions. Conversely, a Pigouvian subsidy would compensate a private agent for public benefits provided by some behavior. In the case of soil health, a Pigouvian subsidy would entail the government paying farmers to engage in healthy soil management practices. However, this is easier said than done. According to theory, the size of the Pigouvian subsidy should be equal to only the benefits *not* captured by the private user. This number is difficult or impossible to estimate in the case of soil health. In practice, a Pigouvian subsidy that is too large will cost society more money than is needed to achieve the desired level of soil health. In other words, public funds can crowd-out privately optimal behavior.

Another way to internalize externalities is to institute some sort of cap-and-trade system. This approach is more naturally suited to managing negative externalities, and is probably not the most appropriate for soil health. However, we already observe carbon cap-and-trade programs affecting land use management as farmers are being compensated for practices that sequester carbon.

Finally, the Coase theorem (Coase, 1960) suggests that private bargaining can internalize externalities if property rights are well-defined and transaction costs are low. In the case of soil health, transaction costs are certainly not low, and a Pigouvian subsidy is likely a more realistic and effective approach for internalizing the externality.

7 Case Study

While the framework outlined in section 6 above has not recently been applied to a US agricultural system in any significant way, a similar framework has been successfully applied to an agricultural system in Kenya. Berazneva *et al.* (2014) estimate a bioeconomic model of agricultural productivity and soil carbon in a maize-based agricultural setting in the western Kenyan highlands. Their findings suggest that optimal management of both the agricultural system and soil carbon would lead to increased yields and increased levels of soil carbon in the long-run.

Berazneva *et al.* (2014) leverage an eight-year panel dataset from an agronomic experiment in the districts of Vihiga and Nandi in the western Kenyan highlands. They use these data to estimate yield and soil carbon functions that can explain how soil carbon, fertilizer use, and crop residues impact both corn yields and future levels of soil carbon. Next, the authors use data from household and market surveys to combine the econometrically estimated production function with the calibrated soil carbon flow equation in a maximum principle framework, similar to the one developed in section 6.

The authors find that farmers can achieve annual soil carbon sequestration rates of 630 and 117 kg/ha on depleted and medium-fertility soils, respectively. Notably, these results come only from *privately* optimal behavior. Sequestration rates would be even higher if farmers could receive Pigouvian subsidies to internalize positive externalities of carbon sequestration.

In the simple model presented by Berazneva *et al.* (2014), farmers have two decision variables: the amount of fertilizer to apply in any given year and the proportion of crop residues to leave in the field after harvest. The authors note that as population density in the western Kenyan highlands has increased over the past century, most farmers have stopped planting trees for wood fuel and instead have turned to cereal residues as the primary on-farm source of fuel. However, leaving crop residues in the field is one of the best ways to build soil carbon levels. Thus, there is an economic tension for farmers between investing in their soil's health and procuring fuel for their household needs.

One relative weakness of the Berazneva *et al.* (2014) study is that it does not incorporate crop rotations or manure applications into its model. The authors note that legume intercropping and animal manure amendments are characteristic of the region, and likely are important in many applied circumstances. This highlights the difficulty of using maximum-control-style models: large amounts of data and computing resources are required to produce statistically robust results. There is a practical tradeoff between realism and tractability.

One important finding of the Berazneva *et al.* (2014) study is that in their "steady state" model solution, farmers have a *private* value of soil carbon near \$120 per Mg, or \$33 per Mg of CO_2. This value is markedly higher than most existing national and sub-national carbon pricing instruments, indicating that farmers probably have a higher private valuation of soil carbon than do existing carbon markets. However, these valuation estimates are in the same ballpark as global shadow-costs of carbon, suggesting that positive externalities of soil carbon sequestration may be small.

While Berazneva *et al.* (2014) provide an excellent case study of how one can apply a model such as the one outlined in section 6 to a real-world context, the Kenyan context is substantially different from the American context. In the Berazneva *et al.* (2014) paper, farm size averages 0.5-2 hectares. Additionally, the only component of soil health analyzed is soil carbon. In an American context, farms are much larger, and soil management techniques are more varied. The average American Corn Belt farmer makes regular use of mechanization, fertilizer, crop rotations, and other practices to maximize profits.

The universe of challenges and opportunities for policy in the United States is significantly different than in Kenya. However, several themes are likely shared. In the case of the Kenyan highlands, it seems the primary barriers to optimal agricultural management are knowledge and credit constraints. In the US context, access to credit is likely less of a burden, but knowledge of how soil health characteristics evolve over time and feed back into productivity may be a constraint.

8 Existing Soil Health Policy

Currently, the primary policies concerning soil health are conservation practices promoted by the Natural Resources Conservation Service (NRCS) of the US Department of Agriculture (USDA). These practices involve things like crop rotations, cover cropping, nutrient management, and residue and tillage management; practices that each address different components of soil health as outlined in figure 1. Farmers can receive cost-sharing from the government (essentially a discount) to implement these practices on their farms.

