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Farm- and community-level factors underlying the profitability of fertiliser usage for Ethiopian smallholder farmers

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ABSTRACT
While adoption rates for inorganic fertiliser are relatively high in Ethiopia, application rates are generally considered agronomically suboptimal. Using recent data on Ethiopian smallholder maize producers, we showed that maize response to nitrogen, and the profitability of fertiliser use depended on maize agronomy. The agronomic optimum ranged from 0 to 344 kg/ha with a mean value of 209 kg/ha. The actual nitrogen application rates were only about half the agronomic optimum, on average, and were less than the farm-specific economic optimum on 80% of maize fields. The average economic optimum level was 145 kg N/ha, but when we account for risk aversion, the resulting average optimum level is very close to the average observed usage level of 88 kg N/ha. Addressing risk aversion may help to induce greater levels of fertiliser investments at current prices and yield response rates. Our analysis also suggests that key pathways for increasing the economic returns to smallholder fertiliser investments include: complementing nitrogen inputs with phosphorus inputs and improved varieties, using lower levels of nitrogen under intercropping and manure inputs, enabling farmers to delay output sales beyond the immediate post-harvest period, and lowering the costs of accessing input and output markets.

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Maize; fertiliser; profitability; intensification; Ethiopia

1. Introduction

Agricultural intensification involving improved production technologies is a cornerstone of most strategies for feeding the growing populations of sub-Saharan Africa (SSA) (Holden 2018; Liverpool-Tasie et al. 2017; Sheahan and Barret 2017; van Ittersum et al. 2016; ten Berge et al. 2019). In Ethiopia, where maize occupies a large and growing share of grain production,[1] the adoption of modern maize varieties and mineral fertilisers has been increasing over time and has contributed to improvements in maize yields (Abate et al. 2015; Assefa et al. 2020; Breman, Schut, and Seligman 2019; Legesse et al. 2019; Rashid et al. 2013). Between 2005 and 2018, fertiliser use has quadrupled, maize area has increased by nearly half, and the share of total fertiliser allocated to maize has increased by 50% (Figure 1). In 2017, one-third of the total fertiliser use in Ethiopia was used for maize production to fertilise about 60% of the maize fields with an average application rate of 225 kg fertiliser/ha (CSA 2018a, 2018b, 2018c, Figure 1).

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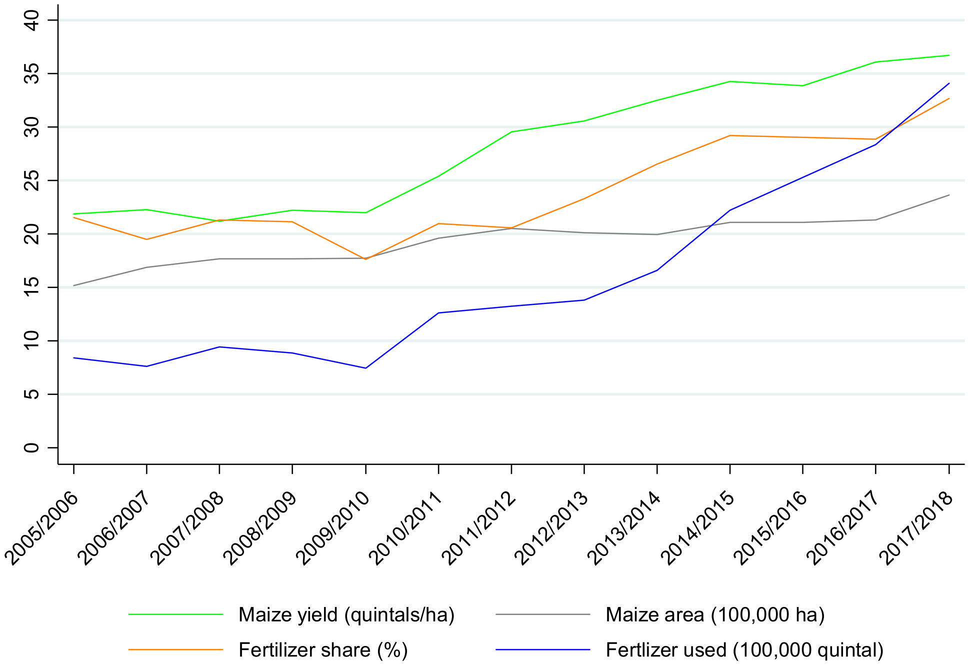

Figure 1. Trends in maize yield, maize area and share of total fertiliser use allocated to maize (2005/2006–2017/2018). Quintal = 100 kg. Source: constructed by authors from CSA Agricultural Sample Survey reports. The list of reports is provided in the reference list (CSA, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2016, 2017, 2018a). Fertilizer data for 2011/2012 and 2015/2016 were calculated as averages of previous and following years due to missing data.

An analysis of the growth in fertiliser use by Ethiopian smallholders suggests that different factors have played a role in enabling this growth. Improved extension services are believed to have been a particularly important factor. Abate et al. (2015) documented that the extension worker to farmer ratio was 1:476 in Ethiopia, compared to 1:1000, 1:1603 and 1:2500 for Kenya, Malawi and Tanzania, respectively. Second, even though Ethiopia stopped directly subsidising fertiliser in the 1990s, the country has continued to spend large amounts of money on fertiliser marketing and distribution. The costs incurred for storage, transport and administration through the cooperative system amount to approximately 15% of the fertiliser price paid by farmers – meaning that if these costs were included in fertiliser pricing, the resulting price would be 15% higher (Rashid et al. 2013). Jayne et al. (2018) also estimated that the average fertiliser price in Ethiopia was 25% lower than the commercial price in neighbouring countries.

Despite the growth in fertiliser application rates, yield gaps remain large (Assefa et al. 2020; Assefa et al. 2021; van Dijk et al. 2020; van Ittersum et al. 2016). Thus, there is a need to understand the agronomic and economic performance of inputs in smallholder systems in order to investigate alternative avenues for continuing to narrow the yield gap. In this paper, we empirically document the agronomic and economic returns to fertiliser use by smallholder maize farmers in Ethiopia, with the aim of clarifying the scope for continued yield gains through expanded smallholder investments in fertiliser.

The low levels of fertiliser adoption and usage by smallholders in SSA is attributed to multiple factors, including low profitability, riskiness of expected returns, lack of credit, lack of information or market failures (Holden 2018). A number of empirical studies indicate that low and/or variable levels of fertiliser profitability are explained in part by agri-environmental factors or production potential (Burke, Jayne, and Black 2017; Marenya and Barrett 2009; Nyssena et al. 2017; Sheahan, Jayne, and Black 2013; Theriault, Melinda, and Hamza 2018), and market access conditions which influence input and output prices (Burke, Jayne, and Black 2017; Fufa and Hassan 2006; Minten, Koru, and Stifel 2013; Liverpool-Tasie et al. 2017; Xu et al. 2009). Other studies have found that fertiliser use appears to be profitable at levels higher than those observed in smallholder populations, and that other constraints may be at play: e.g., missing credit markets (Duflo, Kremer, and Robinson 2008), supply constraints (Koussoubé and Nauges 2017; Theriault, Melinda, and Hamza 2018), including crowding effects of some input subsidy programmes (Jayne and Rashid 2013; Mapila et al. 2012).

In Ethiopia, empirical evidence on the returns to fertiliser investments is limited. Croppenstedt, Demeke, and Meschi (2003) used cross-sectional data collected in 1995 and calculated profitability at community level by asking farmers to estimate yield response to fertiliser, which may fail to provide accurate estimates. Rashid et al. (2013), using household survey data from 2008 and 2010, found that fertiliser use in maize production was profitable on average. However, they did not explicitly show the variables they included in their yield response function. Minten, Koru, and Stifel (2013) used data collected in 2010 and estimated fertiliser profitability in north-western Ethiopia. While they did show the effect of specific variables, they did not include potential interaction effects between nitrogen and other input and management factors when they estimated maize yield response to fertiliser. Other studies that estimated maize response to fertiliser and fertiliser profitability were based on data from experimental stations and on-farm trials where inputs and managements are well managed. Even though such studies are useful to get estimates of attainable yield response to maize, they do not reflect real conditions of smallholder farmers in terms of input use and management (Jayne et al. 2018; Rashid et al. 2013).

