"Returns to fertilizer use: does it pay enough? Some new evidence from Sub-Saharan Africa"

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Abstract

The low level of modern inputs adoption by African farmers is considered to be a major impediment to food security and poverty reduction in Sub-Saharan Africa. The government of Burkina Faso, following the example of a number of other countries in the region, launched a subsidy program in 2008 to encourage farmers' uptake of chemical fertilizers and foster cereal production. This article explores the importance of fertilizer profitability in explaining the relative, apparent low use of chemical fertilizers by farmers in Burkina Faso. Using large-scale plot data, we estimate maize yield response to nitrogen to be 19 kg/ha on average and to vary with soil characteristics. Profitability, which we measure through the calculation of a marginal value cost ratio, is estimated at 1.4 on those plots which received fertilizers, with significant variations across regions. For those plots on which fertilizers were not applied, we predict that fertilizers should have been profitable in most cases under the current level of subsidized fertilizer prices. These findings suggest that the low uptake of chemical fertilizers might have been driven by factors other than profitability, including insufficient supply of subsidized fertilizers to farmers in need. Our results also call for increasing the availability of credit to farmers in order to encourage adoption of chemical fertilizers. Finally, our results also show that not taking into account the endogeneity of nitrogen use in the yield equation may produce biased estimates of the maize yield response to nitrogen.

Keywords: Burkina Faso; fertilizers; maize yield; subsidization program; technology adoption.

1. Introduction

The seemingly low use of modern inputs (including well-known technologies such as chemical fertilizers) by African farmers is considered to be a major impediment to food security and poverty reduction in Sub-Saharan Africa (SSA) (Morris et al., 2007; Dzanku et al., 2015). Average cereal yields and average intensity of modern inputs are stagnant in contrast to what has been observed in most developing regions (World Bank, 2007).

In response to this, in recent years several governments in SSA (with the assistance of international donors) have introduced input subsidy programs to foster the use of modern inputs and increase agricultural productivity (Druilhe and Barreiro-Hurlé, 2012; Jayne and Rashid, 2013). The discussion about these policies is still ongoing, with recent articles focusing primarily on the crowding out of the commercial fertilizer sector, diversion of inputs programs, and other factors related to the design of these programs (e.g. Pan and Christiaensen, 2012; Takeshima and Nkonya, 2014; Jayne et al., 2013).

The results from these subsidy programs are mixed and their performance is found to vary depending on the country and the characteristics of the intervention (for a comprehensive overview, see Jayne and Rashid, 2013). This calls for further rigorous ex-post analyses assessing the effectiveness of these policies. Our article contributes to this literature by studying the profitability of chemical fertilizers using large-scale plot data from Burkina Faso. As far as we know, no such estimates have been produced so far for this particular country.

The government of Burkina Faso, following the example of a number of other countries in SSA, launched a subsidy program in 2008 to encourage farmers' uptake of chemical fertilizers and foster cereal production. The intervention was universal but targeted at specific crops (maize and rice in particular). The program cost was estimated at 9.2 billion CFA

francs[1] in 2008, about 8% of total agricultural spending (MAFAP, 2013). The subsequent decrease in the market price of fertilizers was estimated to be in the range 20-40% depending on the source (Wanzala-Mlobela et al., 2013; Siri, 2013). Although the intensity of fertilizer use has increased since the first year of the program implementation, it has remained low. In 2008, the average fertilizer use intensity (calculated as the ratio of total fertilizer use to total arable land in the country) was around 9.5 kg/ha. This level is slightly below the average level of fertilizer use for SSA (14.7 kg/ha), and well below the targeted level of 50 kg/ha that should have been reached by 2015, according to the 2006 Abuja Declaration.[2] Fertilizer use intensity has increased slightly since 2008, reaching an estimated 11 kg/ha in 2012.

A number of factors explaining the low use of modern inputs by African farmers have been identified in the literature: low profitability (Duflo et al., 2008; Suri, 2011); credit and labor constraints (Croppenstedt et al., 2003; Moser and Barrett, 2006; Lambrecht et al., 2014); risks (Dercon and Christiaensen, 2011; Giné and Yang, 2009); transaction and transportation costs (Zerfu and Larson, 2010; Minten et al., 2013); and limited knowledge of the technology and lack of access to extension services (Conley and Udry, 2010; Krishnan and Patnam, 2014). In this article, we provide new evidence on the role of profitability (or lack of profitability) in explaining the low adoption of chemical fertilizers in SSA.

