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Revisiting the Demand and Profitability of Chemical Fertilizers amid Global Fuel-Food-Fertilizer Crisis

Evidence from Ethiopia

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Abstract

We revisit the state of smallholder fertilizer demand and profitability in Ethiopia in the face of the recent global fuel–food–fertilizer price crisis triggered by the Russian–Ukraine war and compounded by other domestic supply shocks. We first examine farmers' response to changes in both fertilizer and food prices by estimating price elasticity of demand. We then revisit the profitability of fertilizer by computing average value–cost ratios (AVCRs) associated with fertilizer application before and after these crises. We use three-round detailed longitudinal household survey data, covering both pre-crisis (2016 and 2019) and post-crisis (2023) production periods, focusing on three main staple crops in Ethiopia (maize, teff, and wheat). Our analysis shows that fertilizer adoption, use, and yield levels were increasing until the recent crises, but these trends seem halted by these crises. We also find relatively large fertilizer price elasticity of demand estimates, ranging between 0.4 and 1.1, which vary across crops and are substantially larger than previous estimates. We find suggestive evidence that households with smaller farm sizes are relatively more responsive to changes in fertilizer prices. We also document that farmers' response to increases in staple crop prices is not as strong as perceived and hence appears to be statistically insignificant. Finally, we show important dynamics in the profitability of chemical fertilizer. While the AVCRs show profitable trends for most crops, the share of farmers with profitable AVCRs declined following the fertilizer price surge. Our findings offer important insights for policy focusing on mitigating the adverse effects of fertilizer price shocks.

Keywords: Fertilizer demand, yield response, fertilizer profitability, shocks, smallholder farmers, Ethiopia.

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1. Introduction

Global fertilizer markets experienced significant price surges beginning in 2020 due to a combination of factors, including higher natural gas prices as well as supply chain and trade disruptions triggered by COVID-19 and the Russia–Ukraine war (Arndt et al. 2023; Glauber et al. 2022; Glauber and Laborde 2022; Hebebrand and Laborde 2024). Although parallel increases in international agricultural commodity prices may have absorbed these price shocks, the implication of these shocks on fertilizer demand, yield response, and profitability remains unknown, especially in low- and middle-income countries. In many African countries, global fertilizer market shocks are often compounded by domestic challenges (e.g., conflict), disrupting the availability and affordability of fertilizers to farm households. Whereas international fertilizer prices have come down from their peaks in 2022, many countries in Africa continue to grapple with persistent inflation, deteriorating terms of trade, and macroeconomic imbalances that keep domestic prices high. The ultimate impacts of the surge in fertilizer and food prices may vary across countries, depending on several factors, including their dependence on imported fertilizers, farm households' purchasing power, and price elasticity of demand (fertilizer demand responses to price changes) (e.g., Arndt et al. 2023; Dillon and Barrett 2016; Rashid et al. 2013; Sheahan and Barrett 2017). Besides the surge in fertilizer prices, domestic fertilizer markets in Africa experienced supply disruptions after the outbreak of the Russia–Ukraine war (e.g., Abay et al. 2022b).

While these shocks are likely to affect trends in fertilizer intensification and yield, the extent to which farm households respond to these shocks depends on, among other factors, the profitability and price elasticities of demand for fertilizers. Nonetheless, disentangling the effects of these simultaneous increases in fertilizer and output prices on fertilizer demand and profitability is less straightforward and remains understudied in the context of Africa. Specifically, while it is possible that some of the rising fertilizer prices are likely offset by the parallel increase in food prices, particularly in areas that are relatively close to urban centers, this is unlikely to be the case in rural areas, given that fuel costs often increase the rate at which input and output prices change relative to distance to markets (e.g., Arndt et al. 2023; Dillon and Barrett 2016; Minten, Koru, and Stifel 2013; Stifel, Minten, and Koru 2016). Furthermore, such offsetting patterns depend on the relative size of price elasticity of demand to changes in fertilizer and output prices. These responses are complex to understand, given that real-time, detailed farm-level production data are often not readily available in these contexts. Partly owing to this data challenge, the extent to which these compounding malign effects undermine fertilizer intensification and smallholder agricultural productivity in Africa remains less understood, while this remains critically important for policymakers desirous of mitigating the challenge, including through fertilizer price policies (Lunduka, Ricker-Gilbert, and Fisher 2013).

At the backdrop of such creeping turbulence to smallholder agriculture, we revisit the demand and profitability of fertilizers in the context of Ethiopia, using data collected before and after the crisis. While this has recently received significant attention in policy discussions (Hebebrand and Glauber 2024; USDA 2023) and has reinforced calls for integrated management of organic and inorganic fertilizers (Snapp et al. 2023), little work to date is empirically grounded in smallholder farm-level data that can inform our understanding of the implications of such a compounded crisis on smallholder agriculture. To help address this gap, we focus on smallholder farming systems in Ethiopia and provide empirical evidence on the sensitivity of fertilizer demand and profitability at the household level and across time.

We use unique longitudinal household survey data covering three rounds, collected in 2016, 2019, and 2023, and hence covering both pre- and post-crisis production periods. We focus on three major crops that grow in the *Meher*—the main rainy season—in Ethiopia: maize, teff, and wheat, which account for most of fertilizer consumption in Ethiopia. We first estimate fertilizer demand using a double-hurdle model, which incorporates a probit model to identify factors affecting households' decisions to adopt fertilizer and a truncated normal regression to analyze factors influencing fertilizer demand at both the extensive and intensive margins. We then compute price elasticities associated with changes in fertilizer and food prices. We estimate yield response to fertilizer applications based on plot-level data using a household fixed effects model, controlling for plot, household, and community level factors. Finally, we compute the average value–cost ratio (AVCR) using an average physical product (APP) estimated from a flexible production function using detailed plot-level data and ratio of prices.

We find consistently increasing pre-crisis trends in fertilizer adoption, nitrogen application rates, yield responses, and profitability, but with important deceleration in these trends after the crisis. We report fertilizer elasticity estimates ranging between 0.4 and 1.1, which vary across crops and farm sizes. These estimates are substantially larger than previous estimates. We also find that smallholder farmers are more responsive to fertilizer prices than to output prices. Furthermore, we document important trends in the profitability of chemical fertilizers for all crops, with increasing

AVCR values between 2016 and 2019 but declining after the crisis. While the AVCRs show profitable trends for most crops, the share of farm households with profitable AVCRs has declined following the fertilizer price surge. Overall, these trends are consistent with the disproportional recent changes in fertilizer and food prices. Although fertilizer prices have almost tripled recently, this increase was accompanied by high staple crop price inflation, on average, allowing fertilizers to remain marginally profitable despite the important heterogeneities across crops and farm households.

Our findings offer important insights for understanding and informing policy responses to shocks arising from various triggers. The relatively large elasticities we estimate suggest that smallholder farmers in Africa exhibit responsive demand function to surges in fertilizer price, underscoring that smallholder farmers are likely to significantly cut back on fertilizer purchases in response to the recent price increases and declines in AVCRs. Given that smallholder farmers are credit constrained and primarily aim to achieve food security in their production objectives, the surge in output prices is less likely to fully absorb the additional cost of fertilizer and hence maintain demand for fertilizer. These patterns signal the need for effective policy instruments to support smallholder farmers in Africa, with the aim of boosting fertilizer adoption and intensification.

The remainder of the paper is organized as follows. Section 2 provides Ethiopia's policy context in the last two decades, summarizing the key milestones in fertilizer use–driven growth in that period. Section 3 presents the data and methods deployed in analyzing fertilizer demand, yield response, and profitability, while Section 4 presents the empirical estimation strategy, followed by the discussion of main results in Section 5. Section 6 concludes with a highlight of key policy implications.

2. Context and prior work

Ethiopia has made important progress in overall economic growth and development in the last two decades, with agriculture the main driver of growth (Bachewe et al. 2018; Diao, Hazell, and Thurlow 2010; Dorosh and Minten 2020). For example, Ethiopia's agriculture sector expanded by 7.6 percent annually between 2004 and 2014, with a 2.3 percent annual growth in total factor productivity, partly due to doubling in use of fertilizer and improved seeds (Bachewe et al. 2018; Berhane et al. 2018). However, achieving Ethiopia's agricultural transformation remains elusive despite such growth rates for over a decade or so and has faced several challenges in recent years.

Prior studies indicate that despite recent progress in reported production levels, productivity levels remain lower than potential yields, one of the key reasons being the low level of intensification, particularly in using chemical fertilizers (Berhane et al., 2020). While most cereal producers widely adopt fertilizer, application intensities are far below required levels (Abate et al. 2020; Berhane, Abate, and Wolle 2022).

