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Non-Labor Input Quality and Small Farms in Sub-Saharan Africa

A Review

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Abstract

Adoption of non-labor agricultural inputs, including pesticides and mineral fertilizers, remains low among small-scale farmers in many low-income countries. Accurate measurement of the quality of these inputs and of quantities deployed is essential for assessing economic returns, understanding the drivers of agricultural productivity, and proposing and evaluating policies for increasing agricultural production. Reviewing evidence regarding the quality of mineral fertilizers and pesticides available to small farmers in Sub-Saharan Africa, this paper summarizes four key findings. First, the available evidence on non-labor input quality to date centers mostly on urea fertilizer and glyphosate herbicide, with limited assessment of other important inputs, including multi-nutrient fertilizers. Second, the evidence shows that nitrogen shortages are exceedingly rare for urea, although quality problems are more common in fertilizer blends including nitrogen, phosphorous, and potassium blends, as well as diammonium phosphate, and in glyphosate herbicide. Third, although nutrient shortages in nitrogen, phosphorous, and potassium fertilizer blends and diammonium phosphate fertilizer blends are likely attributable to problems with manufacturing and storage, problems with available herbicides could be due to manufacturing issues, counterfeiting, or adulteration. Fourth, although farmers are broadly suspicious of the quality of mineral fertilizer and pesticides, evidence from several studies suggests that these beliefs do not reflect lab-based assessments of quality. In light of these findings, this paper recommends best practices for evaluation of non-labor input quality and summarizes research evaluating farmer assessment of fertilizer and pesticide quality. The paper concludes by identifying key evidentiary gaps related to measuring non-labor agricultural input quality and use, and recommends specific topics for future research.

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Non-Labor Input Quality and Small Farms in Sub-Saharan Africa: A Review

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I. Introduction

Increasing agricultural productivity in Sub-Saharan Africa remains essential to raising regional incomes and improving food security, as well as achieving structural transformation of the region's economies, a sustained transition of labor from low-productivity agriculture into higher productivity sectors (Gollin et al. 2002, McMillan and Rodrick 2011, Timmer et al., 2015). It is widely recognized that while Sub-Saharan Africa is a region of considerable agricultural and economic potential, it faces chronic challenges. Estimated yield gaps from primary staple cereal crops suggest that considerable productivity gains are indeed possible, but growing populations and the threats and uncertainties of climate change lend urgency and complexity to achieving needed agricultural growth (Leitner et al. 2020, Sileshi et al. 2010, Tittonell and Giller 2013). Agricultural productivity gains in this region will require increased use of agricultural inputs including combinations of fertilizer, hybrid seed, and agri-chemicals. Use of these inputs remains on average well below recommended levels across Sub-Saharan Africa, though with important variations across nations and farm types (Sheahan and Barrett 2017).

Numerous studies have estimated potential returns from the application of adequate fertilizer and herbicide by small farmers. Findings suggest that such inputs can be profitable, that they can raise yields and increase farm profits, but with important heterogeneity across farmers (Suri 2011, Duflo et al. 2008, Barrett and Marenya 2009, Harou et al. 2022, Beaman et al. 2013).[2] Research on the returns to herbicide application has focused on quantifying the degree to which application reduces farmer labor costs (Haggblade et al 2016). For example, Tamru et al. (2017) show that herbicide use increases labor productivity by nearly 100%, decreasing labor hours from 7.9 to 4.6 days per plot on average in Ethiopia, and Ashour et al. (2017) show that labor time spent on plot weeding was reduced 65% by glyphosate application.

Because of shortfalls in the application of, and potentially quality of, these inputs, the prevalence and persistence of low agricultural input use by small farmers has been a focus of extensive study by researchers and a major concern of policy makers. Under-use is attributed to a range of related factors, including missing financial markets, uninsured risk, high transport and transactions costs, and information problems (Karlan et al. 2014, Emerick et al. 2016, BenYishay and Mobarak, 2019).

[2] Duflo et al. (2008) find in experimental work in Kenya that returns to fertilizer application are high on average – 36% over a season or 69.5% annualized – but that the full application package recommended by the government is not on average profitable for farmers in their sample. Barrett and Marenya (2009) show that fertilizer is profitable on average but that plots that are sufficiently degraded exhibit limited response to fertilizer, rendering it unprofitable for about a third of farmers in their Western Kenya sample. Harou et al. (2022) estimate that returns to fertilizer are significant in Tanzania but only for farmers who address a widespread sulfur limitation in the soils. Beaman et al. (2013) use an experiment in which they provided free fertilizer to female rice growers in Mali to show that women who received the full recommended quantity of fertilizer increased the value of their output by 31% but also increased labor and herbicide application on their plots, making it difficult to isolate the effect of the fertilizer alone. They conclude, "fertilizer's impact on profits is small compared with other sources of variation" (p. 386). Other recent work assessing the effects of fertilizer includes Corral et al. (2020) in Mexico, Carter et al. (2021) in Mozambique and Laajaj et al. (2020) in Western Kenya.

Recently, research has focused on the relationship of poor or uncertain agricultural input quality to input use (Michelson et al. 2021, Ashour et al. 2019, Bold et al. 2017). Substandard quality, whether actual or merely suspected, could partially explain limited deployment of needed inputs, and consequently crop response and profitability. Accurate measurement of the quality and quantity of agricultural inputs applied by farmers is therefore essential for two purposes: raising farmer confidence about investing in such inputs, and improving farm yields through use of those inputs.

This paper reviews the evidence regarding the quality of mineral fertilizer and pesticides, inclusive of herbicides, available in local markets in Sub-Saharan Africa.[3] We review current evidence from academic studies and published reports by expert agencies including the International Fertilizer Development Center. We discuss best practices for definition and measurement of quality. We also summarize research eliciting and evaluating farmer assessment of fertilizer and pesticide quality. Our contribution is to introduce important distinctions based on the body of extant research into the academic literature on the topic of input quality and to identify important evidentiary gaps and areas for future research.

Our review of available evidence produces four primary findings. First, we show that current research on fertilizer and pesticide quality has focused primarily on two inputs: urea fertilizer and glyphosate herbicide. These are widely used agricultural inputs – especially by smallholder farmers – and both are critical for agricultural production. However, insights related to these inputs are not necessarily relevant to other fertilizers and pesticides, which make up a large share of input use.[4] Our second finding is relevant to this point: available evidence strongly suggests that quality problems vary by input. For example, though nutrient quality problems are exceedingly rare in urea fertilizer, nutrient shortages are more common and more likely in fertilizer blends including nitrogen, phosphorous, and potassium (NPK), calcium ammonium nitrate (CAN), and diammonium phosphate (DAP) and in glyphosate herbicide. The magnitude of the problem also varies by input: while evidence suggests nutrient shortages tend to be relatively modest in the fertilizer blends, economically and agronomically significant problems have been found in packaged glyphosate in the region.

Third, input quality issues have different causes. While the largely modest nutrient shortages in fertilizer blends are likely attributable to problems with manufacturing and storage, problems in herbicide could be due to faulty manufacturing, counterfeiting, or adulteration. Glyphosate quality issues also exhibit considerable spatial variation. Research designed to understand and ultimately

[3] We do not review the evidence on hybrid seed quality, which is still emerging. Measuring seed quality involves assessing three dimensions: analytical purity, germination rates, and varietal purity. Work studying hybrid seeds and farmer beliefs about hybrid seed fidelity includes Gharib et al. (2021) and Barriga and Fiala (2020), with related work on misperception and misreporting of crop variety by Wossen et al. (2022).

[4] For example, data from Malawi's Fifth Integrated Household Survey (2019/20) suggests that ~18% of cultivating households applied urea to at least one plot, while ~53% applied a different type of mineral fertilizer to at least one plot (rainy season; authors' calculation). Similarly, data from Nigeria's General Household Survey Panel (2018/19) suggests 24% of households applied urea on at least one plot, and 34% applied an alternative mineral fertilizer (authors' calculation).

address quality problems in input supply chains should carefully identify and situate these problems. Herbicide dilution will have very different causes, consequences, and policy solutions than poorly blended NPK granules.

