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Theme Overview: Soil Health Policy in the United States and Abroad

Andrew W. Stevens

JEL Classifications: *O13, Q15, Q18, Q28*

Keywords: *Agriculture, Development, Policy, Developing countries, Soil health, United States*

Recently, farmers, ranchers, environmentalists, researchers, and policy makers have become increasingly concerned with soil health. Recognizing this interest, the Food and Agriculture Organization of the United Nations named 2015 the "International Year of Soils." Since then, according to Google Trends data, interest in soil health has roughly doubled in the United States and roughly tripled worldwide (Google Trends, 2019). As researchers and stakeholders, we are deepening our understanding of how soil health—broadly defined—is intertwined with agriculture, the environment, and human wellbeing. Perhaps equally as important, we are also deepening our understanding of how human activity affects the health of our soils.

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Julia Berazneva and David Güereña

This *Choices* theme tackles the issue of soil health from a number of angles, with an eye toward informing future research and public policy. For producers, soil scientists, environmentalists, and policy makers, these articles are intended as an accessible introduction to how economists think about soils. For economists, these articles are intended as an introduction to the existing literature with an emphasis on soil complexity. Our hope is that these articles prompt further research and interdisciplinary collaboration as well as evidence-based policy making in years to come.

In the first article, Stevens takes a broad, theoretical approach to modeling the economics of soil health. He emphasizes that soils are multidimensional and dynamic, necessitating a model that captures both elements. His proposal: a model of optimal control. After discussing the various components of such an approach, Stevens highlights the policy implications of thinking of soil as a dynamic resource. Specifically, he notes that soil policy can reduce information frictions by helping farmers learn about their soils' health and better understand how today's production practices will affect soil health tomorrow.

In the second article, Bowman and Lynch take a closer look at federal- and state-level soil health policies in the United States. Using Maryland's cover crop program as a case study, the authors discuss the specific opportunities and challenges of implementing these policies. In practice, because policy makers are unable to easily measure the health of individual soils, policies are often organized around specific production practices. This approach raises concerns about cost-effectiveness and targeting. Bowman and Lynch provide useful insights for navigating such concerns in program design and implementation.

In the third article, Kim and Bevis shift the focus to soil health in developing countries, where the agricultural, economic, and policy landscape is starkly different than that in the United States. Drawing on recent research, the authors draw convincing and significant connections between soil health and human welfare in countries where households' wellbeing is more closely tied to agricultural production. Encouragingly, there is increasing evidence that policies targeting soils in poor countries can have meaningful impacts on poverty and health.

In the fourth article, Berazneva and Güereña use several case studies from Kenya and Nepal to inform future soil health policies in the context of poor countries. Similar to Bowman and Lynch, the authors note that the devil is in the details. They write, "The technologies needed to create healthy, resilient soil systems were developed decades or millennia ago. What has proven more difficult is delivering proven soil health solutions to the last mile, at scale." Berazneva and Güereña provide readers a list of lessons from past soil health projects that will be valuable to researchers and policy makers alike.

For More Information

Google Trends, 2019. Accessed June 28, 2019. https://www.google.com/trends.

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Economic Theory Provides Insights for Soil Health Policy

Andrew W. Stevens

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Keywords: Agricultural productivity, Land management, Soil health

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.

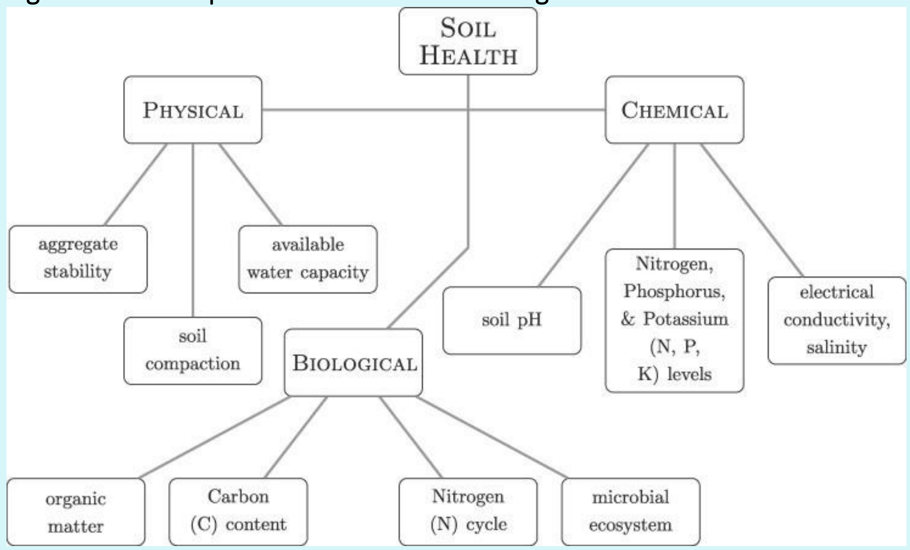
To design effective and efficient soil health policies, stakeholders need to share (i) a common definition of soil health, (ii) an appreciation of the benefits of healthy soils, and (iii) an integrated model of how physical, chemical, biological, and economic processes relate to one another over time. 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 (2019).

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 (2019).

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.

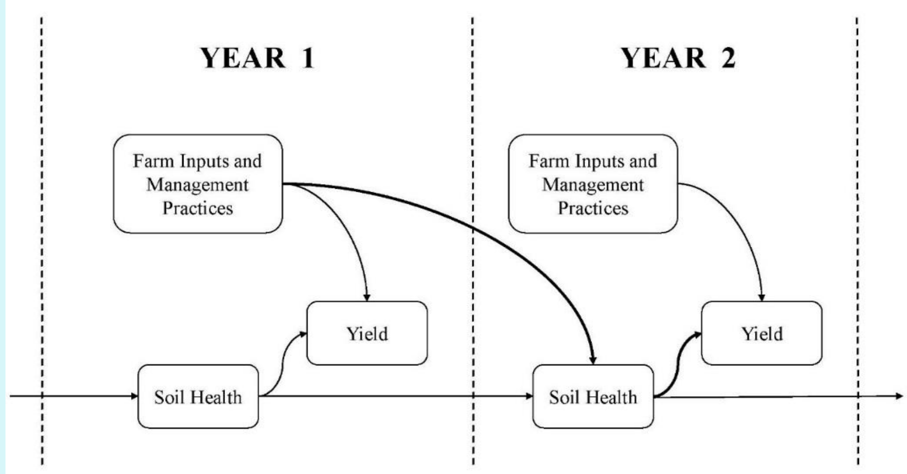
A Dynamic Model of Soil Health

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 (2019). 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 (2019)—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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Soil Fertility and Poverty in Developing Countries

Kichan Kim and Leah Bevis

JEL Classifications: I15, O13, Q10
Keywords: Human-environment, mineral deficiency

In poor, semi-subsistence agricultural settings, soil fertility is a critical input to agricultural production and therefore to human welfare. The importance of soil health is magnified in such settings because poor farming families use fewer agricultural inputs than do farmers in wealthy countries; they also face higher levels of risk and have fewer financial tools to smooth away the impact of a bad year. For instance, while almost 100% of U.S. farmland devoted to corn receives inorganic fertilizer (USDA, 2018), only about a third of sub-Saharan African farmers appear to apply inorganic fertilizer, and those that apply nutrients do so at much lower levels than do American farmers (Sheahan and Barrett, 2017). Input rates tend to be higher in South Asia than in sub-Saharan Africa, but risk is still high; only 4% of Indian households are covered by crop insurance (Rajeev et al., 2016) versus 86% in the United States (Isabel, 2018). The implications of crop failure are so dire that unexpectedly high temperatures drive suicides in rural India (Carleton, 2017). African farmers are similarly at the mercy of rainfall and temperature patterns; less than 2% of farms are irrigated in most African countries (Sheahan and Barrett, 2017). Malagasy farmers in Madagascar are vulnerable to recursive pests and diseases due to the insufficient resources for risk-coping (Harvey et al., 2014).