Low fertilizer applications rates are often linked to access (supply chain bottlenecks and liquidity constraints) (Ali and Deininger 2012; Yu and Nin-Pratt 2014), production risks (Alem et al. 2010), and yield responses (Burke, Jayne, and Black 2017), for instance, due to mismatch between soil nutrient deficiencies and fertilizer type (Abay et al. 2022a) and to some extent, to profitability (Abay et al. 2018; Davis et al. 2010; Rashid et al. 2013; Spielman, Kelemework, and Alemu 2011; Zerfu and Larson 2013). While the country has been making good progress in improving access to fertilizer by leveraging and revitalizing farmer organizations (cooperatives) that serve as distribution centers and facilitating input credit, the recent supply chain disruptions reportedly limit fertilizer availability considerably. For instance, only 33% of households in our sample report timely availability of fertilizers during the 2023 production season (a decline by 29 percentage points compared with 2019), and only a third were able to buy as much fertilizer as they need and could afford.

Production risks are another barrier to intensive use of fertilizer in Ethiopia, due to increasing climate variability and uncertainties related to input and output prices (e.g., Dercon and Christiaensen 2011). Productivity-enhancing inputs such as fertilizer require greater up-front investments that are at risk if crops fail due to climate events or changes in prices. These risks are important given that smallholder farmers in Ethiopia are subject to credit and insurance market failures (Ali and Deininger 2012; Zerfu and Larson 2011).

While fertilizers are generally considered productivity-enhancing inputs, their profitability largely depends on the relative input and output prices and yield responses. In most low-income countries (including in Ethiopia), higher transport costs account for an important share of fertilizer and output prices (e.g., Dillon and Barrett 2016; Minten, Koru, and Stifel 2013), which ultimately can reduce the profitability of input use. For instance, Rashid et al. (2013) suggest that fertilizer use in Ethiopia is profitable only for maize (with an AVCR of greater than 2, a ratio conventionally used to assess fertilizer profitability in low-income countries to account for risks and other unaccounted transaction costs).[1] Ethiopia's agriculture sector has undergone several changes since Rashid et al.(2013) was conducted, partly due to the supply side government investments in agricultural extension services and the delivery of modern inputs, mainly fertilizers. Despite these positive changes, Ethiopia's modern input supply chain faces several bottlenecks that contribute to the overall low level of intensification.

The recent supply chain disruption resulting from the Russia–Ukraine war and local conflicts seems to exacerbate the above-mentioned barriers to fertilizer use. Reportedly, trends in fertilizer use and application intensity slowed down because of the supply chain disruptions and increases in global chemical fertilizer prices. However, it is not clear whether and to what extent these recent changes have affected fertilizer profitability and hence demand vis-à-vis the considerable increases in crop output prices observed during the same period due to high inflation in the country (Ali 2022). Against this background, we revisit fertilizer demand, yield responses, and profitability in Ethiopia using recent data, given the importance of fertilizer to maintain increases in agricultural productivity in the country. Chemical fertilizers are crucial inputs with important implications for food security, as Ethiopia's soils are increasingly depleted due to population pressure and other factors (Abay et al. 2022a; Abdulkadir et al. 2017; Haileslassie et al. 2005).

3. Data and descriptive statistics

We use data from the Ethiopian Agricultural Commercialization Clusters (ACC) surveys conducted in 2016, 2019, and 2023. In 2016, the ACC survey consisted of 4,991 sample households from 333 *kebeles* (villages) and 153 *woredas* (districts) in the four agriculturally important regions: Amhara; Oromia; Southern Nations, Nationalities, and Peoples' (SNNP), and Tigray.[2] In 2019, the sample was expanded to cover new ACC woredas and kebeles, and it covered 5,311 farm households in 154 woredas and 355 kebeles. The sample households were selected following a three-stage sampling procedure. First, the woredas were stratified into agricultural commodity clusters (ACCs) defined by the Agricultural Transformation Agency (ATA), and five sample woredas were randomly selected from each ACC. Second, two kebeles were randomly selected from each district to be part of the survey. Finally, 15 farm households were randomly

[1] The estimated AVCRs for wheat and teff ranged from 1.27 to 1.86, indicating that fertilizer use is not profitable for these two main crops if one goes by the conventional threshold that AVCR needs to be greater than 2 in low-income countries.
[2] *Kebele* is the lowest administrative unit in Ethiopia.

selected from each sample kebele based on the household lists maintained by local (kebele) administrations. In addition, about 20 percent of the sample was selected from neighboring districts outside the ACCs, using the same three-stage sampling. In 2023, 3,904 households were revisited despite the security situation in Ethiopia (i.e., we were not able to revisit all sample households in Tigray and a sizable number of households in Amhara and Oromia).[3]

Table 1 presents the key household and farm characteristics of the sample. Most sample respondents are male, with male-headed households representing about 90 percent of the sample. Around 49 percent of the household heads are literate (able to read and write). The average farm size owned and/or managed by sample households is 1.4 hectares, of which about 10 percent is reportedly poor in its soil quality/fertility status. About 74 percent of the sampled households reported they receive extension services, and a sizable share adopt agricultural inputs such as fertilizer (72 percent) and improved seeds (53 percent). Additionally, use of organic fertilizer is notable, with about 53 percent of households incorporating it into their farming practices. Table 1 also shows the importance of maize, teff, and wheat farming in Ethiopia, with more than 41 percent, 39 percent, and 32 percent, respectively, of our sample households reporting growing these crops across years.

[3] Attritions due to refusal, relocation, absence during the time of the survey, and deceased respondent were limited to 76 sample households (~0.02%). However, we were not able to revisit all sample households in Tigray and a sizable share of sample households in Amhara (45%) and Oromia (20%) regions in 2023 due to insecurity.

Table 1. Sample household and farm characteristics

Variable	Measurement	Pooled	2016	2019	2023
Gender of household head	(Male = 1)	0.90	0.90	0.90	0.89
Age of household head	(Years)	48.27	46.77	48.35	50.02
Household head literacy	(Yes = 1)	0.49	0.45	0.50	0.54
Slope flat	(Yes = 1)	0.58	0.61	0.59	0.56
Slope medium	(Yes = 1)	0.35	0.34	0.36	0.34
Slow steep	(Yes = 1)	0.07	0.05	0.05	0.10
Soil quality					
Poor	(Yes = 1)	0.09	0.10	0.10	0.06
Average	(Yes = 1)	0.53	0.53	0.55	0.49
Good	(Yes = 1)	0.38	0.37	0.35	0.45
Land area	Hectares	1.40	1.46	1.28	1.47
Used chemical fertilizer	(Yes = 1)	0.72	0.68	0.74	0.76
Access to extension service	(Yes = 1)	0.74	0.51	0.89	0.83
Used improved seed	(Yes = 1)	0.53	0.53	0.50	0.58
Used organic fertilizer	(Yes = 1)	0.53	0.60	0.41	0.59
Maize grower	(Yes = 1)	0.45	0.48	0.41	0.48
Teff grower	(Yes = 1)	0.41	0.41	0.43	0.39
Wheat grower	(Yes = 1)	0.33	0.32	0.34	0.32
Number of observations		13,205	4,630	4,853	3,722

Source: Authors' computation from ACC data.

Trends in fertilizer adoption, application rates, and yield

In line with the national fertilizer use trend in Ethiopia, the descriptive results on fertilizer adoption (proportion of fertilizer users) show an increase over time (Table 2, Panel A). However, it is important to note that while the overall adoption trend remains upward, the growth rates slowed down substantially in the recent round. While the proportion of fertilizer users increased by 7 to 22 percent between 2016 and 2019, the growth rate between 2019 and 2023 is limited to 2 to 4 percent. A similar trend is observed for the proportion of fertilized plot and fertilizer application levels. For instance, the 20 to 36 percent increase in share of fertilized plots observed between 2016 and 2019 was followed by a more subdued increase for wheat (3 percent) and a decline for maize (−7 percent) between 2019 and 2023. Similarly, fertilizer application shows lower growth rate for maize and a decline for teff and wheat between 2019 and 2023 (Table 2, Panels C and D).

Table 2. Fertilizer adoption and application rates, by crop and year

	Number of observations	2016	2019	2023	Growth rate, % (2016 vs. 2019)	Growth rate, % (2019 vs. 2023)
Panel A: Proportion of fertilizer users						
Maize	7,420	0.59	0.72	0.74	22	3
Teff	6,589	0.70	0.83	0.86	19	4
Wheat	5,209	0.82	0.88	0.90	7	2
Panel B: Proportion of fertilized plot						
Maize	10,189	0.42	0.57	0.53	36	−7
Teff	10,782	0.53	0.66	0.66	25	0
Wheat	8,306	0.59	0.71	0.73	20	3
Panel C: Nitrogen application rate (kg/ha), all plots						
Maize	9,893	35.8	54.5	64.3	52	18
Teff	10,507	32.4	54.9	51.5	69	−6
Wheat	8,183	42.1	69.9	71.2	66	2
Panel D: Nitrogen application rate (kg/ha), fertilized plots						
Maize	5,331	62.4	78.1	85.9	25	10
Teff	7,058	43.9	64.8	58.3	48	−10
Wheat	5,972	51.8	79.4	78.4	53	−1

Source: Authors' computation from ACC data.
Note: Total observation refers to the total number of sample households or plots across the three rounds. The number of observations by crops and rounds are not reported to conserve space.

