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Breaking Ground: Unearthing the Potential of High-resolution, Remote-sensing Soil Data in Understanding Agricultural Profits and Technology Use in Sub-Saharan Africa

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Summary. — There is a growing interest in how land degradation affects the welfare of the rural poor, especially where environmental conditions continue to worsen and the future of ecosystem health remains uncertain. Nowhere is this more important than in sub-Saharan Africa, where rural poverty remains high and pressure on natural resources continues to build. At the same time, generating more agricultural profits on this land remains crucial to reducing poverty. This research asks how changing land quality, as measured by soil organic carbon (SOC) content, affects agricultural profitability and agricultural technology adoption for poor farmers in Tanzania. It is the first to match high-resolution, remote-sensing soil data to nationally representative household-plot surveys, using the World Bank's Living Standards Measurement Study and World Agroforestry Centre's Land Degradation Surveillance Framework. We employ a household fixed effects model that isolates SOC contributions to plot-level agricultural profits, finding positive changes of $7–8 per acre per year for each gram per kilogram change in SOC, with higher sensitivity to SOC differences for farmers with worse quality land. SOC and fertilizer use also exhibit a positive synergistic interaction with plot-level agricultural profits. Despite this, however, we find that SOC levels do not factor into fertilizer adoption decisions, and land quality has a smaller role in how farmers assign value to their land compared to how it contributes to profits. Partly because of a lack of matched, high-resolution, and nationally representative environmental and socioeconomic data, researchers and policymakers typically have not been able to include land quality as a primary dimension on which to analyze agricultural profitability and technology use in sub-Saharan Africa. We conclude that this should be a major factor in both targeting rural development and environmental policies and understanding impacts of long-run land health declines on the world's poor.

Key words — agriculture, poverty, technology adoption, fertilizer, Tanzania, Africa

1. INTRODUCTION

Environmental stress and ecosystem health are becoming increasingly important topics in the discussion around rural poverty alleviation in developing countries. Understanding the relationship between environmental pressure and agricultural outcomes can help policymakers interested in achieving the dual objectives of natural resource sustainability and economic development for those who remain tied to the land. In this paper, we estimate changes in agricultural profits and management decisions that are linked to land degradation in sub-Saharan Africa (SSA), a region where poverty remains high and pressure on the land continues to build.

This research contributes to the policy discussion at the intersection of environment and economic development by first advancing the quality of data at the core of such studies. We bring together data at the cutting edge of both fields. On the one hand is the World Bank's Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA). This data set features a nationally representative sample of rural households in Tanzania and plot-level information on costs, revenues, input use, and other farm and household variables. On the other hand is the Africa Soil Information Service (AfSIS) and its Land Degradation Surveillance Framework (LDSF), which uses remote-sensing, ground-truthed environmental data to generate variables at 500 × 500 m resolution. We link these to the LSMS-ISA agricultural plots and the accompanying plot-level farm and farmer data using high-resolution geocoordinates provided by the World Bank.

We then use these data to ask three questions that shed new light on the increasingly important relationship between environmental degradation and rural economic development. First, we inquire about the relationship between land quality and human welfare by estimating how changes in soil organic carbon (SOC) link to plot-level agricultural profits. We use a long-run value of total SOC that is exogenous to short-run farmer decisions and behaviors. Conceptually, we focus on how the physical and environmental components of agriculture interact with farmer behavior, profit maximization, technology use, and decision making. We use a household fixed effects econometric model to isolate SOC's relationship to agricultural profits at the plot level and advance our

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understanding of causal pathways. Our focus on plot-level agricultural profits is rare among studies on this topic, where most tend to focus instead on output or yield. We believe this extra step is important as it goes beyond simply evaluating factors that lead to increased production by contextualizing similar hypotheses in terms of profitability to farms. This can help uncover additional contributing factors to farmer welfare and farm management decisions.

Second, we explore how this powerful dataset can lead to a better understanding of the relationship between our improved indicator of land quality and farmers' subjective land valuation. After we estimate the contribution of SOC to farm profits, we then juxtapose this result with how farmers value their own plots of land, conditional on SOC levels. A discrepancy between these results would suggest a disconnect between the value of SOC when it comes to agricultural profits and the understanding or value of this linkage by farmers. This is an important area of research and affects policies that do not take this disconnect into account.