The low-input nature of agriculture in developing nations, combined with the fact that crops are grown for household food consumption as well as for income, results in multiple connections between soil fertility and poverty (Barrett and Bevis, 2015). At the most basic level, soil fertility predicts crop yields and hence impacts food supply and health (Sánchez and Swaminathan, 2005; Tittonell and Giller, 2013; Regmi et al., 2002, Bhandari et al., 2002). Yield-increasing inputs such as inorganic fertilizer or improved varieties are often more effective on better-quality soils (Marenya and Barrett, 2009a,b; Sánchez, 2010). Higher fertility soil also grows food with higher nutrient content in many contexts, linking the health of the land to the health of the families that work that land (Shivay, Kumar, and Prasad, 2008; Shivay et al., 2008). Their health, in turn, affects their ability to labor effectively, to grow crops, and to invest back into their soils, entangling cause and effect over decades or even generations (Bevis, Kim, and Guerena, 2019). And the productivity of land invites infrastructure such as irrigation, markets, and government-built roads (Pender and Hazell, 2000), all of which bring agricultural inputs and advancements, feeding back to impact crop production and soils and poverty through the slow, recursive process of development.

Increasingly, governments and policy makers recognize the importance of soil fertility for economic development. Meanwhile, scientists have begun to speak about soil fertility as a natural resource at risk of depletion. In 2006, 40 African heads of states attended a fertilizer summit in Nigeria to address the role of soil fertility and improved access to fertilizers in addressing yield gaps and food insecurity in Africa. The United Nations launched the Global Soil Partnership in 2012, bringing together a wide range of government and nongovernment organizations, universities, research institutes, companies, farmer associations, donors, and other stakeholders to research and promote the sustainable management of soils, globally. Shortly after, then–Secretary General Ban Ki-moon of the United Nations declared 2015 the International Year of Soils, stating, “A healthy life is not possible without healthy soils.”

We discuss the three main connections between “healthy soils” and human welfare and poverty in poor countries, informed by a long history of work by economists, soil scientists, nutrition scientists, and other researchers. We base this article, intended for a U.S. audience, primarily on Barrett and Bevis (2015), though new points and new evidence are added.

Agricultural Productivity

Soil fertility is particularly important to crop production in poor countries because of access to other inputs such as fertilizer, herbicides, pesticides, or high-yielding crop varieties, is generally lower in poor countries than in rich countries (Sheahan and Barrett, 2017, Chapagain and Raizada, 2017). Arguably therefore, the three most important agricultural inputs in poor, agricultural contexts are human labor, soil fertility, and weather (rainfall and temperature) because all three of these inputs exist on every farm. In fact, many experts regard soil fertility, or lack thereof, as the primary constraint to crop yields in Africa, limiting the ability of improved varieties to boost yields as they did in South and East Asia during the Green Revolution (Sánchez and Swaminathan, 2005; Lal, 2006; Sánchez, 2010).

Of course, soil fertility is a multidimensional concept, encompassing chemical and physical properties as well as biological properties. All of these properties are tied to crop yields and hence to food security and agricultural income in poor countries. For instance, Lal (2006) calculates that increasing soil organic carbon pool by 1 Mg ha^{-1} y^{-1} can increase food grain production by 32 million Mg y^{-1} in developing countries. Crop yields respond to the application of nitrogen, phosphorus, and potassium via fertilizers in most developing countries, though in African countries where fertilizer prices are high, this may not always translate to increased profits (Morris et al., 2007). Soil acidity constraints smallholder yields in many contexts; liming or other practices that increase soil pH will boost yields in these locations (Bationo et al., 2006). Increasingly, many of these soil characteristics, as well as crop yields themselves, are measured using remote sensing source and machine learning (Lobell et al., 2003; Hengl et al., 2017; Bevis, Kim, and Guerena, 2019).

While poor soil fertility is commonly cited as the primary constraint to crop yields in Africa (Sánchez and Swaminathan, 2005; Sánchez 2010), evidence suggests that limited soil nutrients impede yields across the globe (Tan, Lal, and Wiebe, 2005). For instance, yield declines in the Indo-Gangetic Plain seem to track declines in macronutrient availability, declines in soil organic matter, and a degradation of physical soil structure (Regmi et al., 2002; Bhandari et al., 2002; Kataki, Hobbs, and Adhikary, 2001).

Trace minerals concentration also limits crop yields, though less research has been done on this topic due to the expense of testing. For instance, soil zinc concentration is well known to limit rice and wheat yields in much of South Asia, particularly in the Indo-Gangetic Plains, which arguably hold the greatest number of poor smallholder farmers in the world. Similarly, the One Acre Fund (the largest agricultural extension organization in Africa) has found deficiencies in zinc, boron, and manganese throughout East Africa. They also found that boosting the available soil concentration of these minerals with enriched fertilizers increased yields and profits.

Soil fertility is not only a direct input to crop production; it also impacts the effectiveness of other inputs. For instance, fertilizers are less effective in boosting yields on soil with low organic matter or nutrient concentration (Zingore et al., 2008). This was observed in Kenya, where fertilizer was more likely to be effective and profitable on farms with higher soil organic matter (Marenya and Barrett, 2009a,b). In Malaysia, the uptake of nitrogen and phosphorus from fertilizers is impeded on acidic soils (Kasim et al., 2011). Similarly, N-fixing leguminous trees in Kenya only seem profitable if used in conjunction with P fertilizer (Jama et al., 1998). Manure seems more effective and more profitable on higher-fertility plots in Zimbabwe (Rowe et al., 2006). Farmers, knowing that soil fertility impedes the effectiveness of inputs, may be less likely to invest in agricultural inputs, or even less likely to invest in soil fertility itself through time-intensive management practices on-farm or plots that they perceive as too degraded to be remediable (Barrett and Bevis, 2015).

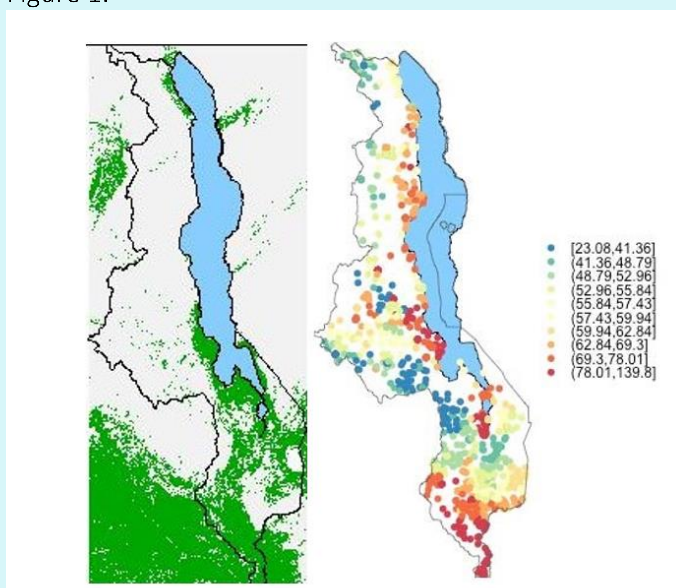
Mineral Deficiencies in Soils, Crops, and Humans

Soil mineral concentration is important not only for crop yields, but also for the mineral concentration of the edible portion of crops (Allaway, 1986). For instance, zinc deficiency in soils, which is the most common soil mineral deficiency worldwide, decreases the zinc concentration of grains, legumes, and even animals grown on the soil (Alloway, 2008). Soil deficiencies in selenium, iodine, and other trace minerals impact crops similarly (Bevis, 2015).