The decline in the fertilizer adoption and application rates in the 2023 Meher seem to have adverse effect on crop yields. In line with the slowdown in fertilizer use, we observe a decrease in crop yields in the recent round. While crop yields have shown meaningful improvements between 2016 and 2019 (by 8–15 percent), yield sharply drops between 2019 and 2023 (by up to 10 percent) (Table 3).

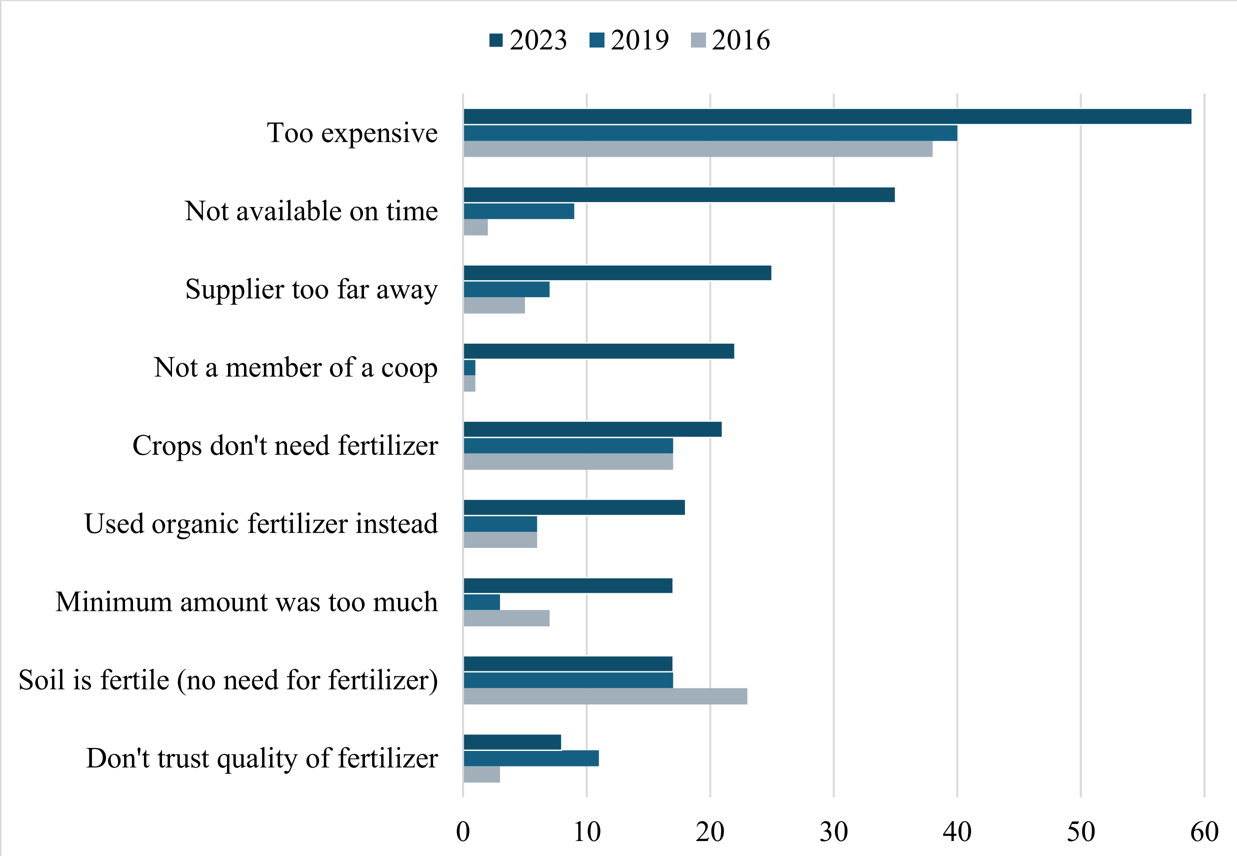
Table 3. Crop yields at the plot level (quintal/hectare), by crop and year

Crop	Total no. of observations	2016	2019	2023	Growth rate, % (2016 vs. 2019)	Growth rate, % (2019 vs. 2023)
Crop yields						
Maize	9,516	22.9	24.8	22.2	8	−10
Teff	10,018	8.9	10.2	9.3	15	−9
Wheat	7,927	16.4	18.3	18.5	12	1

Source: Authors' computation from ACC data.

This deceleration in fertilizer adoption and application levels in 2023 (compared to 2019) and the presumable ensuing adverse effects on crops yields can be linked to the recent disruptions in supply chain, global price surges, and internal conflicts, which adversely affected the accessibility of fertilizer at the right time, right quantity, and affordable prices. In fact, more than a third of sample households surveyed in the 2023 round reported availability as one of the major constraints to using fertilizer (up from 9 percent in 2019). A considerable share of the sample (59 percent) also points to prohibitive fertilizer prices as the main reason for not applying fertilizers on their plots in 2023 (up from 40 percent in 2019). Figure 1 shows the main reasons sample households reported for not using fertilizer in all rounds, including post-crisis (2023), which include deterioration in last-mile fertilizer delivery and prioritization of members by cooperatives (seemingly due to shortage), besides price and timely availability.

Figure 1. Reasons for not using fertilizers



Source: Authors' computation from ACC data.

Trends in fertilizer and crop prices in Ethiopia (2016–2023)

Table 4 presents trends in fertilizer and crop prices reported by sample households in each survey round. While fertilizer price shows a modest decrease between 2016 and 2019, it sharply increased after 2019 following the global fuel–food–fertilizer crisis. Crop prices, however, have continued to increase since 2016, and more so between 2019 and 2023. Specifically, nitrogen–phosphorus–sulfur/diammonium phosphate (NPS/DAP) and urea fertilizers increased by 220 and 247 percent between 2019 and 2023, respectively, while maize, teff, and wheat prices increased by 324, 173, and 47 percent, respectively, in the same period. Overall, while average fertilizer prices for both fertilizer types increased by 233%, average crop prices (for the three focus staple crops in this study) increased by about 181 percent, suggesting for the average staple crop producer that only about three-fourths of the fertilizer price increase is absorbed by the increases in crop prices. However, given their limited roles in food markets, subsistence-based smallholders are likely to respond differently to fertilizer and crop price increases. Thus, the extent to which the relative increases in input–output prices influence fertilizer use is likely to depend on several factors, including the relative crop yield responses (i.e., APP) (Burke, Jayne, and Black 2017) and fertilizer price elasticities of demand for each crop—key questions we address in this paper.

Table 4. Evolution of fertilizer and crop prices, in Birr[4] (2016–2023)

	2016	2019	2023	Growth rate (%) (2016 vs. 2019)	Growth rate (%) (2019 vs. 2023)
Fertilizer price					
Urea	2,269	1,272	4,412	−44	247
NPS/DAP	1,440	1,354	4,334	−6	220
Crop price					
Maize	434	709	3,011	63	324
Teff	2,583	2,157	5,888	−17	173
Wheat	870	2,985	4,390	243	47

Source: Authors' computation from ACC data.
Note: NPS/DAP = nitrogen–phosphorus–sulfur/diammonium phosphate.

Empirical strategy

Understanding and quantifying the implication of the surge in fertilizers and food prices on the profitability of fertilizers entails uncovering implications on components of the profitability function. First, profitability of fertilizers depends on how farmers' demand for fertilizers evolves in the context of a surge in both fertilizers and food prices. Characterizing households' demand for fertilizers entails estimating elasticities associated with changes in both fertilizer prices and crop prices. Second, given the prevailing price ratios, the profitability of fertilizers heavily depends on the evolution of yield responses that is often estimated from flexible production functions.

4.1 Estimating demand for fertilizer

We start by characterizing demand for fertilizers as a function of potential dynamics and spatial variation in fertilizer and food prices. The decision of whether to use fertilizer and how much fertilizer to use involves two distinct stages. First, the farmer must decide whether to use fertilizer on a specific plot. Once this decision is made, the second stage involves determining how much fertilizer to use. Because of this two-stage decision-making process, we need an empirical strategy that captures both decisions jointly. We use the double-hurdle model (Burke 2009; Cragg 1971),

[4] Birr is Ethiopia's currency.