Using data from more than 7,800 maize plots cultivated in Burkina Faso, we estimate maize yield response to nitrogen application. Our modelling framework allows the endogeneity of nitrogen levels in the maize yield equation to be taken into account, along with data censoring issues (in our sample, fertilizer was applied to only about one-third of the plots). One of the main difficulties with ex-post analyses of technology adoption is to isolate the impact of the technology from the influence of farmer- and plot-specific characteristics on yield (Barrett et

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[1] 1 USD ≈ 460 CFA francs (average exchange rate in 2008).
[2] According to the World Bank, average fertilizer intensity is 146 kg/ha in South Asia and 107 kg/ha in Latin America (World Development Indicators http://databank.worldbank.org/data/home.aspx; accessed 2 April 2016).

al., 2004). Our plot data are cross-sectional and refer to the year 2008 only, but about 70% of households in our sample owned more than one plot. This data specificity allows us to partially control for unobserved household characteristics by employing the method used by Mundlak (1978) and Chamberlain (1980), and to estimate a fixed-effects model on the sub-sample of households which cultivated more than one plot. The latter, which allows for household-unobserved heterogeneity to be isolated, is used as a test of robustness for the findings of our preferred model estimated on the entire set of plots. We are unable to control for plot-specific unobserved characteristics but household-unobserved heterogeneity should partially control for differences in soil quality across farms.[3] Our estimates of maize yield response and the profitability of fertilizers are in line with estimates for other countries in SSA. We also show that not controlling for the endogeneity of fertilizer use in the yield equation leads to biased estimates of maize yield response to nitrogen.

The rest of the article is organized as follows. The next section briefly reviews the related empirical literature. Section 3 provides some background information about crop production and modern input use in Burkina Faso. Section 4 describes the data set used in this article. Section 5 presents the empirical model used to estimate the maize yield response to nitrogen application. Section 6 presents the estimation results, followed by a more detailed analysis of marginal returns and profitability of fertilizers in Section 7. Section 8 concludes.

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[3] We expect the variation in soil quality across plots belonging to the same household to be lower than the variation in soil quality across farmers.

2. Literature review

The profitability of fertilizer use depends on both the technical response to fertilizers, i.e. the units of output produced from one unit of nutrient, and the relationship between output price and fertilizer price (Yanggen et al., 1998). The literature on the profitability of fertilizer use in SSA focuses especially on maize, given the importance of this crop and the relatively high intensity of fertilizer use on maize plots in this region (Morris et al., 2007; Smale et al., 2013). A number of estimates of maize yield response rate to fertilizers have been reported in both the agronomic and economic literature, using data from both experiment stations and farm surveys. Earlier studies summarized in Heisey and Mwangi (1996) and Yanggen et al. (1998), primarily conducted by agronomists, reported maize response rates for several SSA countries, varying from a low of 5 kg of grain per kg of nutrient (usually nitrogen) to a high of 25 kg of grain or more. These estimates are found to be in line with those published recently in economic journals and based on farm surveys:[4] response rates of around 8-12 kg of maize per 1 kg nitrogen were reported for Zambia based on a nationally representative survey (Burke, 2012), Malawi (Ricker-Gilbert et al., 2013), and Northwestern Ethiopia (Minten et al., 2013). Higher-range estimates (15-25 kg of grain) were obtained in Kenya (Marenya and Barrett, 2009; Matsumoto and Yamano, 2011; Sheahan et al., 2013), Zambia (Xu et al., 2009), and Ghana (Chapoto and Ragasa, 2013).

Response rates however are highly variable, even within small regions, depending on factors such as weather, planting date, nitrogen application method, and soil type.[5] The role of soil type in conditioning response rate to fertilizers has been the focus of extensive agronomic

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[4] Findings from the recent economic literature are summarized in Jayne and Rashid (2013).
[5] In the context of Ghana for example, Henao et al. (1992) find maize response rate to vary from 7.6 kg per kg of fertilizer nutrient (nitrogen, phosphorus and potassium) in the interior savanna zone to 18.6 kg in the Volta region located in the semi-deciduous forest.

research (e.g. Chianu et al., 2012) since declining soil fertility due to nutrient losses is a major problem in SSA (Henao and Baanante, 2006).

