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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).

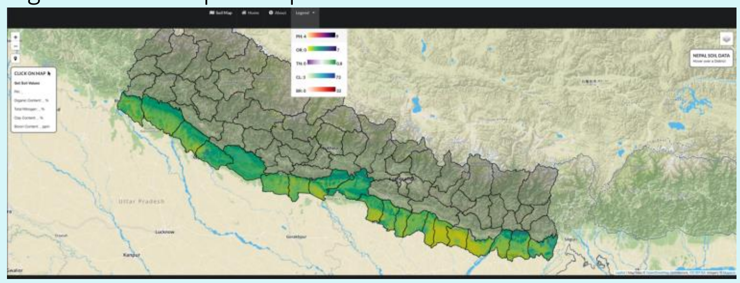
The biophysical data we use come from agronomic experimental sites located on the farms of smallholders in Vihiga and Nandi counties, which were established in 2005 and maintained until 2012 to study the long-term effects of land conversion from primary forest to continuous agriculture (Ngoze et al., 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).

For More Information

Amundson, R., A.A. Berhe, J.W. Hopmans, C. Olson, A.E. Sztein, and D.L. Sparks. 2015. "Soil and Human Security in the 21st Century." *Science* 348 (6235): 1261071–1261071.

Berazneva, J., J.M. Conrad, D.T. Güereña, J. Lehmann, and D. Woolf. 2019. "Agricultural Productivity and Soil Carbon Dynamics: A Bioeconomic Model." *American Journal of Agricultural Economics*, forthcoming.

Berazneva, J., D.R. Lee, F. Place, and G. Jakubson. 2018. "Allocation and Valuation of Smallholder Maize Residues in Western Kenya." *Ecological Economics* 152: 172–182.

Berazneva, J., L. McBride, M. Sheahan, and D. Güereña. 2018. "Empirical Assessment of Subjective and Objective Soil Fertility Metrics in East Africa: Implications for Researchers and Policy Makers." *World Development* 105: 367–382.

Blanco-Canqui, H., C.A. Shapiro, C.S. Wortmann, R.A. Drijber, M. Mamo, T.M. Shaver, and R.B. Ferguson. 2013. "Soil Organic Carbon: The Value to Soil Properties." *Journal of Soil and Water Conservation* 68(5): 129A-134A.

Brown, B., I. Nuberg, and R. Llewellyn. 2017. "Negative Evaluation of Conservation Agriculture: Perspectives from African Smallholder Farmers." *International Journal of Agricultural Sustainability* 15(4): 467–481.

Clark, C.W. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources*. 2nd ed. New York: John Wiley & Sons.

Das, K., G. Pradhan, and S. Nonhebel. 2019. "Human Energy and Time Spent by Women Using Cooking Energy Systems: A Case Study of Nepal." *Energy* 182: 493–501

Giller, K.E., E. Witter, M. Corbeels, and P. Tittonell. 2009. "Conservation Agriculture and Smallholder Farming in Africa: The Heretics' View." *Field Crops Research* 114 (1): 23–34. https://doi.org/10.1016/j.fcr.2009.06.017.

Giulivi, N., A. Harou, D.T. Güereña, S. Gautam, P. Baral, and S. Marharjan. 2019. "Getting the Message Out: The Role of Communication Technologies in Delivering Agricultural Advice to Farmers in Nepal." Working paper.

Grossman, J., and M. Tarazi. 2014. "Serving Smallholder Farmers: Recent Developments in Digital Finance." Focus Note 94. Washington, DC: CGAP.

Güereña, D.T. 2018. "Supporting Smallholders in Maintaining Soil Health: Key Challenges and Strategies." In *Managing Soil Health for Sustainable Agriculture Volume 2: Monitoring and Management*, Don Reicosky, ed. Cambridge, UK: Burleigh Dodds, pp. 317–348.

Güereña, D.T., J. Kimetu, S. Riha, H. Neufeldt, and J. Lehmann. 2016. "Maize Productivity Dynamics in Response to Mineral Nutrient Additions and Legacy Organic Soil Inputs of Contrasting Quality." *Field Crops Research* 188: 113–120.

Harou, A., Y. Liu, C.B. Barrett, and L. You. 2017. "Variable Returns to Fertilizer Use and Its Relationship to Poverty: Experimental and Simulation Evidence from Malawi." *Journal of African Economies* 26(3): 342–371.

Hazell, P.C. Poulton, S. Wiggins, and A. Dorward. 2007. "The Future of Small Farms for Poverty Reduction and Growth." 2020 Discussion Paper 42. Washington, D.C.: International Food Policy Research Institute. Available online: http://www.ifpri.org/publication/future-small-farms-poverty-reduction-and-growth.

Hengl, T., G.B.M. Heuvelink, B. Kempen, J.G.B. Leenaars, M.G. Walsh, K.D. Shepherd, A. Sila, R.A. MacMillan, J. Mendes de Jesus, L. Tamene, and J.E. Tondoh. 2015. "Mapping Soil Properties of Africa at 250 m Resolution: Random Forests Significantly Improve Current Predictions." *PLoS ONE* 10(6): 1–26.

Hobbs, P.R., K. Sayre, and R. Gupta. 2008. "The Role of Conservation Agriculture in Sustainable Agriculture." *Philosophical Transactions of the Royal Society B: Biological Sciences* 363(1491): 543–555.

Hotelling, H. 1931. "The Economics of Exhaustible Resources." *Journal of Political Economy* 39(2): 137–175.