which offers greater flexibility by allowing the use of separate covariates for each of the decisions while also allowing us to include village-level fixed effects, the level at which the price of fertilizer and output often vary. Using this framework, we jointly model both the extensive and intensive margins of fertilizer demand as follows. The first hurdle, representing the decision to use fertilizer (the extensive margin), can be modeled as a binary choice using a probit model. The inverse Mills ratio from the probit model is then used in the second hurdle, the decision of how much fertilizer to use per unit of land (the intensive margin). The second hurdle is estimated using a truncated normal regression. The full double-hurdle model can be expressed using the following two equations:

$$D_{ivt} = \alpha_v + \alpha_r Round_{ivt} + \alpha_p P_{vt} + \alpha_{op} OP_{vt} + \alpha' X_{ivt} + \delta' Z_{ivt} + \varepsilon_{1_{ivt}}, \ \varepsilon_{1_{ivt}} \sim N(0,1) \quad (1)$$

$$F_{it} = \beta_v + \beta_r Round_{ivt} + \beta_p P_{vt} + \beta_{op} OP_{vt} + \beta' X_{ivt} + \gamma \lambda_{it} + \varepsilon_{2_{it}}, \ \varepsilon_{2_{it}} \sim N(0, \sigma^2) \quad (2)$$

where D_{ivt} is a binary variable indicating fertilizer adoption, $Round_{ivt}$ stands for survey round dummies, and α_v and β_v stand for village-fixed effects, which capture any time-invariant differences across villages. F_{it} is the level of fertilizer used per hectare, expressed in logarithmic form, and P_{vt} stands for the median village level price of chemical fertilizer. Similarly, OP_{vt} stands for output price. X_{ivt} stands for a set of covariates included in both hurdles, and Z_{ivt} represents a set of covariates included only in the first hurdle. While numerous factors influence both decisions of the extensive or intensive margin, we recognize that some factors (Z_{ivt}), such as the distance to markets and related fixed cost of accessing the fertilizer market, impact only the initial decision of whether to use fertilizer. These factors are less likely to have much bearing on the subsequent decision of how much fertilizer to use per hectare. λ_{it} is the inverse Mills ratio computed based on the first hurdle (probit model). Our parameters of interest are particularly α_p, β_p, α_{op}, and β_{op}. We are controlling for village fixed effects because prices vary at village level, and we anticipate that these parameters capture the impact of change in fertilizer and output price on demand for fertilizer. Except for the parametric assumptions we impose, the expressions in Equations (1) and (2) are similar to standard fixed-effects models exploiting temporal variations in fertilizer prices. Households have limited control over the evolution of fertilizers and output price in domestic and international markets.

We anticipate that demand for fertilizer responds to both fertilizer and crop output prices. As shown in Section 3, farmers in Ethiopia witnessed a significant surge in both fertilizer and crop output prices. To test the implications of these counteracting factors, we control both fertilizer and output prices in the empirical specification in Equations (1) and (2). While a surge in fertilizer prices will likely reduce demand for fertilizers (and hence we expect α_p and β_p to be negative and statistically significant), an increase in crop output price may trigger demand for fertilizer (and hence expect α_{op} and β_{op} to be positive and statistically significant). We use output prices coming from crop sales reported by households and focusing on the three most important cereals for the Meher season in Ethiopia: maize, teff, and wheat. Estimating responses to changes in both fertilizer and output price helps to gauge whether farmers' fertilizer demand is more responsive to changes in fertilizer or food prices.

4.2 Estimating production function and yield response to fertilizer applications

An important factor farmers consider in fertilizer use and intensity decisions is the agronomic response of fertilizers, given the nature of soils and many other agronomic conditions (Rurinda et al. 2020). Thus, besides the relative prices of fertilizers to output, the profitability of using chemical fertilizers hinges on the response of crop yields to fertilizer application. Thus, we estimate a flexible production function of the following form that enables us to capture nonlinear relationships between fertilizer applications and crop production:

$$Y_{hpt} = \alpha_h + \delta_t + \sum_{i=1}^{n} \alpha_i \, x_{i_{hpt}} + \sum_{i=1}^{n}\sum_{j=1}^{n} \beta_{ij} \, x_{i_{hpt}} \, x_{j_{hpt}} + \epsilon_{hpt} \tag{3}$$

where Y_{hpt} stands for output for household h plot p at time t, α_h stands for household fixed effects that capture household-specific time-invariant heterogeneity, and δ_t stands for round dummies. x_i and x_j are inputs, including both land and nonland inputs. These inputs include fertilizer application, land size, labor days, rainfall, and improved seed use. In the context of fertilizer use in Ethiopia, farmers typically have options to use three primary types of chemical fertilizers: DAP, urea, and NPS. To simplify our analysis, we aggregate the application of these three fertilizer types. The fourth term in Equation (3) includes both the squared terms when $i = j$ and interaction terms across a combination of different inputs when $i \neq j$. Including squared and interaction terms allows us to capture nonlinear relationships between production and fertilizer application. For example, we anticipate that the response of crop yield to fertilizer application may diminish after reaching certain levels of application. Furthermore, production and productivity can be higher when farmers adopt a combination of inputs such as improved seed and fertilizer (e.g., Abay et al.

2018) or when applied in soils with better soil organic matter (e.g., Chamberlin et al. 2021; Marenya and Barrett 2009). ϵ_{hpt} is the error term representing other unobservable factors affecting production.

We note that we implement Equation (3) on a large plot-level panel data, which offers us both substantial cross-sectional variation across households as well as across multiple plots managed by the same household and temporal variation across households. We control for household fixed effects to capture time-invariant unobserved heterogeneity (e.g., farming skill, agroecology, and topography) across households. As we focus on the three key crops, we aim to accurately estimate and comprehend the specific effects of fertilizer application. We also estimate Equation (3) for each crop separately. However, the data are not experimental, and hence the usual endogeneity concerns arising from time-varying unobservable factors remain important. The inclusion of saturated interaction and nonlinear terms in the equation will help to minimize these unobservable factors. Furthermore, the focus on three main crops and the separate implementation of Equation (3) for each crop will likely help reduce confounders.

We also implement and estimate yield function arising from the production function specified in Equation (3) by dividing output as well as all inputs by plot size. For this purpose, we convert quantities of fertilizer application into macronutrients (nitrogen and phosphorus). This serves mainly to examine yield responses associated with the application of nitrogen, while our profitability analysis relies mainly on the production function estimates.

4.3 Evaluating profitability of fertilizer

The most common approach to assessing fertilizer profitability is by computing the value–cost ratio (VCR), which incorporates not only the yield improvement resulting from fertilizer use but also the interplay of output and fertilizer prices. Essentially, VCR is the ratio of the total value of output gained due to fertilizer use to the total cost of acquiring the fertilizer used. Specifically, we compute the AVCR using the following expression:

$$AVCR = \frac{P_o * (Y_{WF} - Y_{WOF})}{P_f * F} = APP_F * {P_o}/{P_f} \tag{4}$$

where P_o stands for price of output; Y_{WF} represents the production level with fertilizer use, and Y_{WOF} signifies the production level without fertilizer; P_f stands for price of fertilizer; F represents the amount of fertilizer used; and APP_F denotes the average physical product of fertilizer. We compute the value of production with and without fertilizer and hence the APP values using the production estimates from Equation (3).

We derive our fertilizer prices by dividing the total cost households incurred to purchase fertilizer by the total quantity of fertilizer purchased. Our output prices are acquired from crop sale data reported by each household. Given that measurement errors can introduce significant noise into fertilizer and output prices computed this way, we instead use village median fertilizer and crop prices for our analysis.

4. Results and discussions

This section presents the main results, starting with the demand for fertilizer and then proceeding to ultimate yield responses and profitability estimates. As pointed out earlier, our results are based on three staple crops (maize, teff and wheat) that are important in Ethiopia in both overall crop area cover and fertilizer use.[5]

5.2 Demand for fertilizer

We first assess what happens to fertilizer demand for the three crops in the face of rising fertilizer and crop prices in recent years. Given the two-stage nature of the fertilizer use decision, we estimate the double-hurdle model described in Equations (1) and (2), which allows us to jointly estimate the decision to adopt (the extensive margin) and intensity of fertilizer use per hectare (the intensive margin). In both hurdles, we control for factors that exclusively affect fertilizer use other than own prices in each round, including household characteristics, crop prices, annual average rainfall patterns, soil quality, and distance to major roads and woreda towns. In addition to year fixed effects, we also control for village fixed effects, the level at which the price of fertilizer and output varies, implying that Equations (1) and (2) are exploiting temporal and cross-sectional variation in prices. Although we include some variables that affect only the first hurdle (such as distance to market and district town because they most affect the first decision and not necessarily the adoption of fertilizer per unit of land), the two equations are mainly distinguishable by the different functional forms we apply, the first hurdle being a probit and the second truncated normal regression. We estimate the demand functions for each crop separately for two reasons: (1) crop

[5] For instance, in 2019 Meher (main production) season, teff covered the largest areas that were fertilized (about 2.6 million hectares), followed by maize (about 1.8 million hectares) and wheat (1.6 million hectares) areas (CSA 2019).

prices vary significantly, maize being the cheapest and teff the most expensive; and (2) agronomic yield responses and hence returns to fertilizer application vary across crops.

In Table 5, we first present the point estimates of our key variables of interest included in the two hurdles. There are three important empirical patterns worth highlighting. First, the estimates from the first hurdle show that despite some differences across crops, the extensive margin of fertilizer application is negatively associated with fertilizer price. While the extensive margin of demand for fertilizer appears to be not responsive to changes in fertilizer prices for maize, we observe strong responses for teff and wheat.