Finally, we seek to help unravel what is a long-standing conundrum regarding farmer decisions in SSA to not apply fertilizers on plots where it appears profitable to do so. After incorporating fertilizer use into our analysis of SOC and plot-level profitability, we then test whether SOC levels influence farmer decisions to adopt fertilizer. Many previous studies point to an underutilization of fertilizer on farms but are limited to coarse soil data, subjective responses, or small soil sampling areas. Testing this relationship with our high-resolution, nationally representative data can help begin to solve these concerns and potentially inform practitioners and policymakers about how inherent soil quality matters in profitability of fertilizer application.

Results show increases in seasonal agricultural returns of roughly $7–8 per additional gram per kilogram of SOC content on a farmer's plot, conditional on household fixed effects, technology use, and input application. This represents an elasticity of profit of 6% with respect to changes in SOC. Poorer farmers with worse quality land experience larger marginal decreases in profits for each unit reduction in SOC on their farms. Interactive effects of fertilizer with SOC are positive, with some indication that this effect diminishes with higher SOC levels, although low uptake prevents conclusive statements on this. Despite this heterogeneity of SOC effects on profits, given fertilizer use, we find no association between decisions to use fertilizer and SOC levels. Subjective land valuations based on SOC are also less precise than what we find for profits, suggesting that other factors play a major role in how farmers view their land beyond soil quality, fertilizer effectiveness, and profitability.

These results factor into current policy discussions surrounding environmental and development goals. First, they quantify the monetary value of the most important indicator of soil health, SOC, which can be used in cost-benefit analyses of policies assessing impacts of long-run environmental change in poor farming areas. Second, they the target groups for policies designed to increase fertilizer use for farmers and encourage sustained uptake beyond pilot projects or controlled interventions. We find that nuanced soil and land conditions are important in designing of cost-effective policies that target the poorest farmers, who are more likely to cultivate the worst quality land, and the poorest soil quality plots within farms, which respond most to fertilizer use. Because we control for household-specific behaviors and market imperfections, we rule out many behavioral and market-level factors that would otherwise confound such results. We, thus, conclude that an increased focus on inherent soil quality can build upon existing policies that focus primarily on input, financial, and other market imperfections. Together, better targeted policies incorporating heterogeneous effects of continuing environmental stress within villages and within farms can contribute most efficiently to poverty objectives.

The remainder of this paper proceeds as follows. Section 2 discusses background literature related to the questions posed here and provides a conceptual framework for our analysis. Section 3 lays out the empirical methodology that allows us to unpack key relationships in the data. The next section details the environmental and economic datasets and how we bring them together for this study, and Section 5 shows results from our household fixed effects model. Finally, Section 6 offers a summary of our findings and a discussion on how these results may contribute to future agricultural, environmental, and development policies.

2. BACKGROUND

Worsening land quality often disproportionately affects social and economic outcomes for the poor (Nkonya, Mirzabaev, & von Braun, 2016). This is becoming an urgent issue in countries like Tanzania, where agriculture accounts for nearly a quarter of GDP, employs half of the country's workforce, and makes up the largest share of rural household income. Some households may diversify their livelihoods away from agriculture, especially when their initial wealth levels are high (Alobo Loison, 2015), but in many cases the farm is still the best available option for generating income. Thus, in this paper we focus on farm responses to land quality changes and, specifically, the role of soil in profit generation and sustainable intensification.

In this section, we provide context for our analysis by first discussing the previous research that has been done on the topic, including a discussion of how various types of land pressures affect household reactions on the farm and the outcomes that have been documented from intensification practices in sub-Saharan Africa. We highlight the important conceptual role of soil and where high-resolution soil indicators are lacking empirically, especially at the intersection of environmental and development economics studies. Finally, we present a conceptual framework that captures our contribution to the discussion and feeds into the empirical framework that follows.

(a) *Previous literature*

We distinguish between sustainable and unsustainable agricultural intensification. The latter is referred to as Boserupian in Jayne, Chamberlin, and Headey (2014), where the authors describe how increasing population pressure in Africa contributes to unsustainable intensification through constraints on the amount of land available to farmers. Similarly, Pretty (2008) suggests that intensification is unsustainable because current ratios of land, water, technology, and inputs will not remain linear in the future, while Scherr and McNeely (2008) call for global models that no longer separate agricultural production from biodiversity conservation.

Alternative cultivation techniques and technology use, on the other hand, can lead to higher levels of crop production that will last longer and increase the sustainability of productive land. The concept of sustainable intensification, or eco-efficiency as in Keating *et al.* (2010), includes an understanding of the benefits of ecological and agronomic management that address energy flows, nutrient cycling, population-regulating mechanisms, and system resilience—all while yielding positive

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