We contribute to the existing literature on fertiliser profitability in SSA in two ways. First, we estimate the maize yield response function by incorporating detailed field characteristics, inputs and biophysical conditions and show how agronomic (and economic) returns to N are conditioned by other inputs and management decisions. This strengthens what has been considered in previous studies, in which generally only a few interactions were considered. For example, Burke, Jayne, and Black (2017) investigated interactions between fertiliser rate, soil type, tillage and improved seed variety; Liverpool-Tasie et al. (2017) investigated the non-linear effect of nitrogen and interaction with phosphorus; Sheahan, Jayne, and Black (2013) related nitrogen use to agroecology, soil type and water stress; Theriault, Melinda, and Hamza (2018) related nitrogen use to agro-ecological conditions including soil water content, fallow, agroforestry, lowland, slope, rainfall and soil and Xu et al. (2009) related nitrogen use to rainfall and maize variety. Second, in contrast to other recent empirical studies which have documented fertiliser response variability in low-input systems, we explored response variability in a medium-input level system, where application rates are close to recommended rates on average, although with large variability. Some limitations relevant for low-input systems may have been addressed, but insights in response variability are needed for more site-specific fertiliser recommendations (Kenea et al. 2021).

Higher fertiliser application rates may not always signify higher profitability and maize yield response depends on other inputs and management factors (Assefa et al. 2020; Nyssena et al. 2017). Furthermore, the question of whether agronomic and economic optimal levels of fertiliser use have already been reached is important, as it may help clarify whether further improvements are possible, and for whom. In setting up our study, we hypothesised that (1) the effect of nitrogen is highly variable across maize fields depending on other inputs and management factors (e.g., manure application, type of maize variety, seeding rate, pesticide and herbicide application) and rainfall; and (2) current nitrogen application is below the economic optimum due to risk aversion of farmers.

2. Methodology

2.1 Data

We collected panel data on 740 farm households from maize producing areas in Oromia and Amhara regions of Ethiopia in the 2016/2017 and 2017/2018 production seasons.[2] These two regions have been the dominant fertiliser users in the country; they account for about 70% of the total fertiliser use for cereal production between 2006 and 2011 (Rashid et al. 2013). The sampling protocol followed a spatial randomisation technique. Four 10 km x10 km grids were randomly generated in each of four maize growing areas of Ethiopia: Jimma, Bako (West Shoa and East Wollega zones), East Shoa and west Gojjam (Figure 2). Within each of the resulting 16 grids, 7–9 1 km × 1 km grid cells were selected randomly. Finally, 5–6 households were selected from each selected grid cell, on the basis of their proximity to the centroid of that cell. After excluding observations below 1 and above 99 percentiles for yield and input variables, our final data set contained 735 households that cultivated 3808 maize plots (1926 and 1882 maize plots in 2017 and 2018 respectively). The households were asked detailed information about household composition, assets, livestock, inputs and outputs of all fields.

We collected output and input prices from all 70 villages of our sample, which are relatively widely distributed in space. The maize price data covers four quarters of the production year. This helps to capture the price variability that farmers face throughout the year. We used mean maize price across the quarters for the main analysis and also calculated profitability using quarterly maize prices. Nitrogen price was calculated as average urea and NPS fertiliser prices adjusted to the nitrogen content (i.e., price per kg of nitrogen) and by adding the transportation cost that farmers paid to transport fertiliser from the market to the farm.

To capture other spatially varying biophysical factors which affect yield responses, we used household GPS coordinates to extract information from geospatial datasets. Rainfall data were derived from the Climate Hazards group Infrared Precipitation with Stations (CHIRPS) dataset described in Funk et al. (2015). Growing degree days (GDD) and temperature seasonality variables were accessed from the Global Yield Gap Atlas (Van Wart et al. 2013).[3]

2.2 Maize yield response function and agronomic optimum

We defined a maize yield response function based on the production ecological concept, which specifies yield as a function of *defining*, *limiting* and *reducing* factors (van Ittersum et al. 2013). Yield defining factors in our model included maize variety, seeding rate, growing degree days,

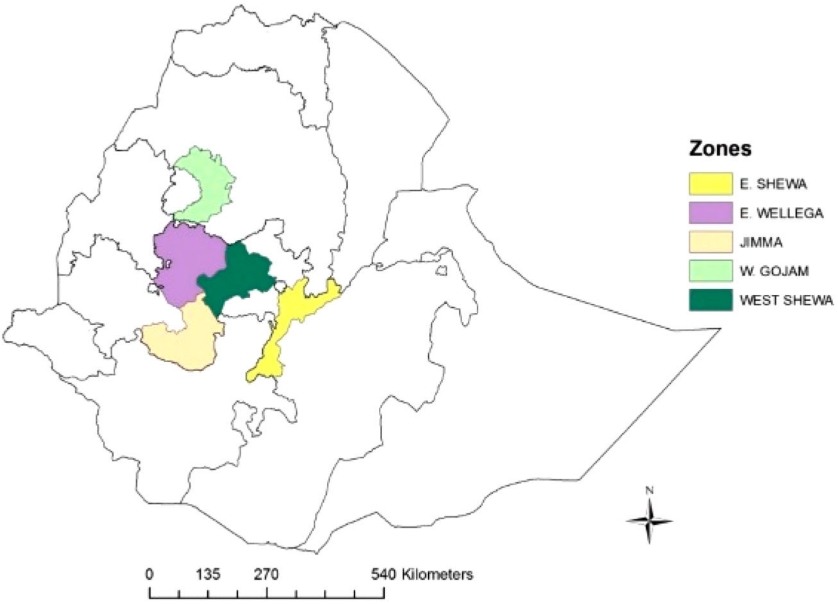

Figure 2. Study zones with farm household survey data.

temperature seasonality and production year. Yield limiting factors included nitrogen,[4] phosphorus, manure, intercropping, total rainfall, rainfall variability and ploughing frequency. Yield-reducing factors include the use of pesticides, herbicides, labour, household livestock assets and field size. We also included the quadratic term of nitrogen to capture non-linearity (Liverpool-Tasie et al. 2017; Sheahan, Jayne, and Black 2013). In addition, interactions were considered between nitrogen and other inputs and management factors (phosphorus, maize variety, seeding rate, manure, pesticide, herbicide, intercropping and rainfall) to test if the agronomic nitrogen use efficiency (kg maize/kg N) is affected by such factors. We included specific interactions in a Cobb Douglas production function, as a full translog function implied an extremely large number of variables, while the current specification yielded similar results as a translog function. We also included administrative zone dummies to account for possible unobserved effects at the regional level which may affect maize yield response.

The resulting maize yield response function is specified as:

$$Y_{ijt} = \beta_0 + \beta_1 X_{ijt} + \beta_2 N_{ijt} + \alpha_1 N_{ijt}^2 + \alpha_2 N_{ijt} * X_{ijt} + \varepsilon_{ijt} \tag{1}$$

where Y_{ijt} is maize yield of field i of household j in year t, X_{ijt} are growth defining, limiting (other than nitrogen) and reducing factors listed in Table 1. It also includes zonal dummies. N is the amount of nitrogen applied, $\boldsymbol{\beta}$ and $\boldsymbol{\alpha}$ are vectors of coefficients to be estimated and ε_{ijt} is error term that composes unobservable characteristics of the production system which include both time constant (ci) and truly random variables (ε_{ijt}).

Table 1. Descriptive statistics of variables included in the yield response function (mean values and standard deviations shown in brackets).