Because semi-subsistent farming households generally consume little meat and rely heavily on locally grown crops for consumption, the mineral concentration of local crops is critical for dietary mineral intake and human mineral status (Bevis, 2015). This directly links the “health” of the soils to the “health” of the people living on them. For instance, Bevis and Kim (2019) find that in Nepal’s flat Terai region on the border of India, children living on lower-zinc soils are more likely to be stunted (too short for their age) than children living on higher-zinc soils. This linkage is not explained by family income or other factors related to health, and other forms of child illness—for instance, being low-weight or deficient in other minerals and vitamins—are not predicted by soil zinc concentration. Stunting is the primary symptom of zinc deficiency, and Bevis and Kim, therefore, conclude that soil zinc deficiency is likely to drive human zinc deficiency in this area through its impact on crop zinc concentration. In Ethiopia, a similar connection has been found between soil zinc deficiency and human zinc deficiency, where the latter was measured in country-wide blood samples (Tessema et al., 2019). A different study in Ethiopia found that soil organic matter influenced the zinc status of crops, though the implications for humans were not directly examined (Wood et al., 2018). Using data from across Africa, Berkhout, Malan, and Kram (2019) find that available concentrations of zinc, coper, and manganese in soils are negatively related to child morbidity, child wasting, and child stunting.

Many other examples exist of such soil-to-human mineral connections. Hurst et al. (2013) and a working paper by Bevis, Kim and Guerena (2019) show that Malawian children are more likely to have adequate selenium status on southern, calcareous soils, which are rich in available selenium and known to grow high-selenium crops (Joy et al., 2015). They are also more likely to have adequate selenium status near the lake, due to fish consumption. Figure 1 illustrates these patterns. The children most at risk of selenium deficiency are those on noncalcareous soils, far from the lake. Severe selenium deficiency can cause Keshan disease, a reversible but potentially deadly heart condition most often found in children. Keshan disease has been found exclusively in soil-selenium-deficient areas of rural China. However, a similar disease, peripartum cardiomyopathy—also attributed to selenium deficiency—has been found in Sahelian Africa, where soil selenium is also thought to be low.

Figure 1.



Notes: To the left is a map predicting calcareous soils (green) versus noncalcareous soils (gray). This prediction is a function of soil zinc, calcium, and pH. To the right is a map of human selenium status, smoothed across space.

Of course, even without this particular connection between soil mineral concentration, crop mineral concentration, and human health, soil fertility may influence human nutritional status through its impact on food supply and dietary diversity. In poor, agricultural contexts, where people rely heavily on their own, home-grown crops for food, the quantity and diversity of crops produced heavily influence the quantity and diversity of food consumed. Higher-fertility soils are therefore likely to increase calorie intake, consumption diversity, and nutrient intake purely through making it easier to grow a variety of foods. The linkage between soil mineral concentration and human mineral status is not necessarily more important, but it is different in that it is not easily observable. Because crop mineral concentration is rarely known, this connection may lead to widespread mineral malnutrition over many generations of poor farmers in particular geographic locations, unknown to any authority or to the farmers themselves.

Long-Term Connections between Soils and Development

Soil fertility may influence economic success and long-term economic development in a few ways, all of which are difficult to observe because they take place over the span of years or decades. In fact, if human health influences economic success and development, then the connection between soil mineral concentration and human mineral status is one example of these long-term connections.

Additionally, a small body of work suggests that farmers are more susceptible and/or less resilient to climate shocks, pest shock, or other negative agricultural events when they are farming on high-fertility soil (Bevis and Barrett, 2015). For instance, crops grown on soils with better water-holding capacity may be less damaged by periods of low rainfall. Degraded cropland also seems to be more susceptible to weeds of the *Striga* genus, which infest around 50 million hectares of farmland in sub-Saharan Africa, causing $300 million of loss every year. A few papers have found that cereals are more susceptible to aflatoxin contamination when they are grown on low-fertility soils. Aflatoxin, a poisonous carcinogen caused by mold, kills a handful of people every year in many African countries and may have more far-reaching, low-level but deleterious effects on child growth and child illness in many African countries. All of these susceptibilities may make communities on low-fertility soils less economically successful over long periods of time.

Fertile soils and productive agriculture may also attract government and private investment in terms of irrigation, roads, and support for markets. High-fertility areas that successfully produce food or cash crops will naturally receive outside investment from stakeholders hoping to profit in some way from the local agriculture. While this may not always bring wealth directly to farmers, in many cases it will.

Conversely, lower-fertility soils often support initially lower-density human settlements, which eventually makes it more expensive for governments to provide supporting infrastructure in the form of roads, electricity, and telecommunications (Bevis and Barrett, 2015). Many pastoral or partly pastoral areas in eastern and western Africa exemplify this historical pattern. A lack of infrastructure will later make it difficult for the farmers who do live in these areas to obtain agricultural inputs like fertilizer or to obtain information on improved farming practices spread by nonprofits, government extension agencies, or even radio. More generally, disconnection from the rest of the country will keep these communities less educated, less healthy, and poorer than the norm.

In some cases, however, land abundance or soil fertility might have the reverse effect on long-term infrastructure and development. While the fertile Indo-Gangetic Plain has long served as a breadbasket for South Asia, during the Green Revolution, farmers in this area specialized in rice and wheat crops rather than higher-production cash crops. This northern area of India has stayed relatively poor since then, an effect that might be hypothesized as a "resource curse." Fernando (2015) explores a similar connection on a micro-scale in India, showing that land inheritance reduces the likelihood migration to an urban area. If such migration leads to improved occupational trajectories, land inheritance might characterize an individual-level resource course.

Policies and Lessons

How can we help poor, smallholder farmers break out of a cycle of stagnant yields and poverty? Nobel-prize-winning economist Theodore Schultz said in 1980,

> Most of the people in the world are poor, so if we knew the economics of being poor we would know much of the economics that really matters. Most of the world's poor people earn their living from agriculture, so if we knew the economics of agriculture we would know much of the economics of being poor (Shultz, 1980; p. 639).

We would add that to better understand the linked economics of agriculture and poverty in developing countries, we must better understand the influence of soil fertility.

Luckily, we have some policy successes to lean on. Improvements in access to fertilizer seem to boost yields and farmer welfare. For instance, government fertilizer subsidies in Malawi doubled or tripled maize yields, resulting in a surplus of maize that could be sold in neighboring countries and causing maize prices to lower country-wide, which likely increased food consumption for rural and urban families alike (Denning et al., 2009). The One Acre Fund has increased farmer income in many African countries by 50%, on average, through a combination of farmer training and providing fertilizer and improved crop varieties.

However, experiments by One Acre Fund also suggest that trace mineral constraints impede yields, and mineral-enriched fertilizer is almost nonexistent in Africa. It is also rare in other poor contexts such as South Asia. This is a shame and may change as new research points to the importance of trace minerals for both crop yields and crop nutrient concentration.

A few interventions have successfully increased human mineral status through targeting the soils (Bevis, 2015). The Finnish government mandated selenium enrichment of fertilizers in the 1980s, after it was realized that the Finnish population was dangerously low in selenium status. This policy resulted in increased selenium concentration in soils, crops, and humans and may have improved human health, though no rigorous evaluation of health impact was possible. In the Xingjiang province of China, where humans were highly iodine deficient, iodine was added to soils and crops through irrigation water. Subsequent sampling found that iodine concentrations in soils, crops, animals and animal meat rose. Human iodine status also rose, and infant mortality rates declined.