In the context of soil health, an excellent resource on existing federal policy is the 2001 "Guidelines for Soil Quality Assessment in Conservation Planning" guide (Friedman *et al.*, 2001). The table beginning on page 30 of the guide, titled "Suggested Management Solutions to Soil Quality Problems" outlines which NRCS practices can be applied to which soil health challenges.

One concern about the NRCS conservation practices is that they likely crowd-out private conservation. In other words, many farmers who engage in soil health practices would likely continue doing so (to a greater or lesser extent) even if the NRCS were not paying them to do so. If this is true, it means that the government is paying not to internalize an externality, but simply to support farmers. From a public finance perspective, this is inefficient.

Another concern about the NRCS conservation practices is that they are often not fine-tuned to a farmer's particular situation. Payments for conservation practices generally do not change depending on the farmer's location or surroundings, even though the public benefits of conservation vary widely across different locations. For instance, adopting integrated pest management on a farm surrounded mostly by prairie or forest provides fewer public benefits than adopting integrated pest management on a farm in the midst of widespread monoculture row-crops.

In addition to NRCS policies, soil health is also impacted by market-based carbon sequestration policies such as the Regional Greenhouse Gas Initiative (RGGI) and the cap-and-trade program in California. Under such policies, farmers are seeking payments for adopting carbon-sequestering behaviors, including the forestation of their land. Haim *et al.* (2015) explore how these policies are affecting agricultural land use and soil carbon levels. They point out that regional carbon policies have often lead to "leakage," where the conservation of carbon in one location is replaced by more carbon-intensive activities in other locations. This highlights the importance of a policy that operates at the same level as the problem it aims to solve. For a global pollutant like carbon, a global policy is the least distortionary. For an excellent recent review of current policies and challenges around soil carbon sequestration in agriculture, I encourage readers to consult Murray (2015).

As soil carbon has become a more and more important component of the global carbon conversation, a new set of tools and resources has emerged to quantify the potential role of soils in carbon sequestration. For instance, the COMET-Farm tool – a new assessment produced by NRCS, USDA, and Colorado State University – allows farmers and ranchers to estimate their entire operation's "carbon footprint" under different management scenarios. A particular benefit of COMET-Farm is that it leverages spatially specific data on soil type and climate patterns to provide spatially differentiated predictions.

9 Current Policy Challenges and Opportunities

Where soil health is concerned, there are several current policy challenges and opportunities. A particularly persistent question for policymakers is: what drives producers' decisions to adopt more sustainable soil management practices? There are two broad ways to approach this question. The first, which I have developed in this current project, is to approach behavior adoption from an economic perspective. This approach focuses on the external conditions for agricultural production rather than individual producer attributes. In this view, behavior adoption does not depend on the specific farmer and her individual perceptions. A classic example of this sort of approach is Caswell & Zilberman (1986). The second way to approach the question of adoption is to explore individual producers' stated reasons for choosing to adopt or not to adopt new practices. While this approach is less generalizable from a theoretical perspective, it may offer helpful insights into the practical implementation of policy. Numerous studies have highlighted how less-educated, less professionally-connected, and less-experienced producers are less likely to adopt soil-conserving production practices (Knowler & Bradshaw, 2007; Traoré *et al.*, 1998; Rahm & Huffman, 1984). Furthermore, there are some behavioral and practical considerations that disseminators of information should keep in mind (Brant, 2003). The broad conclusions of this strand of literature are that in order to adopt soil-conserving practices, producers must (1) perceive negative outcomes from soil degradation, (2) trust their sources of technical information, (3) not face prohibitive costs or lost profits from implementing new practices, and (4) believe that the new practices will produce some meaningful economic, environmental, or human health benefit.

The single largest challenge to effective soil health policy is the lack of data explaining how soil health indicators, agricultural practices, and agricultural production all affect each other over time in all the myriad settings across the United States. Without clear and accessible data or expensive private solutions (such as "precision" nutrient management techniques), farmers and policymakers both are left relying on heuristics, best-guesses, and rules-of-thumb. There is thus a compelling case to be made that the NRCS and US government more broadly should encourage and fund public research exploring the interconnections between soil health and agricultural productivity. Farmers need analytic models that allow them to use data effectively. Without well-established and understood ecological and agronomic relationships, increased access to soil health data is unhelpful. Put another way, public research should be pursued with the explicit goal of implementation. Because of this, I suggest university extension services are the most appropriate venue for further research in this vein.

One opportunity for soil health policy is a revision of existing NRCS payments to account more explicitly for producer heterogeneity. NRCS payments are the closest thing to a Pigouvian subsidy in soil health, and they should better reflect the *public* benefits provided by healthy soils. These benefits will vary across space and situations. Also, existing payments likely crowd-out private conservation behavior.

Another opportunity for soil health policy is a subsidy for agricultural renters to enact soil health production practices. In a situation where a farmer owns her own land, the maximization problem outlined in section 6 is appropriate. However, a renter does not directly benefit from leaving a farm with healthy soils, and may not internalize the full dynamic benefits of maintaining healthy soils. There is an open question to whether this market failure requires public intervention or whether it ought to be resolved privately between the landowner and the renter. If salience of information is a large problem, public intervention may be justified.