Variable	Description	2017	2018	Pooled
Maize yield (t/ha)	Maize yield calculated after adjusting area for intercropping	3.5 (1.8)	3.1(1.7)	3.3(1.8)
Growth defining factors				
Maize variety	Type of maize variety used (%)			
Local variety (=0)		13.8	8.9	11.3
Open Pollinated Variety (=1)		4.3	3.6	4
Hybrid (=2)		81.8	87.3	84.6
Seeding rate (kg/ha)	Maize seed rate	23.4 (10.4)	23.9 (10.9)	23.6 (10.7)
Growing degree days (°Cd)	Growing degree day for maize	1419 (61.3)	1419 (61)	1419 (61)
Temperature seasonality (°C)	Standard deviation of monthly average temperature	10.39 (1.71)	10.39 (1.71)	10.39 (1.71)
Year (1 = 2018)	Survey year			
Growth limiting factors				
Nitrogen (kg N/ha)	Nitrogen content of fertiliser applied	83.9 (67.4)	92.3 (69.8)	88.1 (68.7)
Phosphorus (kg P/ha)	Phosphorus content of fertiliser applied	21.6 (15.7)	23.7 (16.1)	22.6 (16)
Manure (1 = yes)	Manure applied on maize fields (%)	24.6	23.5	24.1
Intercrop (1 = yes)	Maize field was intercropped (%)	3.8	4.9	4.4
Total rainfall (mm)	Total rainfall of growing season in millimetres	1104 (321)	951 (252)	1027 (298)
Rainfall variability	Coefficient of variation of rainfall in dekads in the production season (%)	49 (11)	54 (10)	52 (11)
Ploughing frequency	Number of ploughings of maize fields	3.7 (1.3)	3.7 (1)	3.7 (1.2)
Growth reducing factors				
Pesticide (1 = yes)	Pesticide applied on maize fields (%)	2.2	9.1	5.7
Herbicide (1 = yes)	Herbicide applied on maize fields (%)	31.5	34.8	33.2
Livestock (TLU)	Total livestock holding of households in tropical livestock unit	5 (3.2)	5.1 (3.4)	5 (3.3)
Labour (person days/ha)	Labour used for land preparation, planting, fertilising and weeding	63.9 (42.1)	60 (37.3)	61.9 (39.8)
Field size (ha)	Maize field size	0.4 (0.3)	0.4 (0.3)	0.4 (0.3)
Economic variables				
Nitrogen price (Birr/kg)	Nitrogen price calculated from Urea and NPS prices	20.4 (1.6)	23.6 (1.1)	22 (2.2)
Maize price (Birr/kg)	Average maize price	5.6 (1.4)	5.9 (0.8)	5.9 (1.1)
Number of observations	3808			

Notes: One Ethiopian birr was equivalent to 0.04 USD during the survey years.

Although it is clear that maize producers in Ethiopia are inefficient (Assefa et al. 2020; Silva et al. 2019; van Dijk et al. 2020), in this study we do not use a production frontier function, as our aim is not to assess the response to nitrogen at the frontier or to assess inefficiencies, but to assess the actual responses to nitrogen.

Although we collected a large number of plot, farm and farmer characteristics, unobserved time-invariant factors can still bias our results (see Burke, Jayne, and Black 2017 for a discussion of such concerns in a similar maize yield response function estimation context). If this is the case, pooling the data and estimating our model with ordinary least squares will give inconsistent results. Fixed Effects estimation would address such concerns. However, we are interested in time-invariant regressors (such as GDD and temperature seasonality) which would drop out of a Fixed Effects framework. We, therefore, applied the correlated random effects (CRE) approach (also referred to as the Mundlak-Chamberlain device) that models a relationship between omitted time-invariant factors and the time-averages of time-varying explanatory variables which are observed (Wooldridge 2010). This framework has the advantage of allowing the estimation of coefficients for the time-invariant explanatory variables of interest to us here. The basic assumption of CRE is that time invariant unobserved characteristics (c_i) can be modelled as a function of average values of explanatory variables ($\overline{X_i}$) included in the model. Accordingly,

$$c_i = \gamma\bar{X}_i + \theta_i \tag{2}$$

where γ refers to the coefficient estimates of $\bar{X}_i$ and θ_i is the error term, *i.i.d.* N (0, λ^2). This gives a final yield response function as:

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 N_i + \alpha_1 N_i^2 + \alpha_2 N_i{*}X_i + \gamma\bar{X}_i + \theta_i + \varepsilon_i \tag{3}$$

We calculated marginal effects of each variable at observed values per field to get their individual effects on maize yield and reported average marginal effects under Table 3. The marginal effect for factor levels is the discrete change from the base level (reference group).

The highest yield (agronomic optimum) is calculated as the yield level achieved when the marginal physical product of nitrogen is zero, and the related field-specific nitrogen levels refer to the agronomic optimum level of nitrogen. We calculated this by setting the first derivative of our yield response function with respect to nitrogen to zero, for all individual fields. We used one-way analysis of variance (ANOVA) and a *t*-test to evaluate if optimum nitrogen required to achieve highest yield varies with other inputs and management factors.

2.3 Profitability of fertiliser and economic optimum

We used the average physical product (APP) and the marginal physical product (MPP) to calculate, respectively, the average value cost ratio (AVCR) and the marginal value cost ratio (*MVCR)* to measure fertiliser profitability. *APP* is the average yield gain per unit of nitrogen compared to not using nitrogen and was calculated only for fertiliser users. It was estimated as the difference between predicted yield (in kg/ha) with nitrogen fertiliser ($\hat{Y}_N$) and predicted yield without nitrogen fertiliser ($\hat{Y}_{NF}$), divided by the amount of nitrogen fertiliser used (N) in kg/ha.

Mathematically,

$$APP_{ijt} = (\hat{Y}_N - \hat{Y}_{NF})/N \tag{4}$$

Predicted yield with fertiliser is calculated for the observed level of nitrogen. Predicted yield without fertiliser was calculated by setting nitrogen use to zero. AVCR is then defined as:

$$\text{AVCR} = (APP{*}Pm)/Pn \tag{5}$$

where Pm is the nominal maize price (birr/kg) and Pn is the nominal price of nitrogen (birr/kg).[5] AVCR measures the average net returns to fertiliser use. An AVCR of 2 is often used as a threshold of acceptable profitability for risk-averse farmers who operate under production risks such as climatic variability and price fluctuations, the idea being that farmers may not be interested in investing unless they can expect a substantial return (Burke, Jayne, and Black 2017; Chamberlin, Jayne, and Snapp 2021; Crawford and Kelly 2001; Sheahan, Jayne, and Black 2013; Xu et al. 2009). However, a case may be made for considering higher AVCR values as representing economically attractive returns for risk-averse farmers (Kelly 2006). Theriault, Melinda, and Hamza (2018), in a study of Burkina Faso, argued that an AVCR threshold of 3 was more appropriate for farmers in fully rain-fed production systems with highly uncertain production outcomes. We also assume that smallholder farmers in Ethiopia may be risk averse due to uncertainties in weather, prices and other exogenous factors. We, therefore, evaluated profitability using AVCR values of 1, 2, 3 and 4 to accommodate different levels of risk, as well as unobserved production/transactions costs, that smallholders may face.

To calculate MVCR, we derived the marginal physical product (MPP) from our production function and used *Pm* and *Pn* from our survey. MPP is the partial derivative of the yield response function specified in Equation (3) with respect to nitrogen fertiliser (evaluated at each observed value of nitrogen fertiliser). Mathematically,

$$MPP = \partial Y_i / \partial N_i \tag{6}$$

MVCR is then defined as:

$$\mathrm{MVCR} = (MPP{*}Pm)/Pn \tag{7}$$

where *MPP* measures the extra output (yield) that can be gained by using one additional unit of nitrogen fertiliser, *Pm* is the maize price per kilogram and *Pn* is the price of fertilised nitrogen per kilogram. The general rule is that profit is maximised when MVCR is equal to one, i.e., when the value of output gained from the last unit of fertiliser is equal to the cost of fertiliser. However, an MVCR of 2 (or higher) is often considered to accommodate the risk and uncertainties that most smallholder farmers face in sub-Saharan Africa (Kelly 2006; Theriault, Melinda, and Hamza 2018). We also considered a value of MVCR of 1, 2, 3 and 4 to assess profitability.