More work is needed to understand how soil fertility influences yields, profits, health, and human welfare in poor countries. And some of the lessons learned will surely carry back to the United States, too. For instance, crop nutrient concentration varies within rich countries as well as poor, partly because of soil nutrient availability but also for other reasons. Crop nutrient concentrations seem to have declined in the United States and in the United Kingdom over the last 100 years; this apparent decline has been attributed to both soil mineral depletion and low-nutrient hybrids, though some scientist chalk it up to measurement error (Marles, 2017). We also know that rising CO_2 levels are decreasing zinc, iron, and protein concentrations in a range of cereals crops, threatening to increase global malnutrition rates as climate change continues (Smither and Myers, 2018). A better understanding of the interconnections between soil health, crop health, and human health may help all of us.

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Government Programs that Support Farmer Adoption of Soil Health Practices: A Focus on Maryland's Agricultural Water Quality Cost-Share Program

Maria Bowman and Lori Lynch

JEL Classifications: Q15, Q18
Keywords: Cover crops, CSP, EQIP, Maryland Agricultural Water Quality Cost-Share Program, Soil health

Between the 2012 and the 2017 agricultural censuses, United States farmers increased their use of no-tillage and cover crops on cropland. In 2012, approximately 34.6% of cropland was no-till, and just over 3% of harvested cropland was cover-cropped. By 2017, no-tilled acres represented 37% of cropland, and cover-cropped acreage grew by more than 50%, to 4.8% of harvested cropland (USDA, 2019). Although rates of adoption vary regionally due to soil types, cropping systems, and other economic factors (see Wade, Claassen, and Wallander, 2015; Claassen et al., 2018), these national trends reflect the growing importance of soil health among farmers and in the public policy space. This emphasis stems from the potential of soil health systems to benefit farmers and society, which is discussed in the first article of this theme (Stevens, 2019).

Investing in soil health practices and systems may benefit farmers directly if the private benefits (increased profits, ecosystem services) are greater than the cost of implementation. This growth in soil health practice adoption is fueled, in part, by a number of U.S. federal and state programs that provide financial or technical assistance to farmers to adopt soil health practices that they would not have adopted otherwise because the benefits do not exceed the costs. In part, farmers make this calculation because soil health benefits may accrue slowly over time, making a management change may have high upfront investments and learning costs as a farmer experiments with a practice, and other transaction costs seem high (Bowman, Wallander, and Lynch, 2016; Palm-Forster et al., 2016). Providing financial and technical assistance is one way to overcome these barriers to adoption. Yet is paying for soil health practices an effective policy approach to make farmers more economically sustainable, while providing ecosystem services that benefit society? How important is financial assistance relative to technical assistance in overcoming barriers to adoption? Because many programs' impacts are not well measured, policy makers have a difficult time evaluating the cost-effectiveness of these incentive programs.

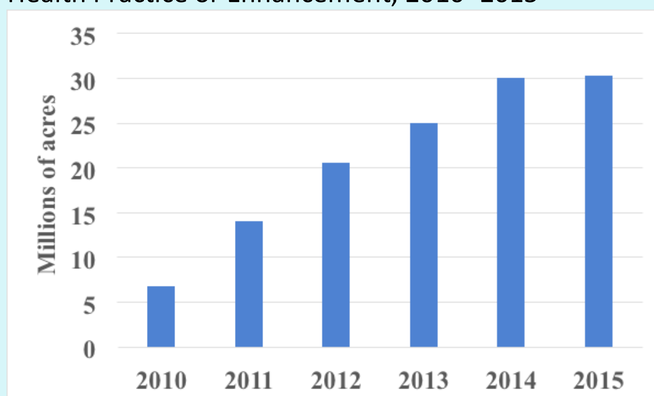
In this article, we summarize the form and scope of federal- and state-level initiatives that provide incentives to farmers to adopt soil health practices in the United States. We also focus a portion of our discussion on the State of Maryland's cover crop program to illustrate the strengths, limitations, and challenges of implementing such programs. Our hope is to raise key issues and motivate future research that will inform the design of future programs that pay for soil-health-related practices.

Federal Programs that Support Adoption of Soil Health Practices

Two primary working lands conservation programs in the United States provide incentive payments to farmers to implement soil health practices, and both are implemented by the USDA's Natural Resources Conservation Service (NRCS). The Environmental Quality Incentives Program (EQIP) provides financial assistance to farmers to implement conservation practices not already adopted on the acreage being enrolled in the program. EQIP practices include a number of soil-health-related practices such as no-tillage, prescribed grazing, and cover crops. Two of the most common soil health practices receiving payments through EQIP are no-tillage and cover crops, but the relative emphasis on these two practices has changed over time. Between 2005 and 2016, annual funding for cover crops through EQIP increased from about $5 million to more than $90 million in nominal terms, and the number of acres receiving EQIP payments for cover-cropping more than quadrupled (from 240,418 to 1,120,311 acres). Over this same period, funding for no-tillage dropped substantially (Bowman and Wallander, 2018). This is likely due to the fact that no-tillage has become a much more common practice in many regions and for many crops and because many farmers choose to adopt no-tillage without an incentive payment (Claassen et al., 2018).

The second NRCS program that provides financial assistance for soil health practices is the Conservation Stewardship Program (CSP). CSP is the largest conservation program (in terms of acres enrolled) in the United States and was established by the 2008 Farm Act. CSP is designed to provide assistance to farmers and ranchers that may already be implementing conservation practices on their land but want to take their management to the next level by implementing "enhancements" to existing conservation practices that address specific resource concerns (USDA, 2016). Some of the most popular soil-health-related enhancements in CSP are related to cover-cropping, pasture and rangeland management or restoration, and no-tillage or reduced tillage (Bowman, Wallander, and Lynch, 2016). Between 2010 and 2015, the number of acres receiving CSP payments for at least one soil health practice or enhancement grew from just under 7 million to more than 30 million (Figure 1).

Figure 1. Acres Enrolled in the Conservation Stewardship Program (CSP) with at Least One Soil Health Practice or Enhancement, 2010–2015



Source: USDA, Economic Research Service calculations using USDA, National Resources Conservation Service, ProTracts database.

These two NRCS programs are structured somewhat differently. For example, most EQIP contracts are for less than three years and are implemented at the field level (Wallander et al., 2019), whereas CSP contracts are typically five years and involve a suite of enhancements to both enhance natural resources and improve business operations (USDA, 2016). Despite these differences, CSP and EQIP both require farmers and ranchers to implement practices or enhancements in accordance with conservation practice standards published by the NRCS. These practice standards specify how a practice is implemented on the landscape. For example, farmers receiving an EQIP payment for cover-cropping cannot harvest their cover crop for grain or seed but can graze their cover crop or harvest it for hay or silage. They must also comply with the practice standard that specifies the type of cover crop to be established, seeding rates and dates, when and how they will apply nutrients, and how they will terminate their cover crop (USDA, 2014).

State Programs Can Be an Additional Source of Support for Farmers Adopting Soil Health Practices

In addition to the two major federal programs discussed in the previous section, a number of U.S. states, counties, and soil and water conservation districts implement programs that offer either financial or technical assistance or both to farmers to adopt soil health practices such as no-tillage, reduced tillage, or cover-cropping. These programs often take the form of cost-share programs, which are designed to offer the farmer financial assistance to cover all or a portion of the costs associated with adopting a practice. Program requirements often include that the farmer document costs associated with adopting a practice, that they submit other documentation sufficient to prove that they have adopted the practice, or that a practice be implemented according to a state or federal practice standard. Many states require that practices adopted as part of a state cost share program conform to the NRCS practice standard for the practice. For a list of a number of state programs that promote soil health or provide financial or technical assistance to support soil health practices, see the Soil Health Institute's Soil Health Policy Resources page.