Second, as expected, the intensive margin of demand for fertilizer—level of fertilizer applied per hectare—is negatively associated with changes in fertilizer price, indicating that recent fertilizer price surges may have reduced fertilizer application rates. The downward sloping local polynomial plots reported in Figure A2 (Appendix) also confirm the consistent negative association between nitrogen application rates and fertilizer prices. These results are consistent with prior works in Ethiopia (e.g., Rashid et al. 2013) and elsewhere (e.g., Liverpool-Tasie 2017; Takeshima et al. 2017).

Third, although the local polynomial plots shown in Figure A2 suggest the expected positive relation between crop prices and fertilizer use, parametrically estimated coefficients for crop prices are not statistically different from zero. This suggests that farmers' response to increases in staple crop prices is not as strong and hence appears to be statistically insignificant. An important result is that, keeping all other factors constant, while farmers strongly respond to increases in fertilizer prices (i.e., by reducing their per hectare fertilizer applications), they seem to fail to respond to favorable crop price increases. This suggests that, to the average farmer in our sample, changes in fertilizer prices are more important determinants of demand than changes in crop prices. We note that the latter may primarily depend on the level of a farm household's subsistence or whether a farm household is a net-buyer or net-seller in these markets, with important implications for policies aimed at cushioning farm households from fertilizer price shocks. We return to these potential heterogeneities in the next sections.

Other complementary inputs included in our estimation also turned out to be important determinants of fertilizer adoption and application intensity. For example, the coefficients for land size, observed in both hurdles, indicate that while farmers with larger land holdings are more likely to adopt fertilizers, those with larger land sizes are likely to apply less fertilizer per unit of land. Improved seed use, on the other hand, is associated with a higher likelihood of fertilizer adoption and intensification, as improved seed use is optimized with fertilizer application (e.g., Abay et al. 2018). Moreover, availability of family labor is strongly associated with fertilizer use and per hectare applications, as family labor remains critical in the absence of mechanized farming (e.g., Croppenstedt et al. 2003). Consistent with these findings, younger farmers are more likely to apply fertilizer in greater quantities per hectare (Table 5). Finally, farmers appear to be substituting organic and inorganic fertilizer, as the application of inorganic fertilizer is negatively associated with manure application. The inverse Mills ratio appears to be positive and statistically significant for all crops, justifying inclusion and control for this ancillary component to account for positive selection in fertilizer application rate.

Table 5. Demand for fertilizer: Estimates from a double-hurdle model

	Maize		Teff		Wheat	
	Fertilizer adoption	**Fertilizer application intensity (log-kg/ha)**	**Fertilize r adoption**	**Fertilizer application intensity (log - kg/ha)**	**Fertilizer adoption**	**Fertilizer application intensity (log – kg/ha)**
Fertilizer price in ETB (log - kg)	-0.054	-0.285***	-0.427***	-0.826***	-0.147**	-0.613***
	(0.036)	(0.105)	(0.061)	(0.213)	(0.069)	(0.128)
Crop price (log-kg)	-0.004	0.127	-0.034	-0.223	-0.038	0.094
	(0.032)	(0.086)	(0.065)	(0.149)	(0.055)	(0.113)
Land area (log-ha)	0.074***	-0.283***	0.087***	-0.258***	0.069***	-0.236***
	(0.006)	(0.024)	(0.011)	(0.040)	(0.010)	(0.032)
Gender of the head (1 = male)	0.020	0.144***	-0.021	-0.085	-0.026	-0.167***
	(0.019)	(0.052)	(0.031)	(0.069)	(0.025)	(0.052)
Age of the head (years)	-0.001***	-0.005***	-0.002***	-0.006***	-0.003***	-0.008***
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.001)
Number of adults	0.001	0.016***	0.006**	0.034***	0.009***	0.037***
	(0.002)	(0.005)	(0.003)	(0.007)	(0.003)	(0.006)
Improved seed used (1 = yes)	0.266***	0.580***	0.037*	0.109**	0.070***	0.128***
	(0.010)	(0.082)	(0.022)	(0.050)	(0.019)	(0.041)
Organic fertilizer used (1= yes)	-0.075***	-0.131***	-0.049*	-0.127**	-0.066***	-0.159***
	(0.012)	(0.033)	(0.025)	(0.063)	(0.018)	(0.046)
Inverse Mills ratio		0.527***		0.834***		1.040***
		(0.136)		(0.238)		(0.233)
Kebele fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	4,664	3,172	2,491	1,755	2,289	1,856

Source: Authors' computation from ACC data.

Note: Probability of using fertilizer (the first hurdle) is based on Probit model; demand for fertilizer (the second hurdle) is estimated conditional on adopting using a truncated normal regression on fertilizer application rate (kg/ha). Woreda fixed effects are used instead of Kebele fixed effects for the Maize model due to nonconvergence when Kebel fixed effects are applied. The additional control variables include slope of plot, soil quality indicators, distance to major road, distance to woreda town, rainfall and access to extension service. Standard errors, clustered by household, are in parentheses.

* $p < .10$; ** $p < .05$; *** $p < .01$.

Using estimates reported in Table 5 and following Burke (2009), we compute fertilizer price elasticities of demand (and hence unconditional average partial effects), as discussed in Section 4. Table 6 reports these elasticities by crop. We note two important results here. First, the results show important differences in fertilizer price elasticity of demand across crops, with teff farmers exhibiting higher price elasticity than wheat and maize farmers, suggesting farmers are more sensitive to fertilizer price surges when applied to teff than to wheat and maize. Intuitively, this may be because teff production is likely more resilient to reduced fertilizer applications than wheat or maize. On average, a 1 percent increase in fertilizer prices leads to a 1.08 percent reduction in fertilizer demand (or applications) on teff plots. This is consistent with other findings in similar contexts (e.g., Komarek et al. 2017). On the other hand, farmers are relatively price inelastic to fertilizer demand (or applications) on maize and wheat parcels, likely due to use of hybrid varieties where fertilizers are often recommended (Duflo et al. 2008). Indeed, maize turns out to be the most price inelastic to demand—a 10 percent increase in fertilizer price reduces demand for (and application on) maize fields by about 4 percent, while wheat and teff stand at 8.2 and 10.8 percent, respectively.

Second, fertilizer users of all crops are relatively less responsive to own-price increases than nonusers (comparison of last two columns of Table 6). This is intuitive, as those who are already familiar with fertilizer are less likely to dis-adopt it than those newly adopting it.[6] Previous studies have documented similar patterns and differences in elasticities across fertilizer users and nonusers in Africa (e.g., Croppenstedt et al. 2003; Rashid et al. 2013).

Table 6. Estimates of price elasticities of demand for fertilizers by crop and over time

	Number of Observations	Total	Fertilizer users only
Fertilizer price elasticity of demand for			
Maize	5,255	-0.40	-0.33
Teff	4,817	-1.08	-0.41
Wheat	4,034	-0.82	-0.57

Source: Author's computation from ACC data.

We assessed potential heterogeneities in fertilizer price elasticity of demand by farm size categories by conducting a subsample analysis for households above and below the median farm size using a simple probit and ordinary least square (OLS) regressions (see Tables A1–A3 in the appendix).[7] The results indicate that the fertilizer price elasticity of demand declines as one goes from those below the median to those above the median farm size for all three crops—suggesting that farmers with larger land sizes are likely to be less responsive to price changes. In other words, those with smaller land sizes tend to cut fertilizer demand when prices increase because they are less likely to be able to afford the higher cost of fertilizers. These results clearly show that households with smaller farm (below the median) are more responsive to increases in fertilizer prices. This is intuitive because in Ethiopia fertilizers are sold in large quantities or unit and less

[6] Some studies have documented dis-adoption of agricultural technologies (Moser and Barrett 2006), although they anticipate that continuous adoption of inorganic fertilizer is likely to dominate dis-adoption.

[7] We resort to ordinary least square for this analysis mainly because the double hurdle and hence maximum likelihood estimation of the truncated normal model was not converging for some of the sample splits.

divisible to accommodate the needs of small-scale farmers. Overall, controlling for other complementary inputs, such as labor, land, and rainfall patterns, these findings highlight that smallholder farmers in Ethiopia respond significantly to price changes, albeit with different elasticities. These responses are likely to have important implications on overall agricultural intensification, especially if the surge in prices continues.

5.2 Yield response to fertilizer applications

Next, we assess yield responses to fertilizer application (i.e., the technical relationship between inputs and outputs of a given farming typology) to lay the foundation for the ensuing analysis on fertilizer profitability. An important question a farmer often asks when making investment decisions on fertilizers is the extent to which the specific agronomic or biophysical conditions respond to fertilizer use and given price ratios, whether the conditions allow profitable use of fertilizers, as well as the extent to which such investments can improve the agronomic feasibility itself (Marenya and Barrett 2009; Rurinda et al. 2020). Thus, to understand the profitability of fertilizers, it is important to take stock of the biophysical relationships between fertilizer use and yield responses. Such a relationship can be captured by the production function in Equation (3) and associated yield response function—or fertilizer response function—that describes the technical transformation of inputs such as fertilizers into outputs.