Since AVCR and MVCR measure relative fertiliser profitability, i.e., ratios of input and output prices, we also considered the expected net revenue from fertiliser application as an indicator of absolute profitability (Sheahan, Jayne, and Black 2013). This is the revenue on maize fields that can be received from using fertiliser use and calculated as:

$$[E(\hat{Y}^F) - E(\hat{Y}^{NF})]E(P_{yt}) - x_{ijt}w_{ijt} \tag{8}$$

where E($\hat{Y}^F$) is the expected yield with fertiliser application, E($\hat{Y}^{NF}$) is the expected yield without fertiliser, $E(P_{yt})$ is the expected price of output at time *t*, x_{ijt} is the amount of fertiliser used on field *i* by farmer *j* at time *t*, and w_{ijt} is the price of fertiliser. Using the relative and absolute profitable measures helps to assess the current performance of fertiliser use and also to evaluate possible avenues for increasing the incentives for fertiliser use.

We calculated economic optimum nitrogen levels that maximise profit as it is relevant for farmers' input use decisions. This value occurs when the value of the last increment in yield from using extra nitrogen is able to cover the cost incurred, i.e., when MVCR is equal to 1. However, we also considered a threshold value of 2 to accommodate risks that farmers could face (Kelly 2006).

3. Results and discussion

3.1 Descriptive overview of the farming system

Mean maize yield was 3.3 t/ha. Average maize field size was 0.4 ha. Animal traction was the main source of ploughing (99%). Improved maize varieties were used on 91% of the maize fields and hybrids were dominant (83%). The average rate of seed was 23.6 kg/ha. Only 5% of the maize fields were intercropped. Manure was applied on 25% of the maize fields. Herbicides were applied on one-third of the maize field, and pesticide use was limited, on only 5% of the fields (Table 1). Fertiliser use in our sample is relatively high compared with other smallholder populations in the region; at least one type of fertiliser was applied on 90% of the maize fields. The mean amount of nitrogen applied was 88 kg N/ha, with 10–90 percentiles of 4–178 kg N/ha.

3.2 Maize yield response function

We compared the estimation of the maize yield response function with and without interactions to check possible collinearity problems and we observed that estimates were not affected by the inclusion of interactions. We present the final maize yield response function estimates in Tables 2 and 3.

3.2.1 Maize yield determining factors

Maize yield response to nitrogen depended on the amount of phosphorus (Table 2). This implies that efforts that target improved fertiliser recommendations need to target the dependencies between P and N. The effect of nitrogen on maize yield was also related to the type of maize variety. This suggests input complementarity in maize production and matches other findings (Assefa et al. 2020; Liverpool-Tasie et al. 2017). The interaction between nitrogen and manure was negative. Timing and quantity of manure and mineral fertiliser when used in combination may also have affected this association. Manure includes nitrogen which could make the total available nitrogen (from manure plus mineral fertiliser) higher and the marginal effect of mineral fertiliser nitrogen smaller. A simple *t*-test also showed that the marginal response to mineral fertiliser nitrogen was significantly lower on fields that used manure (6.4 kg/ha) than on fields without manure (7.5 kg/ha). Nyamangara et al. (2003) showed in Zimbabwe that the ratio of manure and mineral fertiliser N matters as to the dry matter yield and N leaching. Chivenge, Vanlauwe, and Six (2011) did a meta-analysis in SSA and found both positive and negative interactive effects between organic resources and mineral fertiliser depending on soil type, precipitation, amount of organic resources and mineral fertiliser. Essel et al. (2021) also found for Ghana that the ratios of compost and mineral fertiliser determined the benefits or disadvantages from using both jointly. Several other studies also showed substitutive effects between mineral fertiliser and manure (Ahmed et al. 2017; Ewunetu et al. 2021; Teklewold, Kassie, and Shiferaw 2013). We cannot verify this in our study as we did not have data on the timing and quantity of manure applied. In addition, poor manure quality and management may have their own influence on nitrogen cycling efficiencies (Rufino et al. 2006, 2007; Rufino 2008).

Rainfall negatively influenced maize response to nitrogen application. Leaching and run off due to excessive rainfall (the average rainfall was 1027 mm, and for 25% of the field-year combinations more than 1225 mm was reported) could explain this rather unexpected relationship. We did not find significant effects of interactions between nitrogen and seeding rate, pesticides and herbicides.

Table 3 displays the marginal effects of individual variables. Improved maize variety (both OPV and hybrid) showed higher maize yield compared to local varieties. Seeding rate had a positive effect on maize yield. Nitrogen and maize yield were positively related, with an average MPP of 7.3 kg of maize per kg of nitrogen. Livestock keeping and maize yield were positively related. This relationship could be explained directly by that livestock ownership implies farm power (specifically oxen) and/or livestock ownership implies potential use of organic fertiliser (manure). Labour (used for land preparation, planting, fertilising and weeding) had a positive effect on maize yield. Agricultural activities in Ethiopia are dominantly performed manually which explains the positive relationship like for other countries in SSA (Assefa et al. 2020; Baudron et al. 2015; Silva et al. 2019). Field size and maize yield showed an inverse relationship, consistent with empirical findings elsewhere in the region (Assefa et al. 2020; Muyanga and Jayne 2019).

Table 2. Maize yield response function estimates.

Variable	Estimates
Maize variety (1 = OPV)	169.8 (104.2)
Maize variety (2 = hybrid)	402.9 (120.7)***
Seeding rate	56.9 (12.9)***
Seeding rate squared	−0.3 (0.2)
Growing degree days	23.6 (173.2)
Temperature seasonality	5.8 (99.9)
Year dummy (1 = 2018)	−687.7 (132.2)***
Nitrogen	13.4 (4.2)***
Nitrogen* nitrogen	−0.03 (0.01)***
Nitrogen* phosphorus	0.066 (0.03)*
Nitrogen* variety (OPV)	4.716 (2.41)*
Nitrogen* variety (Hybrid)	2.643 (1.45)*
Nitrogen* seeding rate	0.052 (0.07)
Nitrogen* manure (yes=1)	−2.323 (1.26)*
Nitrogen* pesticide	−1.284 (1.64)
Nitrogen* herbicide	0.710 (0.93)
Nitrogen* intercrop(non-legume)	−2.287 (4.21)
Nitrogen* intercrop(legume)	−12.5 (9.017)
Nitrogen* rainfall	−0.01 (0.002)*
Manure (1 = yes)	106.1 (130.63)
Intercropping = non-legume	215.7 (186.4)
Intercropping = legume	786.9 (319.8)**
Rainfall	5.3 (3.09)***
Rainfall squared	−0.003 (0.001)**
Rainfall variability	−1394.2 (1562.6)
Ploughing frequency	16.8 (33.9)
Pesticide (1 = yes)	166.01 (269.5)
Herbicide (1 = yes)	−66.2 (143.8)
Livestock (TLU)	72.5 (40.2)***
Labour (person days/ha)	4.1 (1.4)***
Field size (ha)	−663.3 (382.1)**
Field size squared	328.3 (275.4)
r^2	0.33
Number of observations	3808

Notes: Clustered Robust standard errors in parentheses. CRE coefficients for MC device and administrative dummies are shown in Appendix. *$p < 0.10$, ** $p < 0.05$, ***$p < 0.01$.

Table 3. Average marginal effects of individual variables on maize yields.