One interesting idea has been advocated by the Natural Resources Defense Council (NRDC). O'Connor (2013) suggests that farmers who adopt soil conservation practices face lower premium rates for federal crop insurance. This proposal would encourage farmers to create more ecologically resilient farms that are less susceptible to systematic losses, thus aligning incentives. This is an intriguing proposal and worth considering. However, crop insurance is already a highly distorting policy that is used more as a subsidy to the agricultural sector than as an actuarily fair risk management strategy. *Ceteris paribus*, insurance encourages riskier behavior, and deviations from a second-best policy frequently result in unintended consequences.

In my view, the most basic opportunity for soil health policy is one that incentivizes farmers to learn about (1) how soil health dynamics affect production dynamics and vice-versa, and (2) the values of their own soil health indicators. For many farmers, I hypothesize that search costs are perceived to be too high to incorporate holistic and multidimensional soil health information into their annual production decisions. I gather that many farmers' response to soil health issues is practiced on a year-to-year basis rather than in a long-term dynamic framework: what is the proximate limiting factor to production? What is the immediate method to address that limiting factor? The government may have a role in providing farmers with the low-cost information necessary for them to successfully internalize their own dynamic benefits of managing soil health. Perhaps there is room for a free or highly-subsidized soil testing service from NRCS field agents. Or perhaps a more systematic and subsidized soil testing program run through state extension services. Farmers, just like any other producers, face meaningful trade-offs between the short-term and the long-term. To the extent that public policy can empower farmers to accurately quantify the long-term effects of their soil management decisions, the more optimal will be farmers' behavior.

While there is certainly room for policy to address the soil health issue, I am also skeptical that the economic social optimum is drastically different from what we observe currently. The main benefits of healthy soils are almost certainly internal: farmers likely directly benefit from healthy soils more than society does. And large farmers especially have much to gain from small improvements in farm-wide productivity. I suspect that in many cases, the failure to adopt soil conservation practices is more or less an intentional decision where the farmer's discount rate is sufficiently high to value short-term benefits over long-term benefits. Under traditional economic welfare analysis, this is only a problem if "society" has a lower discount rate than the farmers. Whether or not this is the case is too broad a question for the current project. However, I refer readers to Gardner & Barrows (1985) for an excellent treatment of this question in relation to soil conservation.

10 Future Research Needs

Future research into soil health should fall into two broad categories: scientific and economic. On the scientific front, we need to know more about how different soil health indicators, production practices, agricultural inputs, and production yields affect each other over time. These relationships certainly vary depending on location, soil type, crop type, and climate. Thus a completely different set of studies is needed to understand the US Corn Belt than is needed to understand the southern Mississippi basin, for example. While the numbers we want to know vary with space and setting, a broad framework (see section 6) can be applied to each of these settings.

On the economic front, we need better estimates of farmers' real and perceived search costs for soil health information. Is knowledge really a limiting factor to farmers making optimal decisions, or are farmers appropriately optimizing their (private) behavior already? Also, further work on studying how public subsidies crowd out private conservation behaviors continues to be useful.

Lastly, there may be important scale relationships among the public benefits of soil health. Consider, for instance, erosion. Suppose all farms in county A operate with frequent tillage and high rates of erosion. Now suppose half of the farms in county B engage in no- or low-till farming. The effect of one farmer adopting no-till practices will probably have much higher public benefits in county B than in county A due to scale effects and complementarities over physical space. This is an important component of soil health conservation behaviors, and one that has been relatively unexplored in much of the current public discussion on the issue.

11 Conclusion

In this report, I have proposed and developed an analytic framework for studying the economics of soil health. Such a holistic perspective is a useful tool for analyzing soil health policies, and I highlight a case study (Berazneva *et al.*, 2014) that demonstrates its usefulness in specific settings. To the extent that there remain market failures in soil health, either through high search costs, positive externalities, or owner/renter misalignments in incentive, there is a role for public policy. Policy should focus on making information about a farmer's own soil's health and its dynamic effects on production cheap and easily accessible. Policy should also focus on subsidizing the external benefits of soil health while attempting to avoid crowding out private conservation behavior.

Behaviors that support long-term soil health contribute to sequestering atmospheric carbon, and have a role to play in climate policy. However, permanent carbon sequestration is only achievable with permanent changes to soil management or land use. Short-term policies aimed at carbon sequestration will only have short-term climate benefits.

It remains an open question how far the soil health *status quo* is from an economic social optimum. If farmers are in fact internalizing many of the potential benefits of soil health, their behavior suggests a high discount rate on the future. If this is the case, and farmers' discount rates do not systematically differ from society's discount rate, then the current state of soil health may be very close to an economic equilibrium and our world will see a greater reduction in soil resources and soil health before a meaningful transition to ecological sustainability. On the other hand, if market failures are large enough, or if society's discount rate is small enough, public policy could make a meaningful impact on farmer behavior and the evolution of our soil resources.

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