In the same way that federal programs have increased funding to promote adoption of cover crops, a number of state programs have emerged or expanded to provide financial incentives to farmers to adopt cover crops. Some programs explicitly state that a farmer cannot participate in both state and federal cover crop programs, while others allow the farmer to receive payments from both programs. Participation year limits and acreage caps vary, as do stipulations related to whether the farmer has to be a first-time cover-cropper.

Differences in program requirements may correspond to different program goals; for example, some programs may be trying to offset the learning costs associated with the practices, whereas others may only be concerned with maximizing cover-cropped acreage and associated water quality benefits each year. Few programs measure changes in soil health or water quality benefits at the farm level as a result of cover-crop adoption. One such program run by the State of Missouri requires that farmers take a baseline and follow-up soil sample before and after participating in the cover-crop program (Missouri Department of Natural Resources, 2016). Other regions use models to compute estimated benefits from implementing specific practices. Most programs use a "pay-for-practice" approach; others choose "pay-for-performance," which can be challenging due to the difficulties in measuring performance from each field. Being explicit about the desired goals and measuring whether the practice implementation accomplishes these goals may provide the needed information for adapting programs to elicit the desired outcomes.

Table 1 lists the top five state-funded cover-crop programs (in terms of acreage) in the United States. In terms of both total funded acreage and per-acre payment levels, Maryland has the largest program (400,000 acres). After Maryland, the next-largest programs were in Iowa (250,000 average annual acres between FY16-FY18) and Virginia (200,000 acres in FY 2016). In 2017, Iowa began a demonstration project offering farmers a $5/acre reduction on their crop insurance premium for planting a cover crop (Iowa Department of Agriculture and Land Stewardship, 2017). In addition to the states listed in the table, a number of other states or conservation districts within states provide a per acre incentive payment for cover crops.[1]

Maryland's Agricultural Water Quality Cost-Share Program

In FY 2018, Maryland paid more than 1,400 farmers up to $75/acre to plant almost 400,000 acres of cover crops. This makes Maryland's program the largest state cover-crop cost-share program in the United States (in terms of acres), although Maryland paid for fewer cover-crop acres in 2018 than in any year since 2010. In this section, we discuss the goals of this program, the evolution of the program over time, and some of the takeaways from Maryland's experience paying for cover crops.

Background

In 2004, the Chesapeake Bay Commission deemed cover crops one of the most cost-effective ways to improve Chesapeake Bay water quality. Though Maryland already had a cover-crop program, in most years between 1994 and 2006, the program received fewer than 1,000 applications. In 2004, Maryland developed a Tributary Strategy (a plan to meet Maryland's nutrient-reduction goals for the Chesapeake Bay) that included an annual goal of planting 600,000 acres of cover crops (Maryland Department of Natural Resources, 2008) on a voluntary basis. At that time, available funding only covered about 113,522 acres of cover crops at an incentive of $20/acre.

[1] These include California, Georgia, Idaho, Indiana, Illinois, Minnesota, New Jersey, New York, North Carolina, North Dakota, Ohio, Pennsylvania, South Dakota, Tennessee, Vermont, West Virginia, and Wisconsin.

Table 1. Top Five State Programs (in terms of acreage) Offering Financial Assistance to Farmers to Plant Cover Crops

State Program/Implementing Agency	Program Acreage	Per Acre Payment Range	Annual State Spending
Maryland Department of Agriculture Agricultural Water Quality Cost-Share Program (FY 2018)	395,862	$30–$75	$18.8 million
Iowa Department of Agriculture and Land Stewardship	250,000 (Average FY16-FY18)	$15–$25 (FY 2017)	$5 million (Average FY16-FY18)
Virginia Department of Conservation and Recreation	200,540 (FY 2016)	$15–$33 (FY 2017)	$5,136,313 (FY 2016)
Missouri Department of Natural Resources (FY 2017)	117,175	$30–$40	$3,800,000
Delaware (individual county conservation districts) (FY 2017)	85,438	$30–$50	Not a state-level program

Source: Publicly available information from State websites and personal communication with staff at implementing agencies.

In 2004, Maryland created the Bay Restoration Fund, which was financed by two fees known as the "flush tax": one paid by public sewer users, and one by septic users. The fee paid by public sewer users was used to upgrade Maryland's wastewater treatment plants to remove more nitrogen (N) and phosphorus (P) during the treatment process. Part of the fee paid by septic users was used to upgrade septic treatment systems, but 40% of the revenue collected from this fee was dedicated to funding cover-crop incentives. In addition, the state created the Chesapeake and Atlantic Coastal Bays Trust Fund (2012), funded by fuel and rental car taxes, which began providing substantial support to the Maryland Cover Crop Program.

Evolution of the Program, 2004 to Present

To advance toward initial program goals of funding 600,000 acres of cover crops, the incentives for farmers to participate were increased over time. By 2016, the base and maximum payments had increased to $45/acre and $90/acre, respectively, from the base payment of $20 offered in 2004. Within this base and maximum payment structure, the program incorporated a number of monetary incentives for specific types of cover-crop choice or management. A few examples include bonuses of $10/acre for each of (i) early planting, (ii) using cover crops on fields with spring manure, and (iii) planting rye. In addition to raising incentives substantially to increase program participation, the program addressed other challenges. For example, a program evaluation found that only about 67% of sign-ups actually completed their cover-crop contracts. And, through farmer focus groups and surveys in 2005, the Cover Crop Program gathered concerns and suggestions, leading it to change several key components in 2007 to improve program flexibility. These included (i) splitting payment for the cover crop such that a $25/acre payment to cover seed costs could be received after planting; (ii) extending the planting deadline to November 5 for rye, wheat, and triticale; (iii) providing incentives for earlier planting; and (iv) allowing legumes (crimson clover, Austrian winter peas, and hairy vetch) to be added to the list of eligible cover-crop varieties.

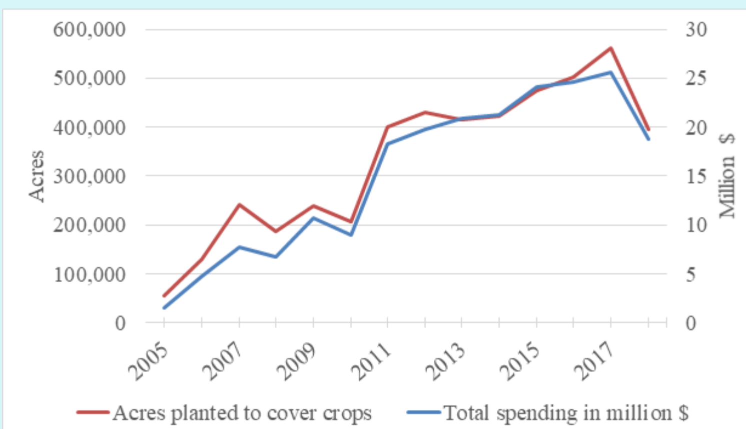
The program also expanded in 2007 to include harvested or commodity cover crops in addition to unharvested, traditional cover crops (see Table 2). This provision allowed farmers to receive a lower payment ($25/acre–$35/acre) in exchange for planting small grains such as wheat, rye, or barley to be harvested in the spring. Although traditional cover crops cannot be harvested, when established they can be grazed or chopped for on-farm livestock forage. Between 2007 and 2017, roughly 20%–40% of the cover-crop acres planted as part of the program were in commodity cover crops that were harvested. In FY 2018, competition for funding resulted in this part of the program being discontinued; program managers thought farmers would plant harvested cover crops without the payment provided previously, which resulted in the acreage decline visible in Figure 2.