Variables	dy/dx (marginal effect)
Maize variety (1 = OPV)	585.5 (200.8)**
Maize variety (2 = hybrid)	635.9 (153.3)***
Seeding rate (kg/ha)	49.7 (6.4)***
Growing degree days	23.6 (173.1)
Temperature seasonality	5.9 (99.9)
Nitrogen (kg/ha)	7.3 (1.1)***
Phosphorus (kg/ha)	5.8 (2.9)*
Manure (1 = yes)	−98.6 (69.5)
Intercropping = non-legume	14.2 (303.9)
Intercropping = legume	−319.9 (635.4)
Rainfall	−0.5 (0.9)
Rainfall variability	−1394.228 (1562.6)
Ploughing frequency	16.9 (33.9)
Pesticide (1 = yes)	52.9 (184.6)
Herbicide (1 = yes)	−3.7 (99.2)
Livestock (TLU)	72.6 (40.2)*
Labour (person days/ha)	4.1 (1.35)**
Field size (ha)	−424.853 (201.4)**

Notes: Standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.

3.2.2 Maize yield response to fertiliser: average physical product and marginal physical product

The APP of fertiliser use in the sample, i.e., the average yield gain from using nitrogen, was 9.8 kg maize /kg N, with similar values across study zones (Table 4). This value is close to other findings in SSA, for example, Liverpool-Tasie et al. (2017) found 8.9 kg maize /kg N in Nigeria, but somewhat lower than reported for on-farm experiments in SSA (ten Berge et al. 2019). The average MPP was 7.3 kg maize/ kg N, and it varied from −9 to 18 kg maize /kg N (Figure 3(a)). This implies that on average, further increasing N input will increase maize yield. MPP was negative on 6% of the maize fields, implying that the amount of N applied was above its optimum. We find that fields with negative MPP were smaller in size and used higher nitrogen, phosphorus, seeding rates and labour (data not shown). Of the maize fields with negative MPP values, 64% and 55% of maize fields used more than 100 N kg/ha and 200 N kg/ha, respectively (Figure 3(b)). While we cannot fully explain these findings, they are consistent with farmers being more likely to make intensification investments under land scarcity (i.e., Boserup's hypothesis) even when the exact production function for a given field is not known with certainty, in which case managers may be more likely to overshoot the economic optimum.

The MPP we found is in between that found in other previous studies in Ethiopia. Rashid et al. (2013) estimated an MPP of about 5 kg maize/kg N in four major cereal growing regions of Ethiopia using data collected in 2008, and Minten, Koru, and Stifel (2013) found an MPP of about 12 kg maize/ kg N in north-western Ethiopia using data from 2011. These studies were in different contexts in terms of market access and also fertiliser response. MPP values elsewhere in SSA were also variable due to differences in yield and input levels: 8 kg maize/kg N in Nigeria (Liverpool-Tasie et al. 2017), 16 kg maize/kg N for Zambia (Xu et al. 2009), 17 kg maize/kg N for Kenya (Marenya and Barrett 2009), 23–25 kg maize/kg N for Uganda (Matsumoto and Yamano 2009), 21–25 kg maize/kg N for Malawi (Haroua et al. 2017), 19 kg maize/kg N for Burkina Faso (Koussoubé and Nauges 2017), and 7–8 kg maize/kg N for Tanzania (Mather et al. 2016).

The maize yield response to nitrogen varied across the study zones (Figure 4(a)). The highest MPP was found in East Shoa zone. Nitrogen use was lowest in this zone (Figure 4(b)), and therefore marginal returns to additional N will have the largest positive impact on maize yield.

Table 4. Overview of actual, recommended and optimum nitrogen level and profitability by study zone.

	Zone					
	East Shoa	East Wollega	Jimma	West Gojjam	West Shoa	Total
Average maize yield (t/ha)	2.5	4	2.7	3.5	4	3.3
Fertilised plots (% of total)	75	95	88	98	96	90
Fertiliser use on fertilised maize plots (N kg/ha)	29	111	68	134	128	98
Fertiliser use on all maize plots (N kg/ha)	22	106	59	131	123	88
Recommended *N* rate (kg/ha)[1]	46	120	92	130	120	97
Agronomic optimum *N* (kg/ha)	200	215	208	209	217	209
Economic optimum *N* (kg/ha) (MVCR = 1)	137	146	139	148	154	145
Economic optimum *N* (kg/ha) (MVCR = 2)	75	78	70	87	90	80
N price (birr/kg)	22	21.7	23.3	21.6	21.3	22
Maize price (birr/kg)	6.2	5.3	5.6	6	5.8	5.8
APP (kg maize/kg N)	10.7	9.9	10.8	8.7	9.5	9.8
AVCR (APP of nitrogen × Maize price/ Nitrogen price)	3.1	2.4	2.7	2.4	2.6	2.6
Absolute profitability (BIRR/ha)	1129	3257	2670	3516	3894	2989
MPP (kg maize/kg N)	10.6	6.6	8.8	4.8	5.8	7.3
MVCR (MPP of nitrogen × Maize price/ Nitrogen price)	3.1	1.6	2.1	1.4	1.6	1.96
Sample size (% of total)	741 (19.5%)	453 (11.9%)	910 (23.9%)	959 (25.2%)	745 (19.6%)	3808 (100%)

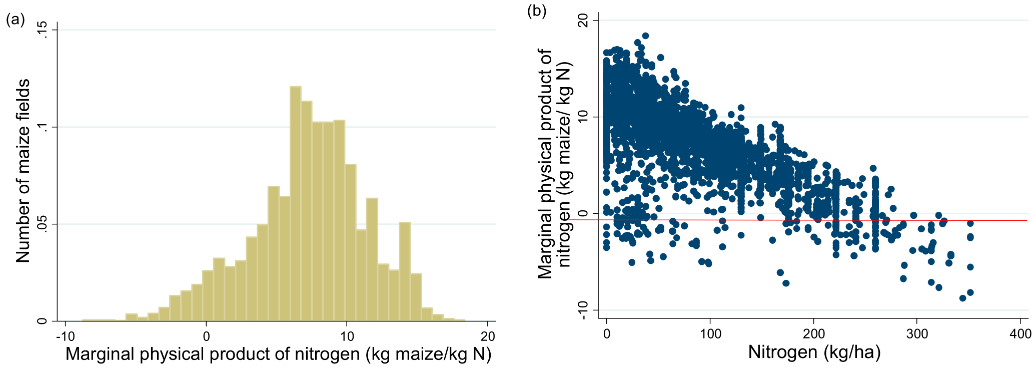

Figure 3. Yield response to nitrogen. (a) shows the distribution of marginal product of nitrogen and (b) shows the relationship between the marginal product of nitrogen and nitrogen fertiliser.

3.2.3 Agronomic optimum level of nitrogen

The agronomic optimum nitrogen application ranged from 0 to 344 kg/ha with a mean value of 209 kg/ha. The actual mean nitrogen rate is close to half the average agronomic optimum. This value varied across the study zones, i.e., only 15% in East Shoa to 64% in West Gojjam (Table 4). We further investigated how the optimum value varied with other inputs and management factors. ANOVA analysis indicated a significant difference in the optimum nitrogen levels across maize variety categories. The Tukey post-hoc test indicated that the optimum nitrogen amount was significantly higher for improved varieties. Maize fields that received manure had a lower optimum nitrogen level than fields without manure. Optimum nitrogen was also lower for intercropped maize fields than sole cropped fields. Fields intercropped with leguminous crops had an even lower optimum nitrogen level than fields intercropped with non-leguminous crops. In fields where herbicides were used, the optimum nitrogen level was higher, whereas pesticide application was accompanied by a lower optimum nitrogen level (Table 5). All of these estimated agronomic impacts make sense except for that of pesticide: *ceteris paribus*, one would expect a higher attainable yield with the use of pesticides and thus a higher optimum nitrogen level. Perhaps, farmers apply pesticides only in cases of pest incidence, and thus in cases of lower yield levels, but this remains speculative.