Jaetzold, R., and H. Schmidt. 1982. *Farm Management Handbook of Kenya, Vol. II: Natural Conditions and Farm Management Information*. Nairobi, Kenya: Ministry of Agriculture.

Kassam, A., T. Friedrich, F. Shaxson, and J. Pretty. 2009. "The Spread of Conservation Agriculture: Justification, Sustainability and Uptake." *International Journal of Agricultural Sustainability* 7(4): 292–320.

Kimetu, J.M., J. Lehmann, S.O. Ngoze, D.N. Mugendi, J.M. Kinyangi, S. Riha, L. Verchot, J.W. Recha, and A.N. Pell. 2008. "Reversibility of Soil Productivity Decline with Organic Matter of Differing Quality along a Degradation Gradient." *Ecosystems* 11(5): 726–739.

Kinyangi, J.M. 2008. "Soil Degradation, Thresholds and Dynamics of Long-Term Cultivation: From Landscape Biogeochemistry to Nanoscale Biogeocomplexity." PhD Dissertation, Cornell University, Ithaca, NY.

KIPPRA. 2013. *Kenya Economic Report 2013*. Nairobi, Kenya: Kenya Institute for Public Policy Research and Analysis (KIPPRA). Available online: http://www.kippra.org/downloads/Kenya Economic Report 2013.pdf.

Kisinyo, P.O., C.O. Othieno, S.O. Gudu, J.R. Okalebo, P.A. Opala, W.K. Ng'etich, R.O. Nyambati, E.O. Ouma, J.J. Agalo, S. J. Kebeny, E.J. Too, J.A. Kisinyo, and W.R. Opile. 2014. "Immediate and Residual Effects of Lime and Phosphorus Fertilizer on Soil Acidity and Maize Production in Western Kenya." *Experimental Agriculture* 50(1): 128–143.

Lal, R. 2004. "Soil Carbon Sequestration to Mitigate Climate Change." *Geoderma* 123(1–2): 1–22.

Liu, E.M. 2013. "Time to Change What to Sow: Risk Preferences and Technology Adoption Decisions of Cotton Farmers in China." *Review of Economics and Statistics* 95(4): 1386–1403.

Maertens, A. 2017. "Who Cares What Others Think (or Do)? Social Learning and Social Pressures in Cotton Farming in India." *American Journal of Agricultural Economics* 99(4): 988–1007.

Marenya, P.P., and C.B. Barrett. 2009. "State-Conditional Fertilizer Yield Response on Western Kenyan Farms." *American Journal of Agricultural Economics* 91(4): 991–1006.

Ngoze, S., S. Riha, J. Lehmann, L. Verchot, J.M. Kinyangi, D. Mbugua, and A. Pell. 2008. "Nutrient Constraints to Tropical Agroecosystem Productivity in Long-Term Degrading Soils." *Global Change Biology* 14(12): 2810–2222.

Palm, C.A., C.N. Gachengo, R.J. Delve, G. Cadisch, and K.E. Giller. 2001. "Organic Inputs for Soil Fertility Management in Tropical Agroecosystems: Application of an Organic Resource Database." *Agriculture, Ecosystems and Environment* 83: 27–42.

Roger, P.A., S.A. Kulasooriya, A.C. Tirol, and E.T. Craswell. 1980. "Deep Placement: A Method of Nitrogen Fertilizer Application Compatible with Algal Nitrogen Fixation in Wetland Rice Soils." *Plant and Soil* 57(1): 137–142.

Schultz, T.W. 1964. *Transforming Traditional Agriculture*. New Haven, CT: Yale University Press.

Sherlund, S.M., C.B. Barrett, and A.A. Adesina. 2002. "Smallholder Technical Efficiency Controlling for Environmental Production Conditions." *Journal of Development Economics* 69(1): 85–101.

Smil, V. 1999. "Crop Residues: Agriculture's Largest Harvest." *BioScience* 49(4): 299–308.

Suri, Tavneet. 2011. "Selection and Comparative Advantage in Technology Adoption." *Econometrica* 79(1): 159–209.

Thornton, P.K., M. Herrero, and R.S. DeFries. 2010. "Potential for Reduced Methane and Carbon Dioxide Emissions from Livestock and Pasture Management in the Tropics." *Proceedings of the National Academy of Sciences* 107(46): 19667–19672.

Tjernström, E. 2017. "Learning from Others in Heterogeneous Environments." Working paper, University of Wisconsin, Madison. Available online: https://www.lafollette.wisc.edu/sites/tjernstrom/Learning%20from%20others.pdf.

Tully, K., C. Sullivan, R. Weil, and P. Sanchez. 2015. "The State of Soil Degradation in Sub-Saharan Africa: Baselines, Trajectories, and Solutions." *Sustainability* 7(6): 6523–6552.

Wall, D.H., R.D. Bardgett, and E. Kelly. 2010. "Biodiversity in the Dark." *Nature Geoscience* 3(5): 297–298.

WRI. 2007. *Nature's Benefits in Kenya: An Atlas of Ecosystems and Human Well-Being*. Washington, DC; Nairobi, Kenya: World Resources Institute (WRI); Department of Resource Surveys and Remote Sensing, Ministry of Environment and Natural Resources, Kenya; Central Bureau of Statistics, Ministry of Planning and National Development, Kenya; International Livestock Research Institute. Available online: http://www.wri.org/publication/natures-benefits-in-kenya.

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