Table 7 reports yield response (marginal effects) associated with fertilizer application based on a household fixed effects model. This model enables us to remove the time-constant household level unobserved heterogeneities that would potentially confound our estimates, including specific farm management talents, which are expected to remain similar across rounds. We also control for year fixed effects to capture aggregate temporal evolution across years. Other important factors determining the fertilizer yield response include rainfall levels, improved seeds, and agricultural labor, each of which interacts with applied fertilizers. After accounting for these factors (complementary inputs), the results in Table 7 clearly show that fertilizer use increases maize, teff, and wheat yields meaningfully. The local polynomial graphical expositions of yield responses to levels of fertilizer applications also suggest similar increasing trends, showing that increased use of fertilizers is likely to result in increased yield responses, at least for the main crops reported here (see Figure A1 in the Appendix). Specifically, 1 kg/ha increase in fertilizer applications is, on average, associated with a yield increase of 7 kg/ha for maize and 4.5 kg/ha for both wheat and teff, which roughly show 1:7 and 1:5 fertilizer to yield ratios, respectively. These results are qualitatively consistent with the findings by Rashid et al. (2013), who, using 2008 data, find 1:5 for maize, 1:2 for teff, and 1:2.5 for wheat. Such yield responses are not surprising at early stages of intensification, as is the case in Ethiopia. Observed yield response improvements are also arguably intuitive, given the significant investments made over the last 15 years. However, these yield responses are still relatively low, even compared to similar studies from sub-Saharan Africa. For example, Chamberlin, Jayne, and Snapp (2021) report 10 to 13 kg for Tanzania, while Liverpool-Tasie et al. (2017) report 8 kg for Nigeria, and Marenya and Barrett (2009) report 17 kg for Kenya.

Table 7. Estimates of yield response to fertilizer use: Household fixed effects model (marginal effects)

	Maize	Teff	Wheat
Nitrogen application rate (kg/ha)	6.97***	4.47***	4.51***
	(1.30)	(0.59)	(0.83)
P application rate (kg/ha)	1.61	−0.71	2.73**
	(1.86)	(0.75)	(1.07)
Agricultural inputs (land, labor, improved seed)	Yes	Yes	Yes
Additional controls	Yes	Yes	Yes
Interaction of inputs	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Number of observations	8,663	9,211	7,428

Source: Authors' computation from ACC data.

Note: Standard errors, clustered by household, are in parentheses. Yield is measured in kg/ha (hectare). $^{*}p < .10$; $^{**}p < .05$; $^{***}p < .01$.

We also find that the other important complementary inputs, mainly land, labor, and improved seeds, are statistically significant and with the expected signs. Overall, while these results suggest the agronomic potential of using fertilizers, cost and profitability considerations are important to understand actual intensification outcomes in the face of price changes, which is the focus of the next section.

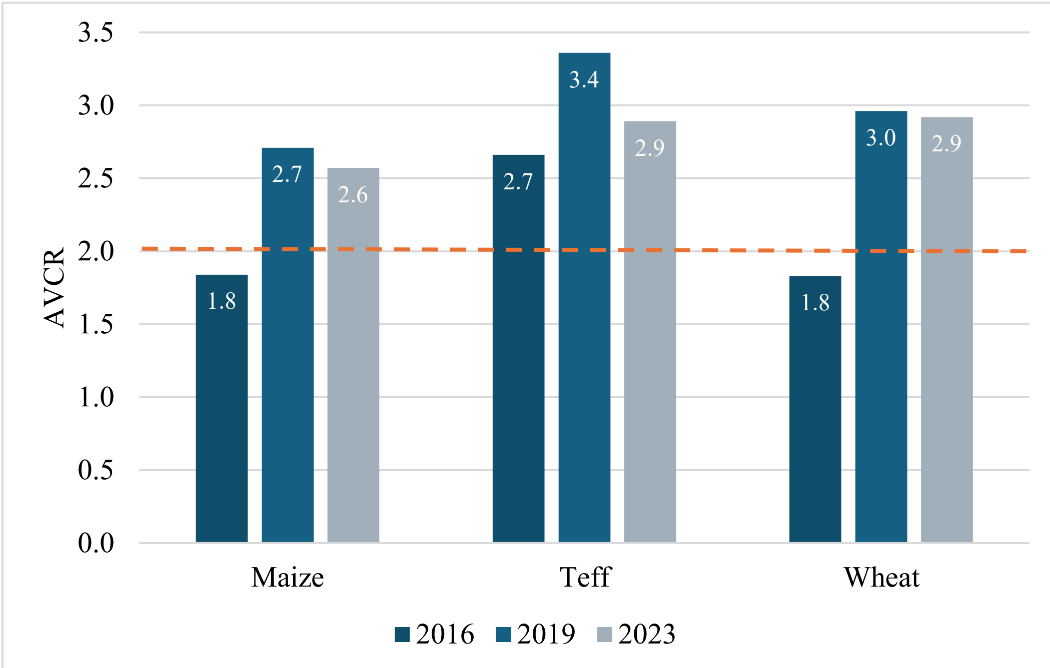
5.3 The profitability of fertilizer applications

This section reports results on the profitability of fertilizer use, focusing on the three main crops considered. Use of the AVCR enables us to measure the economic benefits of fertilizer application. Two important components of the AVCR are the APP, which captures the technical relationship between fertilizer and production levels, and the output to fertilizer price ratio as shown in Equation (4). To compute the APP, we estimate the flexible production function discussed in Equation (3). Table A4 in the Appendix presents the results of the production function estimates, which we use to compute the APP. We then compute the AVCR by combining the APP with the output–fertilizer price ratio. Figure 2 depicts the temporal evolution of the AVCR estimates over time. Four important findings stand out from these estimates. First, starting from a rather low base in 2016, AVCRs on average increased by about 43 percent from 2016 to 2019. Second, following the significant jump in fertilizer and crop prices after 2019, average AVCRs declined for most of the crops. For example, AVCRs for teff declined by about 12 percent, from 3.36 in 2019 to 2.96 in 2023. Third, while the rising trend in AVCRs seems to have been halted by the sharp rise in fertilizer prices, these values remained relatively above the rule of thumb threshold of 2, suggesting fertilizers may have continued to be profitable, on average, despite the recent surge in fertilizer price.[8] A concurrent increase in output price meant that a portion of the cost due to fertilizer price increase is compensated for by the increases in crop prices, in principle leaving fertilizers still profitable. However, we know that farmers in our sample are less likely to respond to fertilizer demand because of favorable crop prices per se but are strongly responsive to unfavorable fertilizer prices. This implies that the reduction in fertilizer use due to fertilizer price rise may be substantial despite the seemingly favorable AVCRs shown in Figure 2. This is likely exacerbated by the supply side constraints reported in Section 3.

Fourth, while AVCRs vary by crop, with teff being on the high side, maize on the low side, and wheat in between the two, more recently teff and wheat are observed to converge to similar AVCRs. This indicates that returns to fertilizer use may vary by crop type. Teff is the most expensive compared to maize and wheat, while maize is the cheapest in domestic markets. The AVCR values are consistent with these patterns.

[8] An AVCR level of 2 is often considered to be the level where fertilizer application is profitable, considering risk and other costs not accounted for in the AVCR calculation in low-income country contexts (e.g., Chamberlin et al. 2021; Morris et al. 2007; Rashid et al. 2013; Sheahan et al. 2013; Xu et al. 2009).

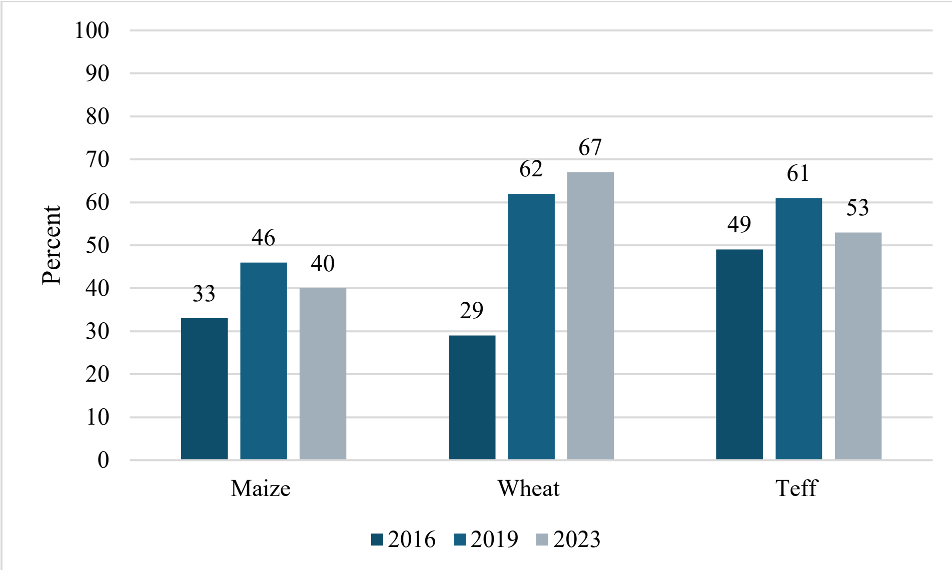
Figure 2. Trends in AVCR: 2016–2023



Source: Authors' computation from ACC data.
Note: AVCR = average value–cost ratio.