Fourth and finally, we show that while evidence across a range of studies suggests that farmers are broadly suspicious about input quality, these beliefs are not generally consistent with measured quality. With regard to urea fertilizer, the most-widely used and recommended fertilizer in the regions under study, no credible evidence on measured quality supports farmer suspicions about this product in local markets. This finding raises new and important research questions about the origin and effects of these misperceptions. Research documents that farmers are also suspicious regarding glyphosate quality but available evidence shows that measured local concern does not predict the severity of the local quality problems in cross-sectional data, a similarly intriguing result.

We begin with a review of the properties of mineral fertilizer and pesticides and evidence on the use of these inputs among small farmers in Sub-Saharan Africa. Section III defines and discusses quality for fertilizer and for pesticides. In Section IV we focus on fertilizer quality measurement and evidence. In Section V we do the same for pesticides. Section VI reviews evidence regarding farmer beliefs about fertilizer and pesticide quality. We conclude with discussion of key evidentiary gaps related to measuring non-labor agricultural input quality and use and offer recommendations regarding areas for future research.

II. Mineral Fertilizers and Pesticides: Properties and Patterns of Use

Mineral Fertilizer

Fertilizers are critical agricultural inputs, providing essential nutrients to crop growth and development and to the preservation and enhancement of soil fertility (Henao and Baanante 2006). Nutrients can be delivered via organic (manure, compost) or mineral additions to the soil. Primary macro-nutrients delivered by mineral fertilizers, also referred to as inorganic fertilizers, include nitrogen, phosphorous, and potassium. Secondary nutrients include calcium, magnesium, and sulfur. Mineral fertilizer blends can also include micronutrients such as copper, manganese, and zinc. Globally, the most widely-deployed plant nutrients in agriculture are nitrogen, phosphorous, and potassium while the most widely used mineral fertilizer in the world is urea, accounting for more than 50% of global nitrogen fertilizer use (Heffer and Prud'homme 2016).

Under-use of fertilizer in crop cultivation is associated with low crop yields in the near term and soil nutrient depletion in the long term if nutrients are not added back into the soils through some other mechanism. Over-use or misapplication of mineral fertilizer contributes to environmental problems including nitrate and phosphate water contamination (Keeney and Olson 1986, Sebilo et al. 2013) and increased greenhouse gas emission (Snyder et al., 2019). Use of an inappropriate fertilizer for a given soil type and quality can also lead to problems including soil acidification (Kennedy 1986).

Most fertilizer is applied in solid granule form but liquid forms of ammonia-based fertilizers are also available. Fertilizers are sold either as single nutrient, "straight" fertilizers or multi-nutrient fertilizers in the form of compounds or blends. Urea fertilizer, for example, is a single nutrient fertilizer, 46% nitrogen by weight. Compound fertilizers contain multiple nutrients in each granule with all granules manufactured to have the same nutrient composition. Fertilizer blends are made by mixing granules of different straight fertilizers to achieve a desired nutrient composition.

Sheahan and Barrett (2017) review Living Standards Measurement Study-Integrated Surveys on Agriculture (LSMS-ISA) data to characterize input use among households cultivating at least one agricultural plot in the primary growing season in Ethiopia, Malawi, Niger, Nigeria, Tanzania, and Uganda.[5] They find that approximately 35% of farm households use some amount of mineral fertilizer in the primary growing season. Variation in the use of fertilizers both across and within countries can also be seen using data from the Rural Livelihoods Information System (RuLIS),[6] which has constructed standardized variables across a range of household and farm surveys. Figure 1 presents mineral fertilizer use among crop-farming households for 12 countries in SSA (with data collected from 2011 or later). Statistics are presented separately for small farmers, also referred to as small-scale food producers, and larger household farms.[7] Small farmers have a lower incidence of fertilizer use in nearly all represented countries, with the gap between the rate of use among small and larger household farms as large as 28% (Burkina Faso and Ethiopia).

Variation in use of mineral fertilizer across and within countries is compounded by variation in quantity of fertilizer applied. Sheahan and Barrett (2017) in their review of LSMS-ISA countries also document that the average application of mineral fertilizer per unit of cultivated area across the six countries is 57 kilograms per hectare (26 kilograms per hectare in nutrients) but emphasize considerable variation across countries; per hectare applications are highest in Malawi, Ethiopia, and Nigeria. Average application rates conditional on use range from 1.2 kg per hectare to 146 kg per hectare in Malawi, across all households irrespective of fertilizer application. Among households using mineral fertilizers in the LSMS-ISA countries, the average application rate was 123 kg/ha (58 kg/ha of nutrients). Average application rates among households using mineral fertilizers varies substantially by country, with 81 kg/ha on average in Ethiopia, 189 kg/ha in Malawi, 26 kg/ha in Niger, 310 kg/ha

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[5] Findings are for the primary agricultural season though there are typically two agricultural seasons per year, with the secondary season generally in the drier stretch of months. For more information on the LSMS-ISA, visit: https://www.worldbank.org/lsms

[6] For more information on RuLIS, visit: https://www.fao.org/in-action/rural-livelihoods-dataset-rulis/en

[7] RuLIS defines small-scale food producers in accordance with the definition put forth by FAO for the monitoring of SDG 2.3, which is summarized as "producers who: [i] operate an amount of land falling in the first two quintiles (the bottom 40 percent) of the cumulative distribution of land size at national level (measured in hectares); and [ii] operate a number of livestock falling in the first two quintiles (the bottom 40 percent) of the cumulative distribution of the number of livestock per production unit at national level (measured in Tropical Livestock Units – TLUs); and [iii] obtain an annual economic revenue from agricultural activities falling in the first two quintiles (the bottom 40 percent) of the cumulative distribution of economic revenues from agricultural activities per production unit at national level (measured in Purchasing Power Parity Dollars) (FAO, 2018; p.3)." The year of data collection for each country in Figure 1 is as follows: Burkina Faso (2014), Cameroon (2014), Ethiopia (2016), Ghana (2013), Malawi (2017), Mali (2017), Niger (2014), Nigeria (2019), Rwanda (2014), Sierra Leone (2011), Tanzania (2015), Uganda (2016).

in Nigeria, 96 kg/ha in Tanzania, and 38 kg/ha in Uganda (Sheahan and Barrett, 2017). Average use rates and even some application rates conditional on use are generally below government recommendations based on experimental trials; Tanzania for example recommends 150 kg urea and 100 kg DAP per hectare for maize production (Mutegi et al. 2015).[8]

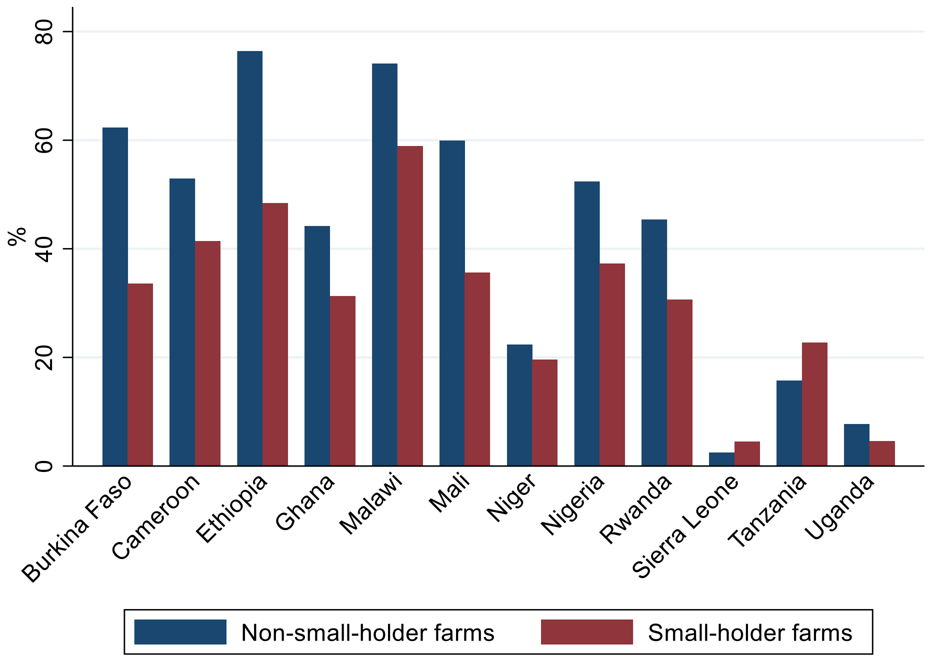

Figure 1. Share of crop farming households using inorganic fertilizers. Source: RuLIS.