A common measure of fertilizer profitability is the so-called marginal value cost ratio (MVCR). The numerator of the MVCR is the revenue generated by the application of an extra kilogram of nitrogen. It is calculated as the marginal maize yield response to nitrogen multiplied by the price of maize. The denominator of the MVCR is the cost of a kilogram of nitrogen. Estimates of MVCRs for maize plots in SSA are summarized in Jayne and Rashid (2013). The estimated MVCRs are found to vary between 1 and 1.75 in two studies conducted in Kenya (Marenya and Barrett, 2009a; and Matsumoto and Yamano, 2011) and to be in the range 0.75-1.05 in Uganda (Matsumoto and Yamano, 2011). Also using data from Kenya, Sheahan et al. (2013) report an average (instead of marginal) value cost ratio varying from 1.3 to 3.7, depending on the region. In theory, an MVCR greater than 1, which indicates that nitrogen is marginally profitable, should induce farmers to use chemical fertilizers. However, it is common to consider MVCRs above 1.5 or even 2 as profitable, in order to account for unobserved transaction costs and the potential risk premium if farmers are risk averse (Jayne and Rashid, 2013; Sheahan et al., 2013).

Recent research has shed light on the importance of non-market factors in explaining the profitability of fertilizer use in SSA. Using cross-sectional survey data from Western Kenya, Marenya and Barrett (2009a, 2009b) show that soil quality (measured in terms of carbon content) conditions the marginal productivity of fertilizer (maize yield response). This result has important policy implications: since poor farmers farm less fertile soils on average, they may benefit less from interventions that aim at increasing fertilizer use. These findings are consistent with analyses from large-scale panel data from Kenya (Sheahan et al., 2013) and other East and Southern African countries (e.g. Xu et al., 2009). Sheahan et al. (2013) use panel data for the period 1997-2010 to estimate the profitability of fertilizer use on maize

plots in Kenya. Their findings suggest that an increase in average fertilizer application rates will only lead to an increase in maize productivity if attention is given to the use of complementary inputs and heterogeneity in soil conditions. They also find that current fertilizer application rates are profitable for many maize growers across the country. However, estimates of the optimal levels of fertilizer use suggest that an increase in fertilizer use (to the level recommended by the government) may not be profitable for most farmers. This latter finding is supported by a study from field experiments in Kenya by Duflo et al. (2008). These authors find that the mean annualized rate of return to fertilizers is 69.5% when fertilizers are used in appropriate quantities but that other quantities of fertilizers (in particular the level recommended by the government) are not profitable for the average farmer.

These findings challenge the common views that explain in part the renewed emphasis on input subsidies in SSA: (i) an increase in fertilizer use will be profitable under current conditions; (ii) low fertilizer use is due mainly to poor infrastructure and market imperfections. Recent analyses of existing programs have raised concerns about the efficacy of input subsidies programs while suggesting ways of improvements (Banful, 2011; Pan and Christiaensen, 2012; Holden and Ludunka, 2014). However, the renewed emphasis on input subsidies has also called for more analyses of fertilizer profitability that take into account the heterogeneous constraints and opportunities faced by African farmers (Jayne and Rashid, 2013). While the body of literature on the costs and benefits of modern inputs use in SSA is growing rapidly, the evidence has come principally from a few countries, and even from a few regions within these countries. These findings may be less informative for other countries in SSA where farmers face different production conditions and constraints.

3. Agricultural production and modern inputs use in Burkina Faso

Burkina Faso is a West African country with a population of about 17 million. The Gross National Income was estimated at 700 USD per capita in 2014, below the SSA average (1,657 USD per capita).[6] In 2009, the contribution of agriculture to the Gross Domestic Product was estimated at 35% (MAFAP, 2013). The sector is dominated by smallholders: in 2008, 72% of the farms were smaller than five hectares (MAFAP, 2013). Agriculture is principally rain-fed and dominated by staple food crops (maize, millet, and sorghum) and cash crops (cotton and rice primarily). Cereal production represents about 77% of the total cultivated area for the period 2001-2010 (MAFAP, 2013). Cotton is the principal cash crop grown by farmers and accounts for a substantial part of the country's exports. Maize is the third cereal crop grown in Burkina Faso, accounting for about 17% of the country's total cereal production. Maize production has been expanding over recent years – production multiplied by a factor of 3.7 between 2000 and 2010. Maize is grown by around 80% of rural households and is primarily consumed nationally (MAFAP, 2013). Currently, average cereal yields in Burkina Faso are 1,209 kg/ha, below the average for SSA (1,427 kg/ha).[7] This may be partly explained by the relatively low use of chemical fertilizers and improved seeds: in our data (which are representative of the whole country), only 13% of plots cultivated in 2008 received chemical fertilizers and only 5% of plots were planted with improved seed varieties.[8]