An important question related to fertilizer profitability analysis is whether fertilizer is profitable for most farmers and who is more likely to generate positive returns associated with fertilizer applications. We assess this using the commonly used AVCR threshold of 2 and compute the proportion of farm households that are profitable despite the price hikes. These results are reported in Figure 3. First, fertilizer is not profitable for half of maize and teff producers and about a third of wheat producers. Second, the proportion of farmers with profitable AVCRs decreased by almost 6 percentage points between 2019 and 2023 for maize growers and by 8 percentage points for teff growers. Thus, while in 2023 the overall AVCRs remained above the threshold of 2, the proportion of profitable farmers given the price rise declined by 6 to 8 percentage points for maize and teff growers.

Figure 3. Proportion of profitable farmers in fertilizer use



Source: Authors' computation from ACC data.

We note that despite the above trends in AVCRs in general, there may be heterogeneities across farmers with varying scale of production (farm size). In Table 8, we further disaggregate the AVCR values by crop and land terciles. The AVCR values in Table 8 show two empirical patterns. First, AVCR values across terciles of farm size show substantial heterogeneity, implying important variations in economic returns to fertilizer application across farm sizes. For most of the crops (except teff), farmers with larger farm sizes generate higher fertilizer returns than those managing small and medium farms. Given the inverse relationship between farm-size productivity, we suspect this may be driven by differences in access to and affordability of fertilizers. This suggests substantial gains associated with the scale of production. Given that land represents a major asset to farmers, these results suggest differential returns to fertilizer application across wealth or production capacity of farmers, with important implications for targeting of interventions to support farmers with a varying wealth profile (e.g., Harou et al. 2017). The heterogeneities we document corroborate previous studies showing important heterogeneities in economic returns to fertilizer use arising from differences in soil organic matter (e.g., Chamberlin, Jayne, and Snapp 2021; Marenya and Barrett 2009), soil acidity (e.g., Abay et al. 2022; Burke, Jayne, and Black 2017), and transaction and transportation costs (Bonilla, Chamberlin, and Hijmans 2021; Minten, Koru, and Stifel 2013). Second, AVCRs have generally increased over time across all crops and land size categories, but this increasing trend seems halted after the surge in fertilizer prices and hence in the last round. In 2023, AVCR values experienced some decreases, especially for wheat and teff. This is not surprising given the disproportional increase in fertilizer price, compared to output price, reported in Section 3. This is also consistent with the trends in fertilizer application and hence implies that even though fertilizer continues to be profitable on average, the recent surge in fertilizer prices may affect agricultural intensification practices.

Table 8. Heterogeneities in AVCRs across time, crop, and land size

Land size tercile		2016	2019	2023	Total
Maize					
	Small	1.97	2.65	2.98	2.60
	Medium	1.70	2.72	2.57	2.40
	Large	2.68	3.31	3.02	3.08
Wheat					
	Small	1.96	3.12	3.00	2.79
	Medium	1.71	2.74	2.93	2.44
	Large	2.59	3.29	3.01	3.04
Teff					
	Small	2.68	3.31	3.02	3.08
	Medium	1.84	2.52	2.25	2.27
	Large	2.71	3.46	2.68	3.02

Source: Authors' computation from ACC data.
Note: AVCRs = average value–cost ratios.

5. Conclusion

Global and domestic shocks to food–fertilizer–fuel markets are disrupting food systems in Africa, with several import-dependent countries grappling with these challenges concurrently. We revisit the demand and profitability of chemical fertilizers in the context of the crisis, focusing on smallholder agriculture in Ethiopia. Despite Ethiopia's significant progress in improving the adoption of fertilizer and crop yield over the last three decades, fertilizer application rates remained below targets even before the fertilizer price surges. The recent global disruptions in fertilizer markets along with domestic conflicts and shocks further hamper access to and affordability of chemical fertilizers in these local markets. Although some of the adverse effects resulting from fertilizer price shocks are absorbed by the parallel increase in domestic crop prices, the ultimate impacts of these compounding crises on smallholder farmers in Africa remain less clear.

Against this backdrop of these crises, we revisit the state of smallholder fertilizer demand and profitability in Ethiopia. Ethiopia presents an interesting context to assess these factors, as its recent input-use driven gains in agricultural productivity growth face drawbacks due to such global and local crises. We particularly examine farmers' response to changes in both fertilizer and food prices by estimating price elasticity of demand to changes in both prices. We then revisit the profitability of fertilizer by computing the AVCRs before and after the crises. We use three-round longitudinal household survey data, covering both pre-crisis (2016 and 2019) and post-crisis (2023) production periods, and we focus on the three main staple crops in Ethiopia (maize, teff, and wheat) that account for most of the fertilizer use in the country.

Our analysis shows important insights into fertilizer adoption and application rates as well as implications for yield response and profitability in the face of the price surges. We find that fertilizer adoption and yield were increasing until the recent price hikes, but they seem to halt afterward. We also find relatively large fertilizer price elasticity of demand estimates, ranging between 0.4 and 1.1, which vary by crop. These estimates are substantially larger than previous estimates, and we find suggestive evidence that farmers with small farms are more responsive to changes in fertilizer price than households with larger farms. Although increases in crop prices can theoretically increase demand for fertilizer, when controlling for fertilizer prices, we find that farmers' response to increases in staple crop prices is not as strong as perceived and hence appears to be statistically insignificant. Our findings highlight that smallholder farmers are more responsive to increases in fertilizer than to output prices. Last, we document important trends in the profitability of chemical fertilizers, with AVCR values increasing from 2016 to 2019 for all crops but declining after the crisis. While the pre-crisis AVCRs show profitable trends for most crops (based on the conventional threshold of an AVCR equal to or greater than 2), AVCRs and the share of farmers with profitable AVCRs have declined afterward.

Our findings offer important insights to inform policy responses to shocks arising from various triggers. The estimated elasticities suggest that smallholder farmers in the study area exhibit important demand responsiveness to fertilizer price changes, underscoring that smallholder farmers are likely to significantly cut back on fertilizer use in response to price increases and declines in AVCRs. Given that smallholder farmers are credit constrained and primarily aim to achieve subsistence needs including food security, the surge in output prices is less likely to fully absorb the additional cost of fertilizer and hence maintain demand for fertilizer. More importantly, our results suggest that the extent of the adverse effects are heterogenous across farm sizes and crop types, disfavoring those with small farm sizes and growing certain crops—with important income distributional policy implications of such compounded global and local crises.

Overall, these patterns signal the need for effective policy instruments to support smallholder farmers in Africa to continue boosting their fertilizer adoption and application rates, especially in countries where achieving the Abuja declaration of doubling fertilizer application target by 2025 remains less likely.