Pesticides

Pesticides are agri-chemicals whose application protects crops from pressures that impede plant growth and development. Pesticides include insecticides, which protect against insect infestation and damage; herbicides, which kill weeds that compete with crops for nutrients, soil, and sun; and fungicides, which protect crops from fungi including rusts, mildews, and blights. These inputs are labor saving relative to the manual work of pulling weeds and dealing with insects and fungi (Tamru et al. 2017). Chemical pesticides can have human health consequences for agricultural workers and for individuals who are exposed to them through water pollution or through direct consumption in food (Jepson et al. 2014) and poor quality and improperly used pesticides can contribute to the emergence of resistance to active chemical ingredients among common weeds and insects (Cerdeira and Duke, 2006). Chemical pesticides have environmental effects as well, contaminating surface water and impacting aquatic life (Annett et al. 2014).

[8] Fertilizer recommendations in many countries in Sub-Saharan Africa remain relatively spatially coarse, set at the region level within many countries.

Recent work by Sheahan and Barrett (2017) also documents pesticide use in Ethiopia, Malawi, Niger, Nigeria, Tanzania, and Uganda using the LSMS-ISA data: 16% of farming households apply at least one agri-chemical to their crop during the primary season but again find considerable heterogeneity in use both across and within countries. RuLIS data on agri-chemical use among crop farming households in 13 SSA countries is illustrated in Figure 2, for small-scale food producers and larger household farms separately.[9] Similar to the observed patterns of fertilizer use, chemical input use is considerably lower among small-scale food producers than among larger farms. In Burkina Faso, for example, only 25% of small-holder crop-farming households apply any chemicals, while 49% of households operating larger farms report using chemical inputs. Among these countries, Ghana exhibits the highest incidence, with 63% of households applying chemical inputs. Haggblade et al. (2021) document that pesticide use has tripled in West Africa in the last twenty years, arguing that growth in use is driven by a combination of increasing labor costs, increasing pest pressures, and falling prices of generic pesticides in markets.

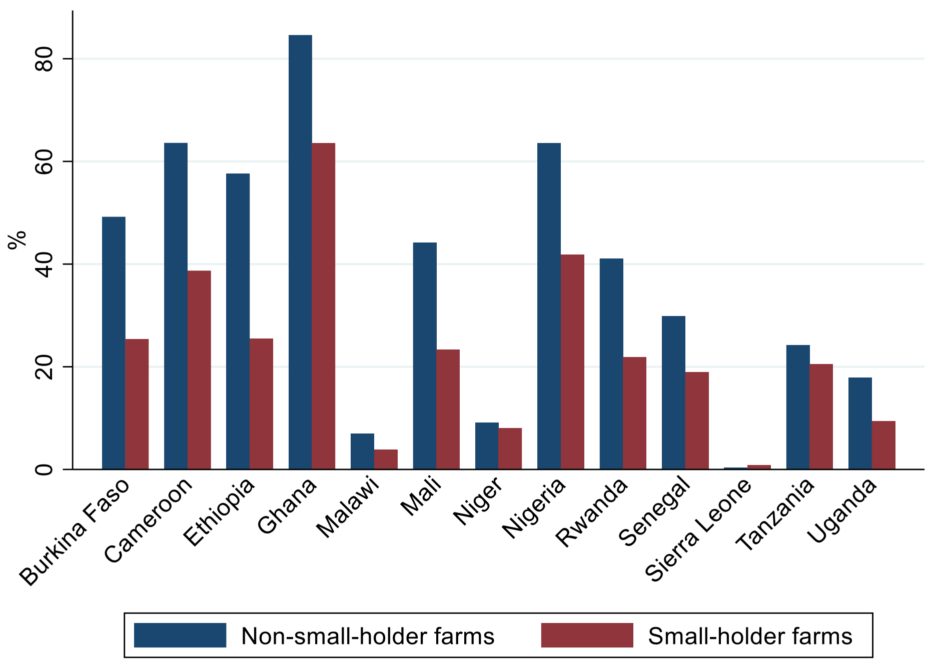

Figure 2. Share of crop farming households using chemicals. Source: RuLIS.

The most commonly used pesticide in the world is glyphosate herbicide (Benbrook 2016). Glyphosate is a non-selective herbicide, often used by farmers to kill weeds before planting. It is sold in concentrated form and diluted with water before application with a sprayer. Use of agri-chemicals remains relatively low in Sub-Saharan Africa but sales of glyphosate have increased in recent years;

[9] Data extracted from RuLIS (https://www.fao.org/in-action/rural-livelihoods-dataset-rulis/en). The year of data collection for each country in Figure 2 is as follows: Burkina Faso (2014), Cameroon (2014), Ethiopia (2016), Ghana (2013), Malawi (2017), Mali (2017), Niger (2014), Nigeria (2019), Rwanda (2014), Senegal (2011), Sierra Leone (2011), Tanzania (2015), Uganda (2016).

prices have declined by as much as 50% in some countries since 2000 as global patent protections on production have expired and new manufacturers have entered markets. Pesticides tend to be sold at the retail level in concentrated form as a liquid in bottles, often of one liter or half liter, sealed and wrapped in plastic. Farmers sometimes purchase glyphosate from agri-dealers in a pre-diluted form from open receptacles such as jerry cans.

Haggblade et al. (2021) argue that the recent rapid growth of pesticide use in Sub-Saharan Africa has outpaced regulatory capacity, creating opportunities for quality problems. Unregistered brands and in some cases locally banned ingredients proliferate in these local and regional markets (Murphy et al. 2012; Haggblade et al. 2018 and 2017a), with potential implications for human health and environmental problems.

III. Non-Labor Agricultural Input Quality: Definition

Mineral fertilizer and pesticides are experience goods, goods whose actual quality is observable by most customers only after purchase and use.[10] Especially in locations where regulation and enforcement of product standards is weak or nonexistent, farmers are largely on their own with regard to quality inference, with lack of information about product quality at the time of purchase. Application of mineral fertilizer with inadequate nutrient content will impact yields, reducing the economic benefits of application accordingly. Mather et al. (2016) calculate a linear maize-nitrogen response rate of 7.6 kilograms of maize per kilogram of nitrogen applied in Tanzania; a 10 percent nitrogen loss from the input means a 10 percent loss in production. Application of pesticides with less active ingredient than advertised will similarly decrease efficacy, requiring additional sprayings to deal with infestations or the use of labor for weeding or field preparation; these costs further reduce the profitability of use. Substandard quality of these inputs could therefore partially explain limited uptake. But beliefs about quality problems could have similar effects over time (Hoel et al. 2022). Accurate measurement of the quality and quantity of agricultural inputs applied by farmers as well as their beliefs about quality and efficacy are therefore essential to understand the degree to which quality is a problem in these markets and the degree to which quality problems or beliefs about quality problems may explain widespread failure to adopt.

