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Soil Fertility and Poverty in Developing Countries

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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).

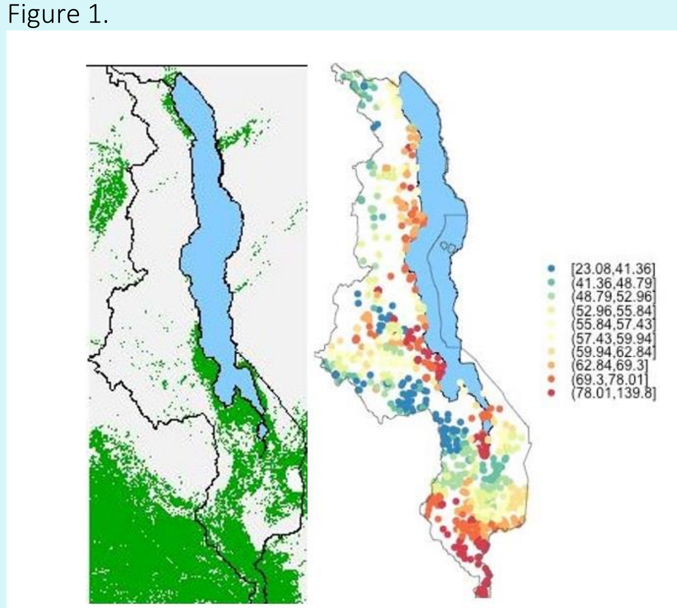
Mineral Deficiencies in Soils, Crops, and Humans

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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