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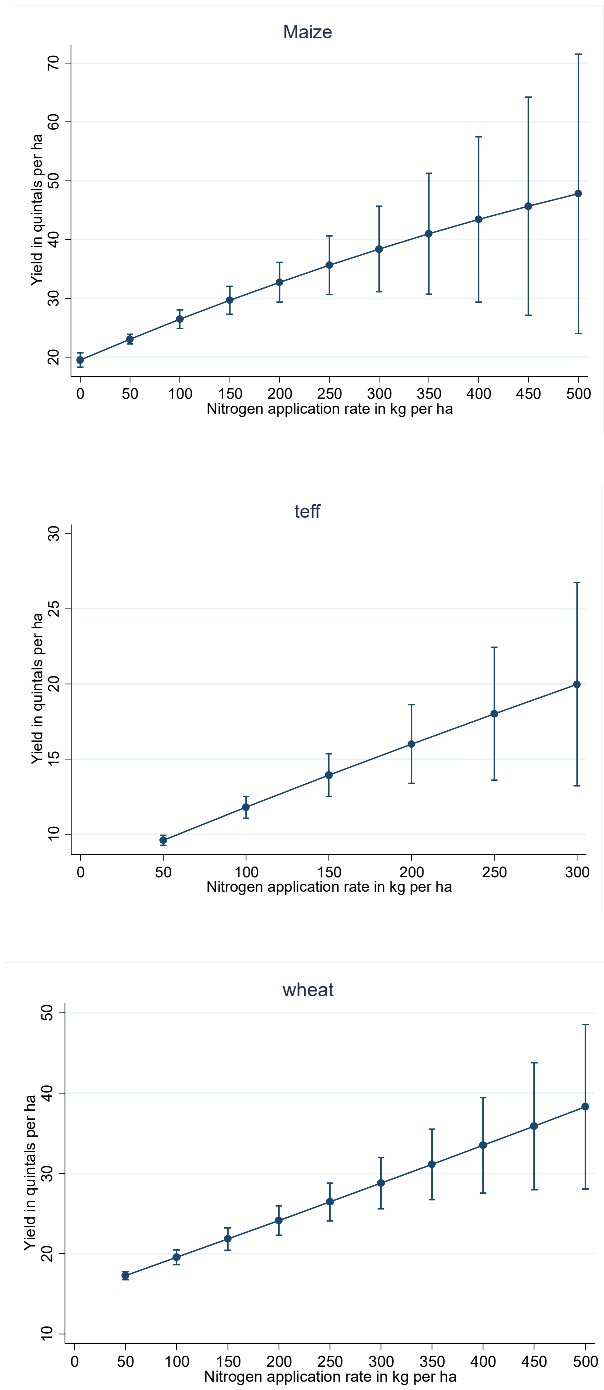
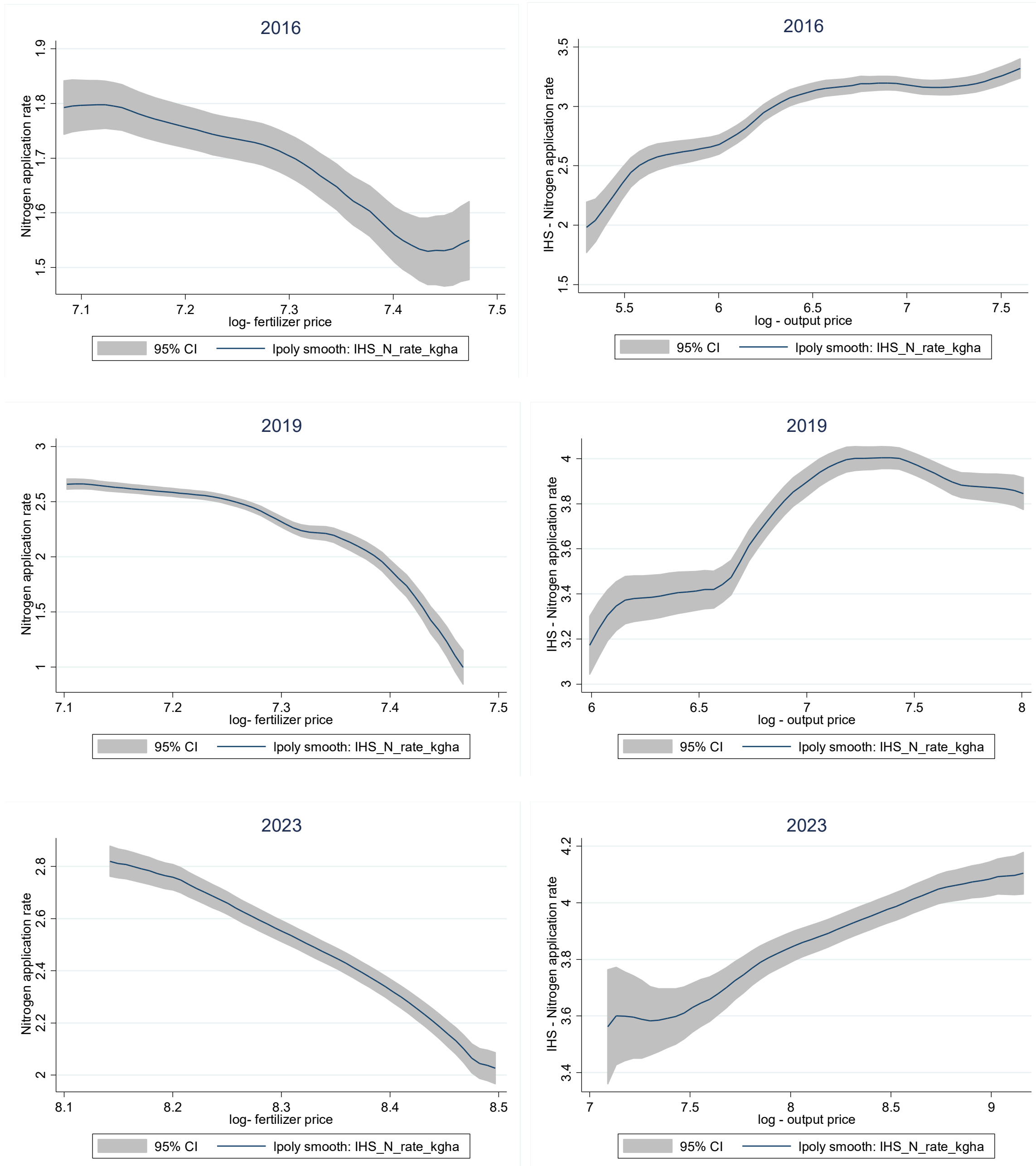
Appendix

Figure A1. Yield (q/ha) response to nitrogen application rate (kg/ha) of maize, teff, and wheat



Source: Authors' computation from ACC data.

Figure A2. Local polynomial - fertilizer price vs. nitrogen application rates



Source: Authors' computation from ACC data.
Note: These variables are transformed using the inverse hyperbolic sine function, and fertilizer prices are shown in a logarithmic scale. Notably, all the graphs exhibit a negative slope, indicating an inverse relationship between fertilizer price and fertilizer use, as expected.

Table A1. Demand for fertilizer by farm size category: Estimates from probit and OLS (maize)

	Above median		Below median	
	Fertilizer	Fertilizer	Fertilizer	Fertilizer

	adoption	application intensity (log - kg/ha)	adoption	application intensity (log - kg/ha)
Fertilizer price in Birr (log)	−0.102*	−0.467	−0.139*	−0.796***
	(0.06)	(0.322)	(0.074)	(0.286)
Mazie price (log)	−0.024	0.338	0.087	0.397
	(0.058)	(0.282)	(0.056)	(0.243)
Additional controls	Yes	Yes	Yes	Yes
Round dummies	Yes	Yes	Yes	Yes
Village fixed effects	Yes	Yes	Yes	Yes
Number of observations	1,671	1,671	2,080	2,080

Source: Authors' computation from ACC data.

Note: OLS = ordinary least square. Probability of using fertilizer is based on Probit model, and fertilizer application rate is estimated using OLS regressions. Standard errors, clustered by household, are in parentheses.
* $p < .10$; ** $p < .05$; *** $p < .01$.

Table A2. Demand for fertilizer by farm size category: Estimates from probit and OLS (teff)

	Above median		Below median	
	Fertilizer adoption	Fertilizer application intensity (log - kg/ha)	Fertilizer adoption	Fertilizer application intensity (log - kg/ha)
Fertilizer price in Birr (log)	−0.461***	−0.576	−0.53***	−10.98***
	(0.101)	(0.531)	(0.101)	(0.598)
Teff price (log)	−0.003	−0.015	−0.126	−0.306
	(0.113)	(0.39)	(0.109)	(0.418)
Additional controls	Yes	Yes	Yes	Yes
Round dummies	Yes	Yes	Yes	Yes
Village fixed effects	Yes	Yes	Yes	Yes
Number of observations	934	934	1,113	1,113

Source: Authors' computation from ACC data.

Note: OLS = ordinary least square. Probability of using fertilizer is based on Probit model, and fertilizer application rate is estimated using OLS regressions. Standard errors, clustered by household, are in parentheses.
* $p < .10$; ** $p < .05$; *** $p < .01$.

Table A3. Demand for fertilizer by farm size category: Estimates from probit and OLS (wheat)

	Above median		Below median	
	Fertilizer adoption	**Fertilizer application intensity (log - kg/ha)**	**Fertilizer adoption**	**Fertilizer application intensity (log - kg/ha)**
Fertilizer price in Birr (log)	−0.089	-0.157	-0.256^{**}	-0.732^{*}
	(0.156)	(0.502)	(0.107)	(0.385)
Wheat price (log)	0.192	0.064	-0.156^{*}	0.054
	(0.139)	(0.601)	(0.082)	(0.287)
Additional controls	Yes	Yes	Yes	Yes
Round dummies	Yes	Yes	Yes	Yes
Village fixed effects	Yes	Yes	Yes	Yes
Number of observations	597	597	1,277	1,277

Source: Authors' computation from ACC data.

Note: OLS = ordinary least square. Probability of using fertilizer is based on Probit model, and fertilizer application rate is estimated using OLS. Standard errors, clustered by household, are in parentheses.
* $p < .10$; ** $p < .05$; *** $p < .01$.

Table A4. Production function estimates using household fixed effects

	Production (log)		
	Maize	**Teff**	**Wheat**
Fertilizer application levels (kg) (log)	0.285^{*}	0.056	0.446^{**}
	(0.154)	(0.213)	(0.201)
Land area (hectares) (log)	0.523^{***}	0.556^{***}	0.584^{***}
	(0.022)	(0.028)	(0.018)
Labor days (number of days)	0.131^{***}	0.127^{***}	0.085^{***}
	(0.014)	(0.0135)	(0.011)
Improved seed used (1 = yes)	0.085^{**}	0.019	-0.058^{*}
	(0.037)	(9.029)	(0.034)
Additional controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes
Number of observations	7,155	6,479	7,848

Source: Authors' computation from ACC data.

Note: Standard errors, clustered by household, are in parenthesis. The additional controls include rainfall levels, rainfall levels squared, and rainfall levels interacting with fertilizer application levels.
* $p < .10$; ** $p < 0.05$; *** $p < .01$.

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