Mineral Fertilizer Quality

Fertilizer has two quality dimensions: agronomic quality that can be measured using lab-based methods and visually observable characteristics. The agronomic quality of all fertilizers is based on the degree to which the measured nutrient content is consistent with its manufacturing standard. For example, urea fertilizer, which is 46% nitrogen by weight, should have at least 45.5% nitrogen by weight to be considered in compliance in most countries. Countries set tolerance limits that determine when a fertilizer is out of compliance. These tolerance limits vary based on whether the fertilizer is a

[10] Given the weather-driven stochasticity of agricultural production and spatially variable and sometimes unknown soil conditions (requiring application of different nutrient combinations) it may be difficult for farmers to detect whether mineral fertilizer is effective at all. For discussion of mineral fertilizer as a credence good, see Hoel et al. (2022).

single nutrient fertilizer or a blend, with larger tolerance limits for multi-nutrient fertilizers. Tolerance limits for nutrient content deviations in West Africa are set by the 15-member Economic Community of West African States (ECOWAS).[11] Standards in East and Southern Africa are set by individual countries, though some work is being done to harmonize standards across the 21 countries that make up the Common Market for Eastern and Southern Africa (COMESA).[12]

Low agronomic fertilizer quality (deficiencies in nitrogen or other nutrients compared to package specifications and compliance standards) can result from manufacturing problems, mismanagement along the supply chain, adulteration, or counterfeiting. Manufacturing problems are more common for blended fertilizers and relatively rare in single nutrient fertilizers such as urea. Adulterated fertilizer is fertilizer that has been deliberately mixed with non-fertilizer material including sand, rocks, dirt, or salt. Counterfeit fertilizer is when an entire bag of non-fertilizer material is sold as fertilizer.

A second dimension of fertilizer quality is its visually-observable properties: the degree to which the fertilizer is too wet, expired, sold in short bags (bags that are underweight relative to the labeled size), powdered, clumped into hard aggregates, discolored or dirty. While observable quality issues like clumping are not associated with nutrient shortages in the fertilizer, powdered, wet, and clumped fertilizer can lead to nutrient segregation in the bag. Clumping and powdering also potentially increase the costs and complexity of application for farmers. Michelson et al. (2020) find no relationship between the observed quality characteristics and the unobserved agronomic nitrogen content in Tanzania. The IFDC (2013) analysis of fertilizer quality in West Africa finds that high measured moisture content was strongly associated with fertilizer caking. IFDC also found that moisture content and nutrient segregation were strongly associated in NPK samples.

In locations with capital-constrained mineral fertilizer supply chains, degradation of observable quality is likely to be a fundamental and recurring challenge, due to limited resources to support investment, transportation, and storage. Storage and handling conditions including humidity and temperature control, preservation of the integrity of the bag and the type of bag used (laminated or merely woven material) and use of pallets for stacking bags in transport and storage can result in caking, powdering, and discoloration.

Pesticide Quality

As with fertilizer, pesticides can be adulterated – diluted with another substance like water – or counterfeit – in which an entirely different product such as water is sold as herbicide or insecticide. Pesticides can also have quality problems due to errors in manufacturing. Counterfeits may present in

[11] Tolerance limits for single nutrient fertilizers with up to 20% nutrient content have a tolerance limit of maximum 0.3 units and those with more than 20% nutrient content have a maximum tolerance of 0.5 units. Multi-nutrient fertilizers and blends have a tolerance limit of maximum 1.1 units for individual nutrients for primary nutrients and 2.5% for all primary nutrients combined. These are presented and discussed in Sanabria et al. (2013). Tolerance limits are also set for secondary nutrients (Ca, S, Mg) and for maximum deviations in fertilizer weight for 50-kg bags.

[12] A range of standards exist across East African countries. The Kenya Standard 158 set in 2011 permits a maximum lower limit for solid compound fertilizers of 1.1%. The Ugandan government has no set tolerance limits for fertilizers. IFDC used Kenyan standards to evaluate Ugandan samples (Sanabria et al. 2018).

the market as sophisticated copies, with high-quality branding and packaging that can pass for the legitimate product. Application of adulterated or counterfeited pesticides can adversely affect crop growth. Pesticides are sold according to a labeled concentration of the active ingredient.

An issue raised by Haggblade et al. (2018) in their work on pesticides in Mali is the widespread presence of unregistered pesticides in markets, including pesticides that are registered in other neighboring countries but not in Mali and pesticides with no registration in the region. Haggblade et al. also document the presence of pesticides with banned ingredients in Mali including pesticides containing atrazine and paraquat. Murphy et al. (2012) evaluate the contents of 128 samples of pesticides purchased in The Gambia and find most products are unlabeled, sold in plastic bags or unlabeled plastic containers; they find a wide range of pesticides for sale, nearly half of which contained components that are banned by the World Health Organization or in the United States.

IV. Fertilizer Quality Measurement and Evidence

Measuring Agronomic Quality

Lab-based measures are required for accurate assessment of fertilizer nutrient content. Nitrogen has measurement requirements that are distinct from other nutrients. The International Fertilizer Development Center (IFDC) uses Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) to measure potassium (K2O), Calcium (Ca), Magnesium (Mg), Zinc (Zn), Boron (B), and Cd (Cadmium) in fertilizer samples and has used both the Kjeldahl method and combustion analysis to measure nitrogen (N) and sulfur (S) (Sanabira 2013; Sanabria 2019a; Sanabria 2019b). Note that determining adulteration once the nutrient content is found to be out of compliance requires a further analysis step to identify and document the presence of non-fertilizer material fillers; this step is essential in order to distinguish adulteration from errors in manufacturing. In addition, best practices for fertilizer testing include calculation and reporting of the analytical error, which is the error from the chemical analysis itself. Analytical error can be due to instrument malfunction (due to mis-calibration for example) or analyst error and is calculated by double-testing samples and comparing the results. Several recent research studies have used two separate labs to test the same samples to assess differences in the analytical error across labs. Ashour et al. (2019a) for example sent 115 samples of urea fertilizer and 72 samples of NPK to both a Ugandan lab – which used the Kjeldahl method - and to a lab based in the United States – which used combustion (also known as the Dumas method) – and the results were substantially different.[13] Michelson et al. (2021) shipped samples from Tanzania, where facilities for measurement of nitrogen content were limited, to both Kenya and to the United States for testing. Ten percent of the samples were tested in both labs. Initial results from the Kenyan lab suggested significant and widespread nutrient problems in the samples but these results were not consistent with the lab results for the same samples from the United States. All samples were subsequently reanalyzed in the Kenyan lab with re-calibration based on results from the US labs. This

[13] While the Ugandan lab found wide variation in the nitrogen content of both the urea and NPK samples; between 20% and 70% nitrogen in the urea and between 5% and 30% for the NPK, the US-base lab found that nearly all urea samples contained 46% nitrogen and that nearly all NPK contained 17% nitrogen.

reanalysis found virtually no nutrient problems in the urea samples, with only 1% out of compliance and then only slightly so.[14]

Nitrogen

The two primary lab-based measures to assess nitrogen content are the wet-chemistry based Kjeldahl method in which samples are ground and then diluted and distilled, and the Dumas method, which uses sample combustion at high heat. Mass spectroscopy (discussed below) is not used to measure nitrogen in samples because of strong background effects in the measurement caused by the presence of atmospheric nitrogen.

The Kjeldahl method is well-established and widely used in nutrient analysis but labor intensive and relatively slow, with a 100-minute analysis time per sample. Developed in 1883 by Johan Kjeldahl, the method is used in a range of applications including analysis of soils, feed, and wastewater. The Kjeldahl method involves several manual steps that can introduce human error. In contrast, the combustion-based Dumas method[15] is fast and automated, with a 4-minute analysis time, and relatively inexpensive. Tate (1994) compared the Kjeldahl and combustion methods and found the two analyses to produce statistically equivalent estimates of nitrogen content in analyzed fertilizer but concluded that combustion analyses were "more time efficient, more accurate, and less hazardous than Kjeldahl analyses" (p.829).[16]

Non-nitrogen nutrients

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[14] Costs for fertilizer testing can vary considerably based on whether the lab is located in the United States or in Sub-Saharan Africa and whether the lab is a university, government, or private lab. Costs for testing nitrogen content in urea gathered by a U.S. based research team in 2021 included and were all based on the combustion-based method (Dumas):

- $60 per test for a private lab in East Africa
- $27 per test for a government lab in East Africa
- $45 per test in a U.S. based private lab
- $38 per test in a U.S. based university lab

Testing compound or blended fertilizers is generally more expensive if the assessment includes multiple nutrients. Lab costs to test NPK gathered by the same U.S. based research team in 2021 found (again, all combustion-based):

- Between $30 and $90 per sample to test for total N and available P in private U.S. based labs
- Between $30 and $40 per sample to test for total N and available P in U.S. university labs
- Between $50 and $152 per sample to test in private laboratories in East Africa

The U.S. based testing costs quoted above do not include the costs of packing and shipping samples via international shippers.