Since the 2007-2008 food crisis, the government of Burkina Faso has intervened to increase fertilizer uptake and cereal yield. These interventions, targeted at specific crops instead of

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[6] Source: World Development Indicators (World Bank), available at
http://databank.worldbank.org/data/home.aspx; accessed 2 April 2016.
[7] For comparison, the average cereal yield is 2,835 kg/ha in Latin America and the Caribbean and 2,376 kg/ha in South Asia. Source: World Development Indicators (World Bank), available at
http://databank.worldbank.org/data/home.aspx; accessed 2 April 2016.
[8] The main types of chemical fertilizers used by farmers are NPK (Nitrogen, Phosphorus and Potassium fertilizer) and urea. About 19% of plots received organic fertilizers, including animal manure, household waste and compost.

categories of farmers as in Malawi and Kenya for instance, consist primarily of the distribution of improved seeds and chemical fertilizer subsidies. Rice and maize are the main cereal crops targeted under Burkina Faso's inputs subsidy programs (see Druilhe and Barreiro-Hurlé, 2012; Siri, 2013). Fertilizer subsidies accounted for about 60% of the total value of input subsidies for cereal crops. NPK and urea are the two types of fertilizers targeted by the program. Over the period 2008-2011, subsidized fertilizers distributed by the government for cereal crop production amounted to 52,460 metric tons (an average of 11% of fertilizer imports), and induced a decrease in the average market price of fertilizer by 20 to 40% in 2008 (Wanzala-Mlobela et al., 2013; Siri, 2013).

Under Burkina Faso's fertilizer subsidy program, fertilizer needs for farmers growing maize and rice are estimated by each Provincial Directorate of Agriculture (DPA) based on the area expected to be planted and recommended fertilizer application rates. Province-level fertilizer needs are then aggregated at the regional level by the Regional Directorate of Agriculture (DRA) before being transmitted to the Ministry of Agriculture. The Ministry of Agriculture imports the fertilizers and distributes them to each region according to the regional expressed needs. Provincial offices are then responsible for the transport of the amount of fertilizers they require from the DRA warehouses to DPA warehouses. Farmers (or farmers' organizations) acquire the subsidized fertilizers from the DPA and are responsible for the transport of the fertilizers to their farms. However, as noted by Wanzala-Mlobela et al. (2013) and Siri (2013), the program encounters important issues related to fertilizer distribution. In addition to delays in delivery and discrepancies between the expressed needs and the amounts of fertilizer distributed in the regions or provinces, farmers have to bear the transportation costs from the DRA warehouses to DPA warehouses (see Wanzala-Mlobela et al., 2013, for further details on Burkina Faso's input subsidies program).

4. Data and descriptive statistics

The data used in this article come from Phase II of Burkina Faso's Agricultural Census (RGA 2008-2009). The RGA was a large scale, nationally representative survey conducted by the Ministry of Agriculture of Burkina Faso (Directorate of Agricultural Statistics – DPSA) between 2006 and 2010. The primary objective of the RGA was to provide statistics on the agricultural sector (crop production, livestock development, arboriculture, and fishery). Data collected during Phase II include detailed household and plot level data on agricultural inputs and outputs, livestock, agricultural equipment, income, access to credit, etc.

The sample selection for Phase II was made using a two-stage stratified sampling method. Villages were selected in the first stage with probabilities proportional to size. Agricultural households were then randomly selected in the second stage. Additional stratification in each stage was introduced in the sampling design using the data collected in Phase I (2006).[9] For instance, in each province, agricultural households were split between two strata: "small-holder farmers" and "large-scale farmers" (for more details on the sampling design, see DPSA, 2007). In total, 7,500 households were selected in 1,311 villages. Household characteristics and plot level crop production information were collected between June and December 2008 for a subset of 6,795 households in 1,283 villages. We have detailed information on the 63,407 plots cultivated by these households. The sample covers the 13 administrative regions and 45 provinces of the country.