Table 2. **Major Changes in Structure of Maryland's Cover Crop Program through the Agricultural Water Quality Cost Share Program**

Year	Major Changes to Program
2005	Maximum payment increased to $40/acre
2007	Introduced payment for harvested cover crops, and made program made more flexible by splitting timing of payment, incentivizing earlier planting, extending the planting deadline for some crops, and allowing legumes as part of the mix of eligible varieties.
2008	Maximum payment increased to $85/acre
2018	Eliminated payment for harvested cover crops and decreased maximum payment to $75/acre

Source: Annual reports from the Maryland Department of Agriculture and Maryland Agricultural Water Quality Cost Share Program.

Figure 2. Total Acres Planted to Cover Crops through the Maryland Agricultural Water Quality Cost Share Program between 2005 and 2018.



Source: Annual reports from the Maryland Department of Agriculture and Maryland Agricultural Water Quality Cost Share Program.

Evaluating the Impact of Maryland's Cover Crop Program

Although cover-cropping can be a key component of a soil health management system, Maryland's Cover Crop Program was designed to increase cover-crop adoption to maximize water quality benefits and reduce nutrient loading to the Chesapeake Bay, not to improve soil health per se. At its peak in FY 2017, the program was estimated to have reduced annual N loading to the bay by 3,353,850 lb and P by 111,795 lb. To the extent that these modeled reductions represent actual reductions, the program can be judged to have been successful at meeting its stated goals. As modeling approaches have improved, we may be able to improve spatial targeting of similar programs to achieve maximum water quality benefits. For example, Lee et al. (2016) find that the effectiveness of winter cover crops at reducing N leaching in two watersheds in the Chesapeake Bay likely depends upon crop rotations and soil characteristics (cover crops were more effective at reducing N leaching where N loads were high in well-drained soils). Improving targeting will enable the limited amount of program funding to be used cost-effectively to achieve the highest benefits.

It is also important to ask about the impact of the program on farmer decisions. For example, would farmers participating in Maryland's program have been planting cover crops, even without a payment? And were there other impacts of the program? Fleming (2017) found that the cover-crop program had a large effect on the share of acreage planted to cover crops and also suggests that the program increased acreage in conservation tillage in the state which had associated, additional water quality benefits. Lichtenberg, Wang, and Newburn (2018) use data from two surveys from 1997 and 2009 to estimate additionality (or how many farmers adopted cover crops that would not have adopted without a payment) for different groups of farmers. Their findings suggest that "higher cover crop payment rates offered by the program and the larger program budget served mainly to attract farmers who would have self-funded cover crops otherwise" (p. 21).

These findings suggest that Maryland was successful in attracting farmers to experiment with cover crops, but additional increases in incentive payments may not have the same impact going forward. Some farmers may find the practice standards imposed by the program too rigid or the transaction costs of applying burdensome.

Conclusions

Programs that pay for soil health practices, such as Maryland's Agricultural Water Quality Cost Share Program and federal programs such as EQIP and CSP, are increasing their funding of practices such as cover crops. To the extent that such programs can accelerate adoption of such practices by funding learning-by-doing, normalizing practice use, offsetting the costs to farmers of implementing a practice, or accelerating a transition to a soil health practice or system, they are an instrumental part of the adoption process. However, as is often the case in pay-for-practice programs, the primary measure of success becomes that which is easiest to measure: the number of acres or farmers participating in a program.

In the case of Maryland's program, increases in program flexibility and increased payment rates induced high levels of participation in the program, and the modeled water quality benefits were substantial. However, such programs raise questions about additionality of such programs, or how many farmers participating in the program would have engaged in the practice without the program benefit. To the extent that the acres enrolled are not additional, such programs may be overstating program benefits or cost-effectiveness. Most federal and state programs in the United States, to our knowledge, do not collect information about whether a farmer continues to use a practice after participating in such programs. This is a lost opportunity to measure program impact.

The Maryland example also highlights how farmer management practices, such as growing a winter cover crop, can generate valuable ecosystem services that have significant public benefits. However, a shift toward outcome-based programs that pay for measured or modeled benefits, such as water quality and carbon sequestration, might ensure that farmers who generate ecosystem services are being appropriately compensated and that good management is incentivized. Finally, Maryland's program suggests that practice-based programs that aspire to high rates of adoption should develop a process for integrating farmer feedback and consider making program requirements flexible such that they are compatible with regional farming practices and timelines.

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Soil Management for Smallholders: Lessons from Kenya and Nepal

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Healthy soil provides food, stores nutrients for plant life, and delivers essential ecosystem services such as water purification and carbon sequestration. Studies suggest soil may be the greatest reservoir of biodiversity (Wall, Bardgett, and Kelly, 2010) and the most valuable single natural commodity, worth nearly US$4 trillion in 2012 alone (Amundson et al., 2015). Soil is also a key factor in building resilience to and combating climate change (Lal, 2004). The UN Food and Agriculture Organization declared 2015 the International Year of Soils precisely to call attention to the important role soil plays in our lives.

In contrast, unhealthy soil can have devastating effects on everything from food security to global commerce to the quality of our environment. The problem of nutrient-deficient soils is particularly acute for smallholder farmers living in sub-Saharan Africa and South Asia, where the land is incredibly diverse, notoriously depleted of vital nutrients, and supports some of the highest population densities on the planet (Tully et al., 2015). Smallholder farmers—those who farm less than several hectares of family land in tropical and subtropical developing countries (Güereña, 2018)—are constrained by poor soils but also by limited access to quality seed and fertilizer, basic agriculture technologies the Western world has had access to for almost a century. As a result, farmers in these regions are the largest group of people living in absolute poverty (Hazell et al., 2007). The irony of hungry farmers is not lost on governments. Development priorities across sub-Saharan African countries over the last two decades, for example, have focused on agriculture in an effort to bring about the kind of Green Revolution that skipped this continent the first time around and partially contributed to rapid economic growth in places like Mexico and India.

The technologies needed to create healthy, resilient soil systems were developed decades or millennia ago. What has proven more difficult is delivering proven soil health solutions the last mile, at scale. Despite decades of research demonstrating the value of soil management strategies and the critical importance of soil health in smallholder farming, there are still very few regional examples of successful large-scale soil health programs. For example, conservation agriculture (CA) has been widely promoted as a sustainable soil management practice for several decades. CA is based on three pillars: reduced tillage, maintaining crop residues as soil cover, and crop rotation (Hobbs, Sayre, and Gupta, 2008; Kassam et al., 2009). While many of the components of CA have been adopted by farmers in North and South America and the benefits are widely documented in scientific literature, adoption rates in smallholder farming systems have been very low (Giller et al., 2009; Brown, Nuberg, and Llewellyn, 2017). Fertilizer deep placement (FDP) is another example. Originally developed in the 1980s for Asian rice systems, FDP consists of placing compressed briquettes of fertilizer deeper in the soil (>10 centimeters), close to the roots of transplanted rice (Roger et al., 1980). When done properly, FDP can drastically increase rice grain yields while reducing the amount of required fertilizer. Despite the well-documented benefits, FDP has not been widely adopted.

Both of these examples illustrate the barriers between the development of soil management technologies and their adoption at scale. Extensive research documents the reasons for these barriers to agricultural technology adoption; explanations range from lack of materials to farmers' access to credit and information to the role of farmers' risk and time preferences, culture, and traditions, among many others (see, e.g., Suri, 2011; Liu, 2013; Maertens, 2017). Yet the agricultural community still needs to better understand why improved soil management practices, despite proven benefits, are not widely adopted by smallholder farmers. More importantly, lessons from past research and implementation projects need to be integrated into current and future programs to better synchronize development efforts of soil management with a greater understanding of real-world farmer limitations.