[15] The Dumas method is also known as method number AOAC 993.13 by the Association of Official Agricultural Chemists.

[16] The research team led by Michelson at the University of Illinois at Urbana-Champaign has developed a means of verifying urea fertilizer quality using a smart phone application. The machine-learning based image classifier can detect the presence of non-urea materials. The tool is designed to be used by farmers and fertilizer sellers to verify urea quality before purchase. The tool has applications for farmer learning and belief updating and is being tested.

Inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma-optical emission spectroscopy (ICP-OES) are two forms of mass spectrometry used to measure the presence and quantities of non-nitrogen elements in fertilizer including Ca, Fe, K, Mg, Na, P, and S. The spectrometer converts elements to a gaseous state and then assesses the wavelengths of the light to detect the presence and quantity of elements present in the sample.

Agronomic Quality: Evidence

Assessment of bag characteristics including bag weight and expiration date and of observable fertilizer quality attributes is done based on observation. Bag weight shortages within 1% of the weight reported on the fertilizer label are permitted in international regulatory systems though these can vary by region and country; a 50kg bag missing less than 0.5 kg would be in compliance and those more than 0.5 kg short are out of compliance (OOC). Granular integrity, caking, and presence of impurities and discoloration is often evaluated based on visual assessment. In Michelson et al. (2021) these characteristics were independently coded by two enumerators from photographs of the sampled fertilizers with each characteristic assessed as either present or not. IFDC assesses bag condition and weight of the bag, granule segregation, granule integrity, caking, moisture content by observation and/or feel of the fertilizer and qualitatively and separately rates these characteristics for a given sample as none, low, medium, or high (Sanabria et al. 2013).

Evidence suggests that agronomic quality issues are relatively rare but are (1) more common in multi-nutrient fertilizers than in single-nutrient fertilizers and (2) are rarely due to adulteration.

Nutrient content shortages in fertilizers tend to be quantified in terms of both the frequency with which they occur in sampling and their severity. Samples are classified as in compliance or out of compliance but also by how much they are out of compliance.

Urea

Evidence on urea fertilizer quality suggests that nitrogen deficiencies in urea are extremely rare. As a single nutrient fertilizer, errors in manufacturing are unlikely; the urea molecule contains 46% nitrogen (N) and reducing that content during manufacturing is difficult and uncommon. Adulteration and counterfeiting in urea are also unlikely given (1) the color, size, and textural uniformity of the urea prills which makes successful adulteration difficult and (2) it is only profitable to dilute fertilizer with something cheaper than the fertilizer itself, and urea is low-cost relative to plausible adulterants (table salt, kaolin). Foreign substances like sand are visually detectable and hard to pass unnoticed.

Table 1 (based on a table in Hoel et al. (2021)) summarizes the results of recent IFDC reports and academic studies based on sampling and testing the nitrogen content of urea fertilizer. All studies are conducted in Sub-Saharan Africa. Nearly all academic studies have focused on urea fertilizer. Studies include samples collected from retail shops, wholesalers, importing ships, and farmers. Quality issues prove rare with the exception of two studies: an analysis of fertilizer quality in Ghana conducted by IFDC in 2010 in which 9% of the samples (21 out of 222) had insufficient nitrogen and a study conducted by Bold et al. in 2014 in Uganda in which 100% of the 369 samples tested were found to be missing nitrogen, and missing on average 30% of their nitrogen, an outlier result in published studies and reports.[17]

Multi-nutrient fertilizers

Evidence regarding the measured agronomic quality of multi-nutrient fertilizers suggests the presence of far more quality issues than in urea. Michelson et al. (2021) report results of tests of DAP and CAN collected in Tanzania and find 15% of DAP samples out of compliance and 63% of CAN samples. While frequency is relatively high, severity is relatively low: mean nitrogen deviations are 7% for DAP and 6% for CAN. Asante et al. (2021) find that NPK sampled in Ghana (15 samples) meets standards for nitrogen, phosphorous, and potassium. Apart from Michelson et al. (2021) and Asante et al. (2021), nearly all published evidence regarding the quality of multi-nutrient fertilizers comes from IFDC reports on West Africa (2013), Uganda (2018), and Kenya (2018). IFDC reports that quality problems are most frequent in NPK fertilizers manufactured through blending; 51% of the 106 samples of NPK 15:15:15 (the most commonly found NPK fertilizer in West Africa in the study) were out of compliance based on the ECOWAS standards as were 86% of the 20:10:10 blend samples and 96% of the 15:10:10 blend samples. More work is required to understand the degree to which these widespread but generally modest shortages are economically and agronomically significant.

The IFDC report on the quality of fertilizer in West Africa (Sanabria et al. 2013) argues that nutrient deficiencies in some blends is likely attributable to uneven distribution of granules in the bags due to improper blending (mixing). In such cases, the nutrient composition of the entire bag may be in compliance with the labeled nutrient content but non-uniform distribution within the bags means that samples taken from the bag are not in compliance. In addition, small farmers purchasing blends from open bags or in repackaged smaller bags are likely to receive products with nutrient contents that do not reflect the manufactured standard. Nutrient deficiencies in blends can also be attributable to manufacturing problems, poor control of blending procedures, and poor-quality blending equipment. Quality issues were much less prevalent in the compound fertilizers sampled in the IFDC studies.[18] Results from IFDC studies in Uganda and Kenya are consistent with the findings of quality issues arising in blends, likely due to problems in manufacturing (Sanabria et al. 2018a and 2018b).

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[17] Sanabria et al. (2018) write in their Uganda fertilizer assessment of the Bold et al. (2017) findings of these widespread and significant nitrogen shortages in urea: "the report does not identify or quantify the presence of materials that may be used to dilute nitrogen content in the urea samples. Dilution is the only possible way of reducing nitrogen content in urea. The nitrogen content in the samples used as evidence could be below 46% as a result of deficiencies in the use of the Kjeldahl method, especially when the method is applied manually and by personnel with limited experience analyzing fertilizers. A very common mistake is assuming that a lab with experience analyzing soils will perform well analyzing fertilizers." In fact double testing of NPK samples by Asante et al. (2021) showed discordance between results of samples double tested in a Canadian lab and a Ghanaian lab. Both labs had used the Kjeldahl method. The Ghanaian lab initially identified significant nitrogen deficiencies but retested the samples after the Canadian lab found that the samples met nitrogen standards. Upon retesting, the Ghanaian lab identified a problem with the nitrogen digester and found that nitrogen levels were also good in the samples.

[18] Crystal and liquid fertilizers, which comprise a small share of the market, were found to have significant quality issues with considerable nitrogen shortages documented in Kenya (Sanabria et al., 2018a).

Adulteration and counterfeiting in mineral fertilizer is rare. The IFDC report argues, "the perception that fake or adulterated fertilizers in West African markets is a dominant quality concern is not supported by the findings of this study." Of the 2,037 samples IFDC collected in West Africa, only seven were found to contain no materials with fertilizer properties and were classified by the IFDC researchers as adulterated and misbranded.[19, 20] These seven samples were all of the same type and location of origin: a superphosphate fertilizer collected from Nigeria. IFDC analyses conducted in Uganda (2018a) and Kenya (2018b) similarly found no evidence of fillers or foreign materials suggesting adulteration.

Visually Observed Quality: Evidence

Michelson et al. (2021) find a high incidence of fertilizer with degradation in observable physical characteristics including the presence of powdering (in which granules lose their structural integrity), caking (in which the fertilizer forms a hard aggregate), and impurities. More than 30% of fertilizer sampled in Morogoro region, Tanzania, had evidence of at least one of these issues. IFDC reports also document that these visually observed quality characteristics are commonly degraded: 15% of bags sampled in Uganda, 90% of urea samples in Senegal, and 59% of samples of urea from Togo and Côte d'Ivoire exhibited medium or high levels of caking. Fifty percent of the samples from West Africa were assessed by IFDC to have fine particles, with granular integrity moderately or significantly compromised. Asante et al. (2021) find that 13% of NPK samples from Ghana have some degree of modest granule segregation and 19% have some caking.