3.3 Profitability of fertiliser use

AVCR was higher than 1, 2, 3 and 4 on, respectively, 98%, 81%, 30% and 7% of the maize fields (Figure 5). Considering a threshold of AVCR = 2 to account for risk aversion, fertiliser use was on

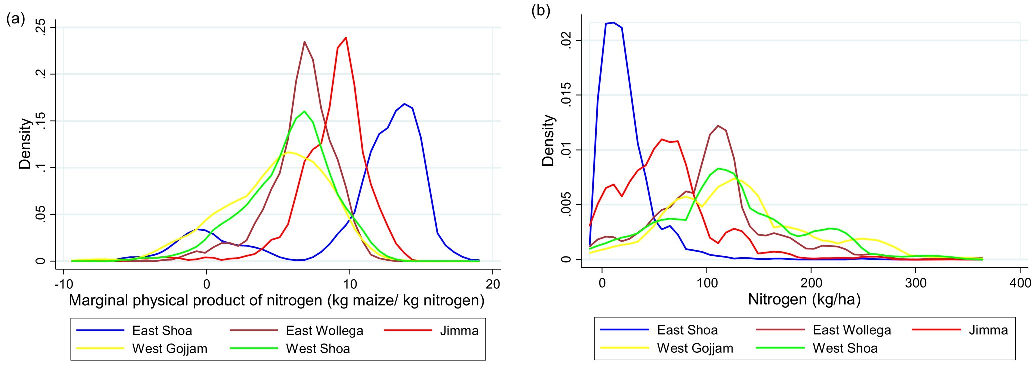

Figure 4. Density functions for marginal physical product of nitrogen (a) and nitrogen use (b) per zone.

Table 5. Agronomic optimum amount of fertiliser nitrogen as affected by other inputs and management factors.

Input /management	Optimum *N* (kg/ha)	Statistical test
Maize variety: Local	134	One-way ANOVA ($F(2, 3805) = 789.36$, $p = 0.0000$)
Maize variety: OPV	226	
Maize variety: Hybrid	218	
Manure (yes)	173	*t*-test, $t(3806) = 27.6$, $p = 0.000$
Manure (no)	221	
Intercropping (yes)	55	*t*-test, $t(3806) = 54.4$, $p = 0.000$
Intercropping (no)	216	
Herbicide (yes)	221	*t*-test, $t(3806) = -10.8$, $p = 0.000$
Herbicide (no)	203	
Pesticide (yes)	180	*t*-test, $t(3806) = 9.2$, $p = 0.000$
Pesticide (no)	211	

average profitable for 81% of the maize fields. This reflects that income can be increased as a result of fertiliser use in maize production. AVCR was higher in study zones (East Shoa followed by Jimma) that reported lower nitrogen input levels and relatively lower proportion of fertilised plots compared to all study zones. Using a threshold of 3 for AVCR, nitrogen was profitable on average only in East Shoa (Table 4).

MVCR was higher than 1, 2, 3 and 4 on respectively 82%, 47%, 17% and 5% of the maize fields (Figure 6). On average, the MVCR was very close to two (1.96). This indicates that on average income could be increased with increased fertiliser rate for a risk-neutral farmer (whose optimum would be the level of N at which MVCR = 1), but also for a risk-averse farmer (for which MVCR should be > 1). No differences were observed between years (results not shown). MVCR was highest in East Shoa followed by Jimma, which had lower level of nitrogen usage compared to other zones. This shows that fertiliser would be more rewarding if it is increased in these zones.

Absolute profitability estimation also showed that the extra income from maize production at observed level of nitrogen fertiliser was 3028 birr/ha on average and ranged from −1552 birr/ha to 9969 birr/ha (Table 4). Absolute profitability was variable across the maize fields: 4%, 30%, 38% and 28% of the maize fields had profit less than zero birr/ha, 0–2000 birr/ha, 2000–4000 birr/ha and greater than 4000 birr/ha, respectively. West Shoa followed by West Gojjam showed the highest absolute profitability. These zones had also used higher level of nitrogen input on

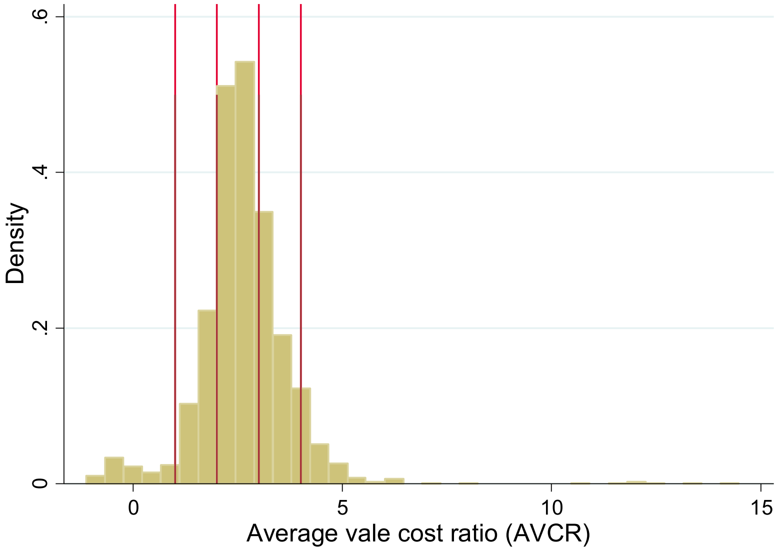

Figure 5. Distribution of average value cost ratio (AVCR). Vertical lines show AVCR values of 1, 2, 3 and 4.

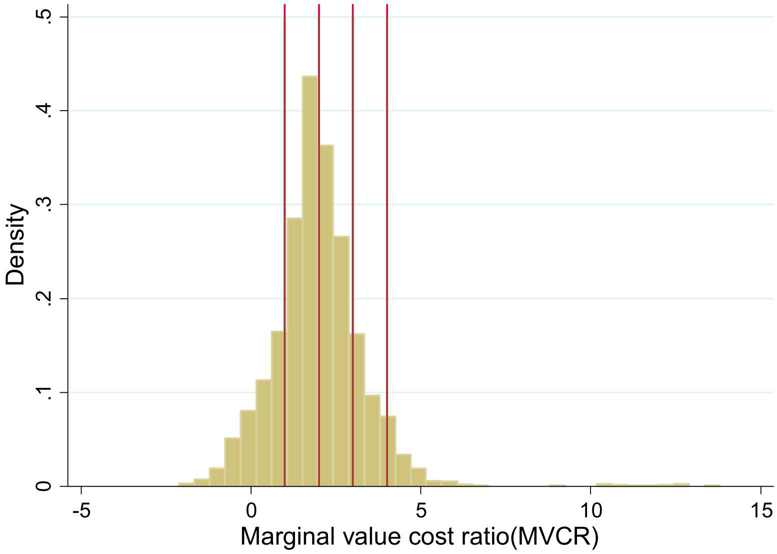

Figure 6. Distribution of marginal fertiliser profitability (MVCR). Vertical lines show MVCR at 1, 2, 3 and 4.

average. On the other hand, East Shoa zone had the lowest average nitrogen level and lowest absolute profitability value (lowest income gain from fertiliser use). The MVCR was the highest in this zone, indicating the largest relative opportunity to increase income through additional fertiliser investments.

3.4 Economic optimum level of nitrogen

At the economic optimum level of nitrogen fertiliser use, MVCR equals one, i.e., the returns from using extra fertiliser cover the associated extra costs. About 3% of the maize fields had MVCR values at or below zero, indicating that no additional economic gains to fertiliser were possible. The average economic optimum nitrogen was 145 kg/ha. This value is close to the value van Dijk et al. (2020) found in Amhara and Oromia regions (138 kg/ha). Current nitrogen application was less than the economic optimum on 80% of the maize fields (MVCR = 1). When using an MVCR threshold of 2, i.e., taking into account risk aversion, the economic optimum level decreased to 80 kg N/ha on average (Figure 7), close to the average observed level of 88 kg N/ha. Current nitrogen application was less than the level of nitrogen corresponding to MVCR = 2 on 50% of the maize fields. This shows the role of risk in farmers' input decisions. Addressing risk aversion, e.g., through insurance, may help to induce greater levels of fertiliser investments at current prices and yield response rates. In addition, it seems likely that returns to fertiliser investments would be improved by addressing efficiency issues in the fertiliser supply chain: late supply of fertiliser has been identified as one of the reasons for the suboptimal fertiliser usage rates in the country (Rashid et al. 2013). Among our surveyed households, 36% of them reported that they faced fertiliser shortages in their area at some point within the previous three years prior to the 2018 survey. Delay and shortage in supply were the dominant reasons mentioned. Among those farmers, 79% of them responded by travelling to another location to purchase, while 21% of them did nothing. The average recommended rate of nitrogen in the study zones was between the economic optimum using MVCR = 1 and MVCR = 2 (Table 4) showing that recommended fertiliser application rates are likely to give insufficient returns to risk-averse farmers. As expected, the economic optimum nitrogen application (MVCR = 1 and MVCR = 2) was lower than the agronomic optimum (Figure 7). The economic optimum nitrogen (MVCR = 2) was 38% of the average agronomic optimum nitrogen.