Drawing from our experiences in soil management research and development projects in East Africa and South Asia, we offer insights and recommendations relevant for programs and policies aimed at the adoption and scale of sustainable soil management practices. Apart from several notable exceptions (see, e.g., Sherlund, Barrett, and Adesina, 2002; Marenya and Barrett, 2009; Harou et al., 2017; Tjernström 2017), there has been limited focus on soils and smallholder soil management practices in the agricultural economics community. Here, we report on our recent and on-going work in Kenya and Nepal that specifically examines soil management practices that rely on the use of organic resources. While the two regions differ in many respects, they are dominated by surprisingly similar smallholder systems and can offer insights for smallholder systems in other tropical and subtropical countries.

Organic Resources and Regional Focus

Most sustainable soil management technologies are based on the use of organic resources—traditional organic inputs such as crop residues and animal manures but also trees, shrubs, cover crops, biochar, and composts. While they differ in terms of their quality, decomposition, and nutrient release rates, all of these resources can contribute to both short-term nutrient availability and longer-term soil organic matter formation (Palm et al., 2001). The sheer volume of organic resources also suggests their importance in smallholder systems. For example, while it is hard to accurately quantify the global production of organic resources, some estimates suggest that an annual output of crop residues for the mid-1990s was about 3,750 x 10^6 metric tons or about 1.4 times the size of the annual aggregate crop harvest (Smil, 1999). Organic resources also often have competing uses. In many tropical contexts, they are burned as cooking fuel and contribute up to 50% of livestock diets (Thornton, Herrero, and DeFries, 2010).

Research in Kenya

The Western Kenyan highlands is one of the most densely populated regions of sub-Saharan Africa, with about 40%–50% of the population living in poverty (KIPPRA, 2013). Average farms in the area are 0.5–2 hectares in size. Farming households cultivate maize, beans, and other staple food and cash crops, keep chickens and livestock, and grow trees on woodlots for timber and fuel. Farms in the area have medium to high agricultural potential (WRI, 2007), but most suffer from severe soil degradation. Soil types are predominantly volcanic (Jaetzold and Schmidt, 1982), often characterized by high soil acidity and phosphorus deficiency (Kisinyo et al., 2014). Farming is mostly rain-fed and uses few inputs (hybrid seeds, mineral fertilizers, or agrochemicals). Farmers apply some fertilizer (about 18 kg/ha), leave crop residues on fields, and intercrop maize with legumes. However, average maize yields remain at a small fraction of yield potential (average yields of 1.7 t/ha, potential above 10t/ha).

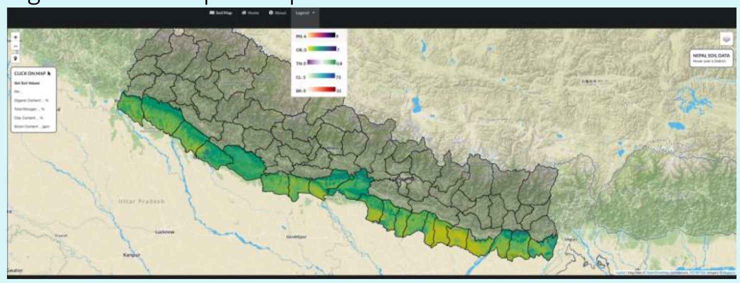
The biophysical data we use come from agronomic experimental sites located on the farms of smallholders in Vihiga and Nandi counties, which were established in 2005 and maintained until 2012 to study the long-term effects of land conversion from primary forest to continuous agriculture (Ngoze et al., 2008; Kinyangi, 2008; Kimetu et al., 2008; Güereña et al., 2016). The socioeconomic data are from household production surveys conducted in 2011–2012 in the same research area, which covered a wide range of agricultural production and natural resource management topics as well as collected soil samples and detailed spatial and market data (Berazneva, Lee, et al., 2018; Berazneva, McBride, et al., 2018; Berazneva et al., 2019).

Implementation in Nepal

As in Western Kenya, agriculture in Nepal is dominated by smallholder farms. Nestled in the foothills of the Himalaya, Nepal contains most of the agroecological zones found throughout the world, ranging from tropical hot and humid to cool and temperate, making a one-size-fits-all approach to agricultural management unsuitable. In addition, the challenging terrain of the Himalaya and expensive, tortuous road networks prevent efficient communication. As in Western Kenya, smallholder farmers in Nepal have many competing uses for organic agricultural residues, including using animal manure for cooking fuel (Das, Pradhan, and Nonhebel, 2019), rice straw for human and animal bedding, and maize stover for cattle feed. Despite these challenges, the government of Nepal has set ambitious targets to increase soil carbon levels at the national level.

Over the past ten years, new datasets and analytical approaches have been developed that can make sense of this complexity and new technology, such as mobile phones, can overcome traditional logistical challenges to communication. Various public and private satellite initiatives (Copernicus, Planet Labs) routinely provide huge amounts of high-resolution data from which insights can be derived about soils, agriculture, and the landscape, while machine learning and artificial intelligence (AI) techniques are ideally suited to help make sense of these data. In Nepal, we coupled satellite data with AI via an innovative micro-work platform and advancements in soil mapping methodologies (Hengl et al., 2015) to create high-resolution, interactive digital soil maps for Nepal (see Figure 1). These maps were used by the government to identify regional and topical priorities for national soil health programs. The technologies and approaches also provide the basis from which to deliver location-specific soil management information directly to users (policy makers, agrodealers, fertilizer companies, seed companies, farmers) via existing information and communication technology channels (SMS, smartphone apps, and others).

Figure 1. Soil Map of Nepal



Notes: Soil data were collected from detailed soil survey from 11,000 locations distributed across southern Nepal. Soil in each location was analyzed for morphological characteristics and properties such as texture, structure, consistency, mottles, porosity, compactness, pH, color, slope, and drainage. Texture (percentages of sand, silt, clay), pH, total N, available P, available K, boron, zinc, and organic matter were analyzed from physical and chemical analyses of soil samples at a soil lab. The map shows the availability of organic resources.

Lessons from Past Projects

Do Not Assume Organic Resources Are Free

Cereal residues in smallholder agriculture are used for multiple purposes, leaving none wasted. In Western Kenya, for example, about half of aboveground maize residues (both stover and cobs) is used for soil fertility management; the other half is equally split between livestock feed and household cooking fuel. Residue use varies by wealth; richer farmers have more livestock and allocate a greater share of residues for animal feed, while poorer farmers, who cannot purchase chemical fertilizer, use a greater share of residues for soil fertility management. While maize residues have value to households, they are rarely purchased and formal market prices for residues do not exist. In our research, we calculated the shadow value of maize residues by estimating a household-level production function using detailed input and output data. Our estimates suggest that maize residues left on the fields for soil fertility management are worth $0.07/kg (in terms of increased value of yields). This value (or shadow price) extends beyond providing nitrogen and is similar to the price of fuelwood and charcoal, the preferred market substitutes for maize residue (Berazneva, Lee, et al., 2018). We show that maize residues applied as soil amendments are valued, on average, at $129 per farm, while all maize residues produced make up around 38% of the total value of annual maize production and constitute about 23% of median household income.

While the exact value of cereal residues will differ across settings, our research highlights the significant contribution they make to agricultural production and emphasizes the importance of not assuming that organic resources are free. Adoption of soil management practices that rely on organic resources may be hampered by their limited availability, given that they often satisfy multiple household objectives. Failure of development projects to account for the value of organic resources may inhibit technology take-up. Properly accounting for the value of organic resources is, therefore, crucial in the planning and evaluation of agricultural extension, research, and education programs and policies that address sustainable agricultural intensification.