IFDC reports (Sanabria et al. 2013; 2018a; 2018b) document that fertilizer bags are often underweight.[21] For example, 41% of bags in Nigeria, 28% in Côte d'Ivoire, 13% in Senegal, 12% in Ghana, 7% in Togo, and 10% in Uganda were underweight. Results in Kenya showed that the frequency of underweight bags increases as the bag size decreases, with 38% of sampled 10kg bags underweight, 28% of 25-kg bags, and 19% of 50-kg bags. IFDC researchers caution that they are unable to ascertain whether they are underweight due to deliberate tampering or due to poor process control during bagging or re-bagging.

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[19] The classification of these samples as adulterated was based on careful assessment. The samples were initially tested in West Africa, then sent to the IFDC laboratory in Alabama, United States. After initial analyses indicated that the samples contained no phosphorous, the researchers used X-ray mineralogical methods to characterize the spectrum of each sample.

[20] The authors of the 2013 IFDC report write (p. xiv): "Trained inspectors reported evidence of adulteration in 31 of 134 (23 percent) samples collected in Côte d'Ivoire but only 14 of 414 (3.4 percent) samples from Nigeria. However, the only cases of completely proven adulteration are the seven samples of SSP from Nigeria that were found to have no P_2O_5 content or any of the minerals that carry P in phosphate rock. While high percentages of nutrient deficient samples in some NPK blends found in some countries could be interpreted as fraud during manufacturing or along the distribution chain, this is not substantiated by findings of this study; the lack of or poor control of blending procedures and use of inadequate blending equipment are also possible explanations.

[21] As discussed, tolerance limits for weight shortages are 1% of the labeled weight based on international standards. A 50-kg bag with a shortage greater than 0.5kg is considered out of compliance, for example.

As noted above, powdering and granule segregation can lead to uneven distribution of nutrients in fertilizer bags. This can be important both for sampling to assess quality and for small farmers who may purchase fertilizer in small quantities of one or two kilograms scooped directly from open bags or repackaged for sale, or for famers who purchase larger quantities but with use spanning a longer time period, such as multiple agricultural seasons. IFDC notes a relationship between high moisture content of the samples and high caking. Moisture content and granular segregation were found to have a negative relationship with nutrient content in NPK blends in West African samples (Sanabria et al. 2013) but this mapping is not clear. Urea, for example, often exhibits caking and granular degradation without any deviations in nitrogen content. Samples with observed quality issues related to powdered granules and discoloration are often found to have good nutrient content and samples with no observable problems (especially blends) can be found to have deficiencies. Evidence in Michelson et al. (2020) suggests that farmers use these observables as a signal of unobservable nutrient content (more below on farmer assessment).

V. Pesticide Quality Measurement and Evidence

Glyphosate herbicide is generally sold in concentrations of 36 and 43.9 percent glyphosate by weight. Glyphosate formulation verification is done in a lab using high-pressure liquid chromatography with ultraviolet detection. The method compares tested samples to a reference sample and is the standard procedure to measure glyphosate concentration (Morlier and Tomkins, 1997). Samples are tested in duplicate. Haggblade et al. (2018) use this method to test 100 samples of glyphosate acquired in Mali and Ashour et al. (2019b) use the method for their 483 Ugandan samples. Haggblade et al. (2018) note that Mali had no accredited lab to test for glyphosate concentration and so samples were tested both in a West African lab outside of Mali and also in the United States. Costs for glyphosate testing are high relative to fertilizer testing: $175 per test at a private Ugandan lab (2014), $195 per test in a private U.S. lab, and $50 per test at a Ugandan university laboratory.

Several recent studies and reports (*Counterfeit Pesticides Across Europe* 2008; Fishel 2008) argue that counterfeit pesticides are increasing globally. Only a handful of academic studies have tested the quality of pesticides for sale in markets in low-income countries. These studies have primarily focused on glyphosate. Haggblade et al. (2018) test 100 samples of glyphosate collected from four primary agricultural markets in Mali and find that one-third contained either too much or too little of the active ingredient. They find a large experimental error in the tests conducted however, and stress that improvements in laboratory testing capability in West Africa are critical. Ashour et al. (2019b) find that sampled bottles (483 samples from 120 markets in 25 districts in Uganda) are missing on average 15% of the advertised amount of glyphosate, with 31% of the samples containing less than 75% of the advertised concentration. Ashour et al. are unable to distinguish between counterfeiting, adulteration, storage problems, or manufacturing errors.[22]

[22] Ashour et al. also found that some glyphosate samples had a concentration of the active ingredient that exceeded the manufacturing standard. One way this can happen for pesticides is improper storage and product expiration, which can lead to evaporation of some water from the product, leaving a higher concentration of the active ingredient. There could be other reasons, but this was one that was offered.

Haggblade et al. (2021) find a strong relationship between bad formulation and a brand being unregistered in their study. They find no relationship between price and the accuracy of the stated concentration, nor do they find that older products (based on the labeled date) are more likely to have quality problems.

VI. Farmer Beliefs

For both fertilizers and for pesticides, it can be difficult for farmers to evaluate quality. The quality signal may be somewhat easier for farmers to detect with pesticides as evaluating the effectiveness eliminating a weed is likely more direct and immediate than fertilizer's effect on plant growth and yields, however problems related to pesticide suitability and application technique can obfuscate and obstruct learning. Non-labor agricultural inputs are experience goods but the weather-driven stochasticity in agricultural production and lack of knowledge about proper use can make them effectively credence goods whose quality cannot be evaluated even after use. Farmers may not be able to assess for days or weeks after application whether the applied input "worked". They need to see if the plant grew, if the leaves developed discoloration characteristic of unaddressed nutrient shortages, whether the weeds or the insects died. But other factors can also contribute to the effectiveness of these inputs: whether the farmer uses the right input or formulation given particular pest pressures, soil quality, or growing conditions; the timing and amount of rainfall; the timing of application and whether the input was correctly applied. Bold et al. (2017) and Hoel et al. (2021) demonstrate through modeling and simulations the difficulties that these factors present for farmer learning about the quality and effectiveness of the inputs they purchase and apply.

Farmer beliefs about fertilizer quality

Evidence suggests that small farmers have concerns about fertilizer nutrient content and that those concerns may negatively affect their purchasing. Sanabria et al. (2013) indicate in a study of fertilizer in West Africa that farmers report beliefs that adulterated urea is widespread in their markets but that this suspicion lacks scientific support (p. 39). A possible contributing factor: many small farmers purchase fertilizer in quantities less than the 50 or 25kg bags available from manufacturers. Small farmers purchase one or two kilograms at a time from open bags in agri-dealer shops or in small plastic bags that are repacked for sale from opened bags by agri-dealers. This practice of selling fertilizer from open or repacked bags is a source of considerable suspicion regarding fertilizer quality in many markets, both among farmers and among fertilizer regulators. In several countries the practice of purchasing from open bags is illegal but still a primary means by which small farmers acquire fertilizers.

Five studies (Bold et al. 2017, Ashour et al. 2019a, Hoel et al. 2021, Maertens et al. 2021, and Asante et al. 2021) have directly elicited farmer beliefs about mineral fertilizer quality. Consistent with other academic studies on fertilizer quality in low-income countries, these elicitations have focused on urea. These studies all find that farmers on average believe that there are quality problems in urea in their local markets, despite evidence to the contrary.

Bold et al. (2017) survey 312 small farmers in Uganda about their beliefs about urea fertilizer in the closest shop by asking respondents "to assess the quality of fertilizer on a scale of 1 to 10, where 0 means there is no nitrogen, 5 means that half of the official nitrogen is there, and 10 is the best possible quality". Bold et al. find that farmers expect urea in their local shop to contain 38% less nitrogen than the manufactured standard; this means that farmers on average expect urea to contain 28.4% nitrogen by weight rather than 46%.