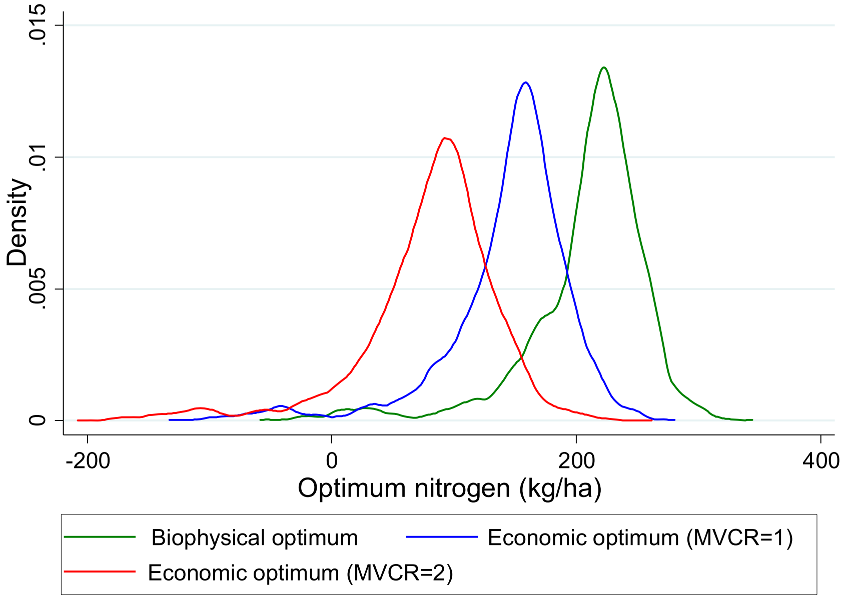

Figure 7. Frequency distribution of agronomic and economic optimum levels of nitrogen input (kg/ha).

3.5 What explains the magnitude and variability of profitability?

First, the results confirmed diminishing yield and economic returns to nitrogen input levels (Section 3.2.2), and thus that profitability depends on the nitrogen input level. The significant interaction terms from the yield response function estimation (Section 3.2.1), show that the response to nitrogen and the profitability depend on other inputs and management factors, in short on the agronomy of the maize crop. In general, the profitability and the optimum nitrogen fertiliser input is higher if nitrogen fertiliser is combined with complementary inputs (such as improved cultivars – Figure 8 (a) and Table 5) and profitability of using nitrogen fertiliser (and the optimum nitrogen input level) is lower if it is combined with other inputs that also provide nitrogen to the crop (manure and intercropping with leguminous species – Figure 8(b) and Table 5).

Clearly, profitability depends on the nitrogen fertiliser prices and on the maize price.[6] We evaluated profitability using four different quarterly prices of maize and showed that farmers can benefit by selling their maize between August and October, the period just prior to the harvest (Figure 9).

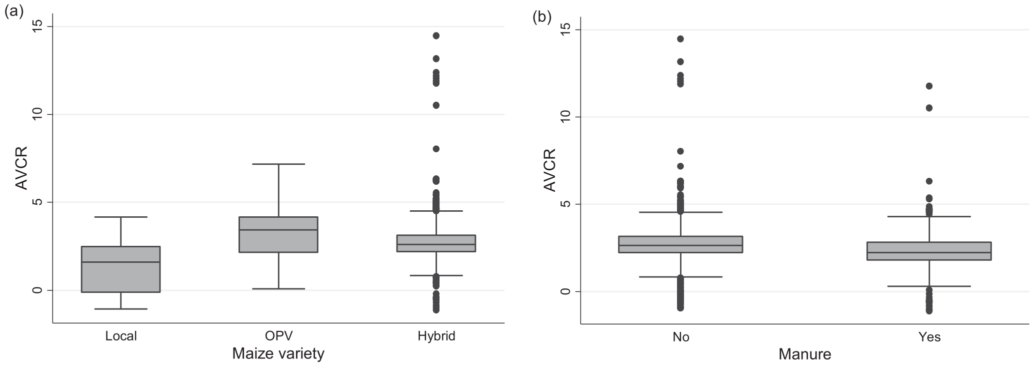

Figure 8. The profitability of using fertilisers for maize production (based on AVCR) was higher when combined with improved maize varieties (a) and profitability was on average lower on fields that were fertilised with manure (b).

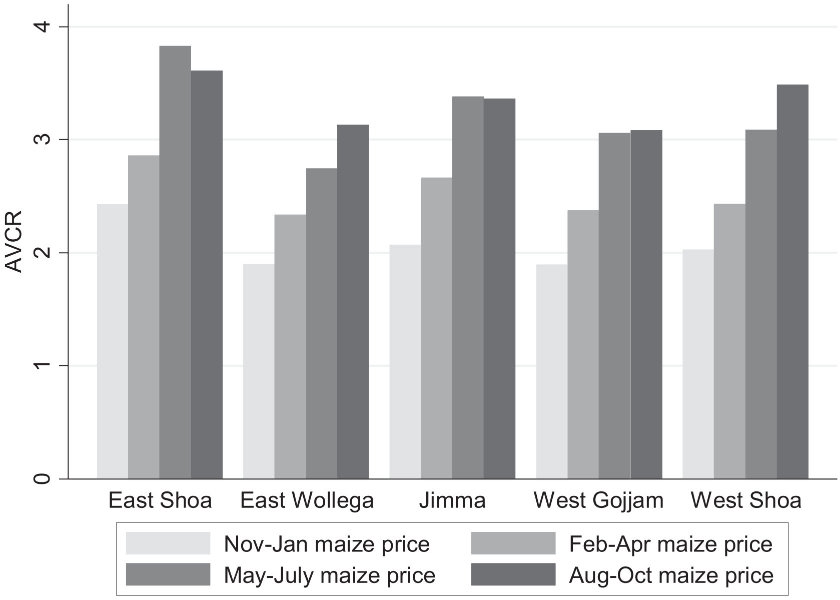

Figure 9. The profitability of using fertiliser for maize production (based on AVCR) was variable over the year when evaluated using quarterly maize prices.

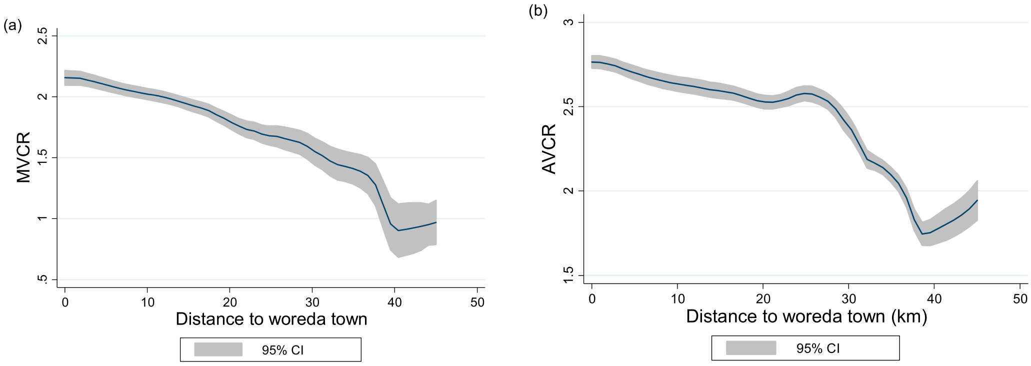

Figure 10. Fertiliser profitability as a function of distance (km) to woreda town, based on (a) MVCR and (b) AVCR. The figures show that income that could be increased using extra fertiliser and also average yield gain from fertiliser decreased when the distance to woreda town increased.