For the purposes of this study, the analytical sample consists of 7,845 maize plots belonging to 4,481 households.[10] Around 70% of the surveyed households grew maize on more than one

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[9] Phase I of the RGA consisted of the listing of all agricultural households in the country, and data collection on activities undertaken by the households, as well as on livestock and equipment owned.

[10] Plots for which yield (measured in kg/ha) was declared to be 0 were removed from the database and yield values below the first percentile and above the 99th percentile were eliminated. Extremely low values are likely to reflect neglected or abandoned plots while extremely high values are likely to be due to measurement error. We also deleted observations for which nitrogen application (in kg/ha) was above the 99th percentile.

plot. The average maize yield in our sample was 1,300 kg/ha, varying from a low of 112 to a high of 3,960 kg/ha (median 1,200 kg/ha). Chemical fertilizers were applied on 35% of the plots and the average application rate was 32 kg of nitrogen (N) per hectare (the median is 26 kg of N), varying from almost 0 to 198 kg/ha.[11] The latter is in the range of application rates recorded for maize plots in Kenya (Sheahan et al., 2013) and Zambia (Burke, 2012); for other estimates on SSA, see Jayne and Rashid (2013, Table 3).

The average maize yield on plots receiving chemical fertilizers was 1,590 kg/ha while the average yield was 1,145 kg/ha when no chemical fertilizers are applied (the difference is statistically significant at the 1% level). The difference in yields between plots with and without chemical fertilizers is further illustrated in Figure 1, which features non-parametric (kernel) estimates of the density of yields for the two types of plots.
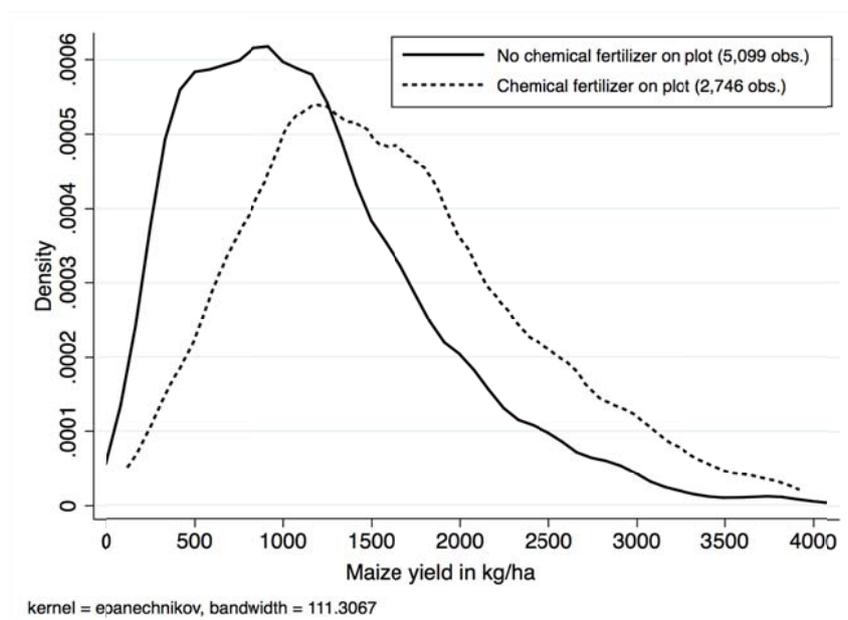

kernel = epanechnikov, bandwidth = 111.3067

Figure 1: Non-parametric (kernel) estimation of the density of maize yields (7,845 plots)

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[11] The quantity of nitrogen applied is of the form NPK (14% nitrogen) and urea (46% nitrogen).