- Hoel et al. (2021) and Maertens et al. (2021) elicit farmer beliefs about fertilizer quality in Tanzania by asking farmers to think of their local market and "imagine that ten farmers from your village would visit agro-dealer shops in [this market] during the long rains season and each purchase 1 kg of fertilizer." Then they ask, "If 10 farmers in your village purchase 1 kilogram of fertilizer at [this market] during the long rains season, how many would get good quality bags? They ask farmers how certain they are about their response. Hoel et al. find that 70% of farmers believe that some fertilizer in their local market is bad; on average, they believe that 34% is bad quality. Only 28% of the farmers believe that all fertilizer in their local market is good. They also report considerable uncertainty about these beliefs. Maertens et al. find that farmers believe that about 30% of fertilizer in their local market is bad.
- Ashour et al. (2019a) in Uganda also ask how many out of ten farmers who went to a local market to purchase fertilizer would buy bad fertilizer. They elicit the full distribution of beliefs – asking the maximum number of farmers that would purchase bad fertilizer and the minimum number. They divide the elicited range into eleven bins and provided farmers with 15 beans to distribute across the bins. Ashour et al. find that farmers believe that 35 percent of the fertilizer in their local market is of bad quality; but elicited distributions exhibit considerable uncertainty in this stated belief. [23] They find that 47% of farmers who purchased herbicides in the previous season reported believing that herbicides are often counterfeit or adulterated and 30% of farmers who had used mineral fertilizer reported believing that these fertilizers are often counterfeited or adulterated.
- Asante et al. (2021) asked both input dealers and farmers in Ghana to assess the quality of fertilizer in their district by estimating how many bags out of every ten bought and sold were good quality versus substandard quality. Researchers asked the question separately for commercial fertilizer and for fertilizer available through Ghana's subsidy program. Input dealers proved more pessimistic than farmers. Based on their own experience, input dealers estimated that 45% percent of the commercial fertilizer was of bad quality and 31% of the subsidized fertilizer. Farmers reported that 28% of the commercial fertilizer in their district was likely substandard and 19% of the subsidized. And 47% of agri-dealers reported that fertilizer quality issues are among the most frequent complaints they receive from their customers.

[23] Ashour et al. (2019a) also asked qualitative questions regarding how much of the fertilizer was likely counterfeit/adulterated: all of it, most of it, some of it, none.

Given the strong evidence that urea fertilizer for sale in markets is of good quality and given the difficulty of compromising the nitrogen content of urea fertilizer either through manufacturing problems or adulteration/counterfeiting, farmer average beliefs about urea quality problems do not appear to reflect the truth. Michelson et al. (2021) argue that evidence suggests the presence of an equilibrium where beliefs are not consistent with and are not converging to the truth. Some work has focused on why and how such an equilibrium can persist.

Fertilizer quality can be difficult for a farmer to assess based on observation or experience, especially given the stochasticity of production outcomes driven by weather variability (Bold et al. 2017). In particular, Hoel et al. (2021) argue that farmers are prone to misattribute low yields to bad fertilizer rather than to weather shocks, misapplication, or timing issues. In the presence of uncertainty about fertilizer quality beliefs, Hoel et al. show that this tendency to misattribute bad outcomes to bad fertilizer can make it impossible for farmers to learn about the true (good) quality of urea fertilizer over time. Some error could stem from information problems related to appropriate fertilizer type or correct application rates. Other error could result from bias in farmer estimates of plot size as they transfer application quantity recommendations to their own plots (Abay et al. 2022; Bevis and Barrett 2020; Abay et al. 2021; Gourlay et al. 2019).

Evidence suggests farmer beliefs about quality issues may affect fertilizer adoption. Hoel et al. (2021) and Michelson et al. (2021) provide some evidence of the relevance of beliefs to purchasing using willingness to pay assessments. Both studies find that farmers are willing to pay more than 40% more -- and 40% more than the prevailing market price at the time -- for urea fertilizer that has been lab tested and found to be pure. Ashour et al. (2019a) also find that 69% of farmers avoid buying fertilizer because they worry about quality.

A single study (Maertens et al. 2021) has used a randomized controlled trial to show that information can change beliefs about urea quality and by changing beliefs also change purchasing and use. They use a randomized and low-touch information campaign of posters and flyers to inform farmers and agri-dealers that urea tested in the markets two years previously was of good quality. They find that the information exposure improves farmer beliefs about urea quality and increases purchasing. The effect is driven by changes at the extensive margin, by farmers who were not previously using fertilizer.

Farmer beliefs about pesticide quality

Haggblade (2021) notes that farmers are generally unable to distinguish the registered pesticides from those that are fakes in the marketplace. Ashour et al. (2019b) use a field experiment to measure beliefs. They asked 1,390 households to imagine that "10 farmers like themselves" were to go to their local market and purchase one bottle of herbicide apiece. They were asked how many of those 10 purchased bottles would be counterfeit or adulterated. 82% of surveyed farmers who had previously used herbicide believe that herbicide quality in their markets is likely to be tampered with. Farmers believe that 41% of herbicide (glyphosate) in their local market was counterfeit or adulterated. They find that farmers living in areas with worse quality glyphosate (based on the test results) on average believe that quality is worse. The relationship is statistically significant but economically small in magnitude: beliefs about the prevalence of bad herbicide are only 4.8 percentage points lower in the worst market than in a "perfect market" with no quality problems in their data. Their results suggest that farmers may have only limited ability to identify quality problems on average.

VII. Discussion

The results of our review suggest at least four implications for future research. First: these results indicate the importance of additional work to document the market-level quality and actual deployment of non-urea fertilizers as well as pesticides. This work will require careful lab-based assessment. Further testing of urea fertilizer in East Africa, however, may not be worthwhile, given the documented lack of variation in its quality, the difficulty and lack of economic incentive for urea adulteration, and the scarcity of manufacturing problems for single-nutrient prills. Instead, future testing might more constructively focus on NPK, which is also widely used by small farmers and more prone to quality issues due to manufacturing problems, or on problems with granule segmentation in storage. NPK has many different nutrient formulations in the market, however, so care would need to be taken to record accurately the sampled blend for testing.

Though fertilizer or pesticide samples can be gathered directly from farmers and shops, few good options currently exist for in situ testing. Consequently, samples need to be tested in a certified lab, with a subset of samples double-tested (in the same lab) to establish an estimate of experimental/analytical error.[24] Portable apparatuses using spectrometers are potentially useful for measuring fertilizer or pesticide quality, but such measurements would need careful calibration to assure reliability. The range of components in fertilizer products can interfere with detection and quantification of spectra used to evaluate nutrient presence. Moreover, the capabilities of such portable apparatus may vary considerably with regard to fertilizer products with the same nutrient rate but different manufacturing processes. According to at least one reliable report, many labs in Sub-Saharan Africa currently have insufficient access to a sufficient range of fertilizer samples to achieve the needed calibration; a second problem is limited statistical expertise for performing these calibrations (personal correspondence with Joaquin Sanabria, 2021).

Second: results also suggest that research interventions related to mineral fertilizer and pesticide quality should clearly evaluate and specify the input quality at issue. Research on herbicide quality might usefully focus on understanding exactly where quality problems emerge in the supply chain and on testing various incentives or policy strategies to raise quality. Research on fertilizer blends may need to take a different approach – especially if quality issues in blending originate in manufacturing.

Third: as discussed above, we see evidence of widespread concern among farmers regarding the quality of non-labor inputs available in their local markets in Sub-Saharan Africa. In the case of urea, these concerns are not consistent with measured quality. With regard to other fertilizers – especially blended fertilizers – concerns about quality are more likely to reflect actual quality issues in the market. Farmer

[24] A second randomly-selected subset of samples should be tested in a second lab, likely in an ISO-certified lab in the United States, South Africa, or Europe.

concerns about herbicide quality are also widespread and seem to reflect quality problems, but there is enormous spatial heterogeneity in what farmers believe about quality (Ashour et al. 2019b), and evidence suggests that market prices do not correlate with verified quality (Michelson et al. 2021; Ashour et al. 2019b).