Profitability was lowest when maize was sold right after harvest, between November and January. This result was almost similar across the study zones. This result implicates the benefits of harvest time loans to address liquidity constraints and also the economic advantage of storage facilities to get maximum benefits from maize sales.

The profitability of fertiliser use was negatively related with distance to the nearest woreda (Figure 10). Minten, Koru, and Stifel (2013) found that farmers who lived about 10 km away from distribution centres paid additional costs equivalent to the costs of bringing fertiliser from an international port to a distribution centre. Our results reflect the potential of improving infrastructure and otherwise lowering the costs of transportation services to make fertiliser use more profitable in rural areas.

4. Conclusions

We estimated a maize yield response function that accounted for detailed management decisions and biophysical and marketing context, in order to evaluate fertiliser yield responses and economic profitability of fertiliser investments by smallholder maize producers in Ethiopia. Three major findings emerged from our study. First, agronomic (and economic) returns to N were strongly conditioned by other inputs and management decisions. Maize yield response to N was positively affected by phosphorus input and type of maize variety, and negatively by manure input and high rainfall. Our findings underscore the importance of accounting for the effects of other inputs and management decisions in the estimation of returns to nitrogen investments.

Second, even though the average fertiliser use in our sample (and in Ethiopia generally) is higher than found in smallholder production elsewhere in SSA, we document high variability in fertiliser application rates – and in maize yield responses – within our sample. On average, we show that agronomically and economically optimal levels of fertiliser use have not been reached, reflecting the potential for further gains from expanded fertiliser use. The observed mean N application rate (88 kg N/ha) was less than half the average agronomic optimum (209 kg/ha). Current nitrogen application rates were also less than the risk-neutral economic optimum (145 kg/ha, the average level at which MVCR = 1 in our sample), on 80% of the maize fields. When using an MVCR threshold of 2, in order to account for risk aversion, the economic optimum level decreased to 80 kg N/ha on average, close to the average observed level. Actual nitrogen usage was lower than 80 kg N/ha on half of the maize fields in our study, indicating substantial potential for profitably increasing fertiliser use by these farmers even under moderate risk aversion assumptions. However, we acknowledge that we did not consider the environmental impacts of nitrogen use while this is clearly needed to provide a more holistic picture of the implications of increasing fertiliser use under sometimes low efficiencies.

Third, increased maize/fertiliser price ratios would translate to higher profitability of fertiliser investments even at current levels of agronomic response. Improved price ratios could be achieved through decreased transport and transaction costs, which would lower the costs of linking local markets with urban centres, as well as reduce the cost of accessing local markets by farmers in surrounding areas. Furthermore, farmers receive better output prices if they delay selling their grain beyond the period immediately following harvest (with prices generally increasing through the lean season, reaching a maximum just prior to the next harvest).

While attention to fertiliser profitability has received considerable empirical attention in recent years, most studies have focused on areas with relatively low levels of fertiliser usage, seeking to explain such low levels as the result of low and/or highly variable fertiliser profitability (e.g., Burke, Jayne, and Black 2017; Koussoubé and Nauges 2017; Liverpool-Tasie et al. 2017; Marenya and Barrett 2009; Nyssena et al. 2017; Sheahan, Jayne, and Black 2013; Theriault, Melinda, and Hamza 2018; Xu et al. 2009). Our study shows the value of such analysis in relatively medium-adoption systems. In summary, our analysis suggests that key pathways for increasing the profitability of fertiliser use by smallholder maize producers in Ethiopia include: improving yield responses with better management (e.g., use of improved maize varieties, complementary phosphorus where appropriate, and targeting more N to fields which are not intercropped or already receiving manure inputs, on which additional N is expected to have lower impacts on yields); addressing risk aversion (e.g., via crop insurance) in order to strengthen economic incentives for fertiliser investments; enabling the delay of crop sales to take advantage of higher output prices (possibly through expanded access to storage facilities and/or post-harvest loans to alleviate liquidity needs); and improving farm gate price ratios through improved access to markets.

Notes

1. In 2018, maize accounted for 17% of total grain production, the largest share by crop, and 19% of total grain crop area, the second largest share after teff (CSA 2019).
2. Our panel data follow households, not maize plot, over the survey years.

3. http://www.yieldgap.org/en/web/guest/ethiopia.
4. Urea and NPS were the major fertilisers used during the survey period. However, we only considered nitrogen as the main nutrient and exclude other nutrients to prevent a potential correlation problem. We considered interaction between nitrogen and phosphorus to capture the effect of phosphorus on the yield response to nitrogen.
5. One Ethiopian Birr (ETB) was equivalent to approximately 0.04 USD during the study period.
6. It was not possible to capture the cost that the government spends on fertiliser provision while calculating fertiliser profitability. We acknowledge that profitability estimates would be lower had we been able to include such costs.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix: Maize yield response function estimates with CRE coefficients for MC device and administrative dummies

Variable	Estimates
Maize variety (1=OPV)	169.823 (203.199)
Maize variety (2=hybrid)	402.927 (131.941)***
Seeding rate	56.970 (8.717)***
Seeding rate squared	−0.249 (0.116)**
Growing degree days	23.568 (88.627)
Temperature seasonality	5.890 (43.373)
Year dummy (1=2018)	−687.757 (126.515)***
Nitrogen	13.456 (2.968)***
Nitrogen* nitrogen	−0.028 (0.006)***
Nitrogen* phosphorus	0.066 (0.019)***
Nitrogen* variety (OPV)	4.716 (2.294)**
Nitrogen* variety (Hybrid)	2.643 (1.488)*
Nitrogen* seeding rate	0.052 (0.033)
Nitrogen* manure (yes=1)	−2.323 (0.838)***
Nitrogen* pesticide	−1.284 (1.653)
Nitrogen* herbicide	0.710 (0.854)
Nitrogen* intercrop(non-legume)	−2.287 (4.951)
Nitrogen* intercrop(legume)	−12.559 (4.106)***
Nitrogen* rainfall	−0.005 (0.002)**
Manure (1=yes)	106.133 (94.417)
intercropping=non-legume	215.792 (510.275)
intercropping=legume	786.967 (296.863)***
Rainfall	5.300 (1.349)***
Rainfall squared	−0.003 (0.000)***
Rainfall variability	−1394.228 (1277.317)
Ploughing frequency	16.897 (35.635)
Pesticide (1=yes)	166.010 (201.210)
Herbicide (1=yes)	−66.247 (121.329)
Livestock (TLU)	72.562 (19.851)***
Labour (person days/ha)	4.071 (0.898)***
Field size (ha)	−663.351 (313.895)**
Field size squared	328.325 (232.187)
mean nitrogen	1.291 (1.009)
mean seed	−11.014 (5.062)**
mean number of ploughing	−5.773 (54.858)
mean TLU	−20.283 (21.738)
mean labor	−6.656 (1.393)***
mean maize variety	18.786 (91.409)
mean manure	94.238 (138.991)
mean intercrop type	318.068 (192.160)*
mean pesticide	−259.680 (223.643)
mean herbicide	−178.106 (125.351)
mean maize area	−407.425* (234.589)
mean total rain	−0.081 (0.586)
mean rainfall variability	610.018 (1611.089)
East wollega	248.337 (526.696)
Jimma	−746.077 (474.912)
West Gojjam	49.907 (429.747)
West Shoa	129.301 (496.601)
Constant	−686.860 (1430.560)
Number of Obs.	3808
r2	.33

Notes: Clustered Robust standard errors in parentheses. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$.