Account for Farmers' Time and Risk Preferences

Investments in soil not only have a positive impact on immediate crop yields, they also contribute to improving long-term soil fertility and nutrient use efficiency. Applications of organic resources, for example, replenish soil organic matter stocks that enhance soil physical, chemical, and biological processes (Blanco-Canqui et al., 2013). Conversely, soil degradation in the immediate term results in lower crop yields and potentially higher input expenses for many years to come. Therefore, investments in soil fertility ideally need to be evaluated in an intertemporal framework. Such analysis is data intensive. Moreover, it requires accounting for farmers' time and risk preferences and deciding on the appropriate discount rate—the rate at which farmers discount the future payoffs—to use. Higher discount rates suggest that the future is less valuable and lead to lower-than-optimal quantities of renewable resources (e.g., soil organic matter) and faster depletion rates of nonrenewable resources (Hotelling, 1931; Clark, 1990). Using both socioeconomic and agronomic data from Western Kenya, we extended the traditional bioeconomic model of renewable resources to soil carbon management and investigated the effects of changes in agricultural practices on farmers' soils and livelihoods (Berazneva et al., 2019). Accounting for prevailing price levels, we found that the optimal management strategies (in terms of quantity of nitrogen fertilizer and organic resources to apply) result in yields that are more than double those observed in the region. One of the explanations for such diversion is precisely farmers' time and risk preferences. Our results suggest that the current agricultural practices and yields are explained by a discount rate in the range of 5%–25%. Farmers also differ in terms of their rates of time and risk preferences, so that their agricultural practices lead to different stocks of natural resources.

Since smallholder access to credit is still quite limited, short-term priorities often trump long-term investments in things like soil health. Understanding the role of farmers' time and risk preferences, and accounting for them in analysis, is important for the design of effective agricultural programs and policies. Given farmers' shorter-term horizons and risk aversion, we may not see widespread adoption of soil management practices that often deliver benefits in the long run. Designing programs that deliver more immediate benefits and subsidizing the initial investments will be important for their take-up.

Understand Smallholders' Value of Soil Information

Soil serves as an important input in smallholder agricultural production, yet, researchers rarely account for both soil fertility metrics and farmers' behavioral responses in the analysis. More recent work has started doing so (see, for example, the World Bank's Living Standards Measurement Study—Integrated Survey in Agriculture that includes questions on farmers' perceptions of soil fertility and soil data from the Food and Agriculture Organization's Harmonized World Soil Database), yet there is no consensus on what type of soil information is best to use for both research and implementation projects. Soil fertility information can come from costly and time-intensive laboratory analysis, digital maps that better capture provincial or regional soil heterogeneity, or farmers' perceptions that may be prone to cognitive biases. Merging data from all three sources, we took stock of what can be learned about the links between subjective (reported) and objective (measured) soil fertility information in Kenya (Berazneva, McBride, et al., 2018). We found that farmers base their perceptions of soil quality and type on crop yields, yet do not change management practices (fertilizer application rates) in response to their perceptions. We also found that farmers' perceptions of soil type reasonably predict several objective soil indicators from the laboratory analysis, while the currently available high-resolution geo-spatial soil data (Hengl et al., 2015) do not sufficiency capture local soil variation at the plot level.

We need a better understanding of farmers' value and use of soil fertility information. Is it a limiting constraint in agricultural production, and if so, what kind of information would be most valuable to increase smallholder crop yields and welfare? Once we have these answers, there is tremendous need to invest in development of more detailed (and time-variant) soil fertility data and maps and in dissemination and use of these data by agricultural practitioners and extension agents, so that smallholders and those interacting with them have the most up-to-date and accurate soil information possible.

Embrace New Technologies

In the past, soil mapping efforts have largely been developed and used for academic purposes. For example, what are the patterns of chemical nutrients across landscapes? What are the spatial patterns of taxonomic soil types? These research questions have produced some very beautiful soil maps, but these maps are usually relegated to a dusty storage shed in a back office or for the use of scientific "experts." Modern geoinformatics technology, however, has changed our ability to interact with soil maps and make the outputs relevant to general audiences or farmers. In Nepal, we worked with the government to aggregate their soil data and run advanced analytics to create soil maps and associated fertilizer recommendations. Private agritech start-ups then took the analytical soil outputs and transformed these into smartphone apps to deliver, for example, fertilizer type selection information to smallholder farmers. In addition, we conducted a randomized control experiment that looked at the efficacy of providing fertilizer application timing information to smallholder farmers via various channels: traditional face-to-face extension, radio broadcasts, IVR (interactive voice response), and a smartphone app. We found that distributing the information via smartphone apps was the most effective method to increase farmer literacy and induce behavior change (Giulivi et al., 2019).

Disruptive technologies have transformed many sectors of the global economy. These technologies are uniquely suited to adapt to the diverse needs of users. However, the adaptation of these new technologies to agriculture, especially in the developing countries, has been slow. Evidence of early applications to soil management has been informative, but further investment across all sectors of the agricultural service economy is needed to bring about system transformation. Updating the interfaces of analytical efforts in soil resource mapping has the potential to better match research efforts with real-world applications.

Work with Governments

In many developing countries, governments spend considerable financial resources on collecting valuable soil or other agricultural data, yet these data often sit idle and are accessed by few within the government. Data can be used to generate important insights and drive pro-farmer policies, but only if open and shared. Public sector investments, however, have historically played a critical role in catalyzing innovation. Through strategic policy programs and collaborations with researchers and development organizations, public sector investment can play a critical role in catalyzing the innovation process in soil management as well, particularly in the context of developing countries.

Conclusions

While the research we highlight here has emphasized the challenges to adopt and scale soil management technologies in Kenya and Nepal, organic resources and soil organic matter are some of the few things that have practically universal benefits in any context: the more, the better. The lessons we discuss here, therefore, can be applicable when testing and targeting soil management interventions in any tropical or subtropical developing country. For example, accounting for competitive uses of on-farm organic resources, as well as for farmers' shorter-term horizons and risk aversion, is crucial for successful implementation of any soil management practice that relies on organic resources. Deriving insights from farmers through surveys is also an important, but costly, tool; the surveys are needed to, for example, help better understand farmers' value and use of soil fertility information. At the same time, new technology may be the bridging tool that enables greater connectivity between the farming and development communities. The information technology revolution (including mobile phones, smartphones, and artificial intelligence) has already spread and been established among smallholder farmers in both Kenya and Nepal. When linked to policy via national governments, this may be a way to better synergize the needs of farmers with policy priorities.

The world's population is slated to reach over nine billion people by 2050, with the majority of growth taking place in developing nations. The UN estimates that food production must increase by 70% in order to meet the projected rise in demand. The UN also estimates that there are nearly 450 million farmers worldwide who cultivate less than two hectares of land (Grossman and Tarazi, 2014). Increasing these farmers' productivity and resilience by encouraging adoption of soil management techniques at scale is an important, far-reaching investment in the long-term health of our planet. It is also a huge opportunity to end global poverty on a massive scale.

Tremendous research on soil management techniques has been done over the past few decades. We need to place additional intention on how these advancements can be adopted by farmers and scaled for the impacts of this research to make a difference. Doing so requires an interdisciplinary approach that integrates diverse fields such as soil science, economics, technology, and business, all wrapped in a conducive policy environment. But beyond all else, we must increase our ability to listen to and learn from smallholder farmers. Too often, agricultural development programs derive their priorities from the narrow expertise of scientific experts or from topical interest of donor organizations. Despite good intentions, these approaches then lead to a mismatch between development initiatives and the needs and concerns of farmers. Often times, smallholder farmers are actually "poor but efficient" users of agricultural technologies, given their constraints and limited inputs (Schultz, 1964). Much of the challenge in understanding their priorities and behavior lies in the wide geographical distribution of smallholder farmers, arguably, the most important stewards of the world's soil (Güereña, 2018).

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