Measuring farmer beliefs about the quality of these inputs is possible and scalable in a survey context. Further investigation of such beliefs may be important in their own right for understanding adoption frictions, but may also lead to broader insights about learning, the evolution of suspicions over time, the social dynamics of input beliefs, and documenting and interpreting patterns of spatial heterogeneity. The appendix to this paper includes three examples of survey questions that have elicited farmer beliefs. However, research strongly suggests that elicited beliefs will not provide a good proxy for actual quality available in the local market. Instead, they can provide a measure of these concerns at the household level, and how these concerns correlate within and across villages. Beliefs will probably also correlate with other economically consequential attributes: liquidity, risk aversion, experience. If inaccurate perceptions are a bottleneck to adoption, measurement of beliefs about quality could be important for empirical analysis and policy initiatives. Farmers within the same village can hold very different beliefs about fertilizer and pesticide quality. Maertens et al. (2021) find that farmers who have never used fertilizer are more suspicious of its quality.

Pesticide use has consequences for local environments and also for human health. Use of counterfeit herbicides, especially those with locally banned ingredients, brings additional risks. Additional evidence should be gathered with special attention to the health and environmental effects of counterfeit and adulterated herbicides. Related future work could focus on the way that farmers understand these environmental and health risks, and to what degree their concerns about the special dangers of counterfeit pesticides might interact with and inform the uptake decision.

Fourth: our review suggests the importance of research focusing on local and regional agri-dealers. If quality concerns arise from asymmetric or unobservable information in the marketplace because farmers lack access to reliable information on mineral fertilizer quality, a complementary question is what agri-dealers know and believe about the quality of the inputs they sell and how they manage real or perceived quality risks in the supply chain.

Research on non-labor input quality should be complemented by efforts to improve measurement of the quantity and timing of non-labor agricultural inputs application. In particular, farmers may be incorrectly timing input application, they may be using incorrect techniques to apply them, or they may simply not be applying enough of the right nutrients. Resulting low yields may be at least in part due to bad or insufficient application rather than quality problems but may further contribute to farmer perceptions of bad input quality. The existence of potentially reinforcing relationships between application practices, low yields, and beliefs about input quality and efficacy suggests the importance of understanding not merely the amounts of inputs that farmers apply but also when and how they apply them.

A small literature has studied the effects of the timing of non-labor inputs application. Jagani et al. (2021) use a household panel in Kenya to show that farmers respond to variation in temperature within the growing season, adjusting input application and labor use to short-run temperature shocks. Islam and Beg (2021) randomize farmers into a treatment that improved the timing of urea application among rice farmers in Bangladesh, reducing urea use by 8% without reducing yields. They find in their baseline survey that farmers are applying urea earlier than recommended in the growing season, and are applying more than recommended quantities. Farmers who experience outreach about this issue reduce applications of urea early in the season, when returns to application are low.

Though accurate measurement of application quantity is undoubtedly important, there has been minimal research to date on this topic. Beegle et al. (2012) suggest that because fertilizer purchase and application are generally salient and singular events, this particular domain of agricultural data is less prone to recall bias than other domains, such as agricultural labor. Indeed, they generally support this hypothesis in their analysis of data from national surveys in Malawi and Kenya, taking advantage of the 12-month fieldwork design to assess the impact of recall duration on quantity reported, where they find no evidence of recall bias with respect to fertilizer use (binary), and minimal evidence of recall bias with respect to quantity of application, though findings do differ slightly by crop type and household headship. More recently, Wollburg et al. (2021) find that longer recall periods lead to recall bias both in fertilizer use (binary) and in the quantity of application. With increasing recall periods, farmers are less likely to report the use of fertilizers but report higher quantities applied.[25] While differences in methods of elicitation exist across research and data collection efforts, head-to-head within-survey experiments to compare methods for measuring quantity of input application does not seem to have been undertaken as yet. Within-survey experiments about mineral fertilizer and pesticide quantity application could center on recall periods or applications over different units (by plot vs by crop, for example) compared against a benchmark of farmer diaries or weekly calls to assess week-by week quantities applied, also with a view to best addressing measurement issues associated with non-standard reporting units. Similar within-survey experiments about agricultural non-labor input timing could be conducted. We have encountered no research empirically exploring methods for measuring the quantity of fertilizer or pesticide applied using within-survey variation in recall periods or input application diaries.

VIII. Conclusions

Agricultural input quality in Sub-Saharan Africa is beginning to receive needed attention from researchers and policy makers; however, the focus so far has been on urea fertilizer nutrient quality and on glyphosate herbicide. Results in this review document that urea quality does meet listed specifications, but that nutrient shortages can characterize other market-available fertilizers,

[25]Recent work by Mueller et al. (2022) assesses recall bias in reported pesticide use, disaggregated by active ingredient, over a two-year period, finding that reported prevalence rates (irrespective of quantity applied) of most of the main pesticides increased after a two-year recall period relative to the baseline.

particularly blends, and that glyphosate herbicide also exhibits widespread but variable deficiencies in the active ingredient. We argue that more attention to these issues is warranted. Researchers have also identified widespread evidence of degradation in physical, observable quality characteristics including granule integrity in fertilizer and packaging condition but evidence suggests that these do not decrease the efficacy of the fertilizer, though they may increase the difficulty of application and affect farmer beliefs about quality.

We are drafting this review in the spring of 2022, during a time when fertilizer prices are high and climbing, already exceeding the elevated levels of 2008. High fertilizer prices may change the incentives associated with adulteration and counterfeiting, especially as supply shortages and high prices hit low-income countries. Input quality may very well be dynamic, responding to relative prices and opportunities in markets. It is important to gather data over time on quality and on farmer beliefs about quality, which may also be dynamic and move in response to price changes and perceived shortages.

Results regarding farmer beliefs have begun to suggest that uncertainty regarding unobserved quality of agricultural inputs may affect purchasing and use. Variable input quality and beliefs about variable input quality may partially explain problems with uptake across Sub-Saharan Africa, but more research is needed on the determinants and the consequences of extant quality problems and on farmer beliefs impacting their decisions about inputs.

Table 1. Overview of urea fertilizer quality sampling test results: published studies and reports (reproduced from Hoel et al. (2022))

Year sample collected	Country	Acquired from	Authors/study	number of urea samples	Percent of samples out of compliance	Nitrogen OOC shortage severity
2014	Uganda	Retail sellers	Ashour et al. (2019a)	137	All in compliance	n/a
2014	Uganda	Retail sellers	Bold et al. (2017)	369	100%	30.0%
2017	Uganda	Importers, wholesalers, retailers	Sanabria et al. 2018b (IFDC)	38	7%	1.25%
2010	Ghana	Retail sellers, gov depots	Sanabria et al. 2013 (IFDC)	222	9%	<2.0%[a]
2010	Nigeria	Retail sellers, gov depots	Sanabria et al. 2013 (IFDC)	147	All in compliance	n/a
2010	Côte d'Ivoire	Retail sellers, gov depots	Sanabria et al. 2013 (IFDC)	42	All in compliance	n/a
2010	Senegal	Retail sellers, gov depots	Sanabria et al. 2013 (IFDC)	64	All in compliance	n/a
2010	Togo	Retail sellers, gov depots	Sanabria et al. 2013 (IFDC)	59	All in compliance	n/a
2016	Kenya	Retail sellers	Sanabria et al. 2018a (IFDC)	31	All in compliance	n/a
2015-2016	Tanzania	Retail sellers	Michelson et al. (2021)	300	2%	5.0%
2016	Tanzania	Farmers	Michelson et al. (2021)	121	4%	4.0%
2019	Tanzania	Retail sellers	Michelson et al. (2021)	45	All in compliance	n/a
2018	Tanzania	Warehouses	Michelson et al. (2021)	8	All in compliance	n/a
2018	Tanzania	Ships at the port in Dar es Salaam	Michelson et al. (2021)	11	All in compliance	n/a

Notes:
[a] not precisely discernable from the report. 20 samples were out of compliance with nitrogen content between 44% and 45.5%.

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