Using local polynomial regression on plots which received chemical fertilizers, we find a non-linear and concave relationship between nitrogen application rate and maize yield (Figure 2). The graph suggests a positive effect of nitrogen on yield up to a threshold (around 50-60 kg/ha) but detrimental effects on yield with application rates above this threshold and large negative effects when more than 150 kg of N per ha were applied on the plot.

kernel = epanechnikov, degree = 3, bandwidth = 19.08, pwidth = 28.62
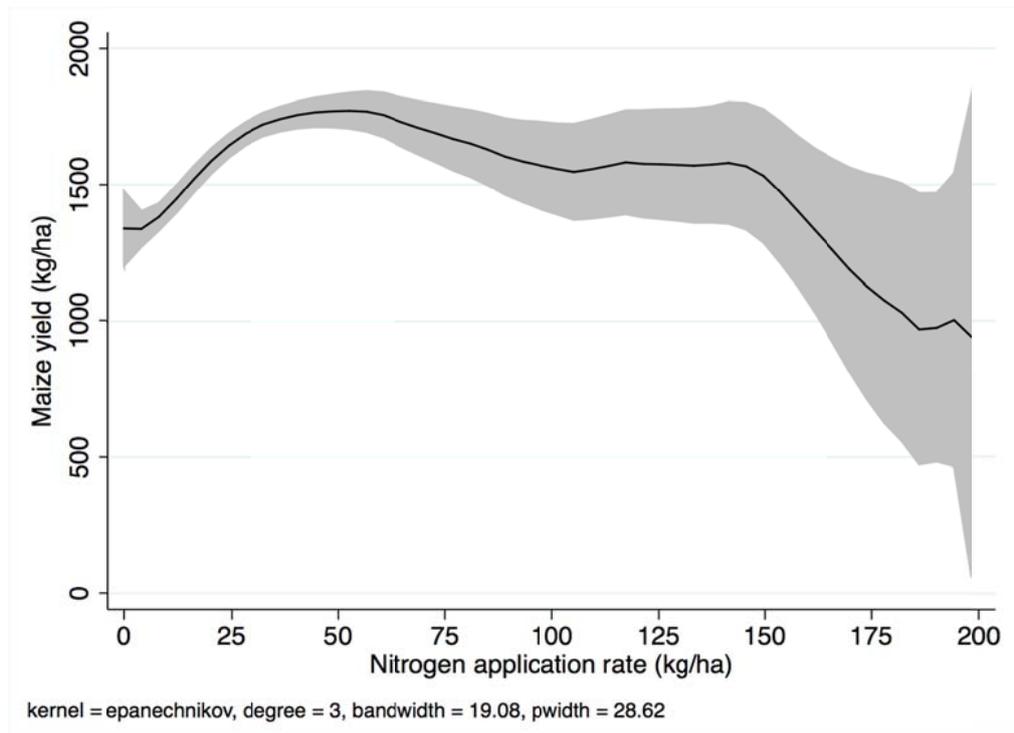
Figure 2: Local polynomial regression (with 95% confidence interval) of maize yield on nitrogen application rates (2,746 plots)

We next compare average plot and household characteristics for plots with and without chemical fertilizers (Table 1). Plots on which chemical fertilizers were applied were larger in size (0.91 ha versus 0.26 ha for those plots which did not receive any fertilizers) and more often pure maize plots (88% versus 76%). Only 52% of the plots which received fertilizers were planted with maize the year before while this proportion is 81% for plots which did not

receive any fertilizers. Plots on which fertilizers were applied were more often borrowed or

rented than the other plots (15% versus 10%),[12] and external paid labor was more likely to be

used on plots which received fertilizers.

Table 1. Comparison of mean characteristics of plots with and without fertilizers

	No fertilizer used on plots	Fertilizers used on plots	Test of mean equality[a]
Plot-level characteristics			
Maize yield (kg/ha)	1,145	1,590	***
Plot size (ha)	0.26	0.91	***
Plot is located in the plains (0/1)	0.90	0.90	n.s.
Pure maize on plot (no intercrop) (0/1)	0.76	0.88	***
Maize grown on plot year before (0/1)	0.81	0.52	***
Plot is borrowed or rented (0/1)	0.10	0.15	***
Use of external paid labor (0/1)	0.17	0.32	***
Household-level characteristics			
Head of household is male (0/1)	0.95	0.98	***
Age of household head (0/1)	50.1	47.4	***
Household head is illiterate (0/1)	0.77	0.64	***
Price of fertilizer (CFA franc/kg)[b]	333	301	***
Access to credit over last 3 years (0/1)	0.09	0.34	***
Less than one hour to market (0/1)	0.81	0.84	**
Total livestock units	6.46	8.63	***
Household owns a plough (0/1)	0.45	0.73	***
Household owns small material (0/1)[c]	0.36	0.66	***
Poor soil quality (0/1)[d]	0.30	0.23	***
Drought or flooding event (0/1)	0.12	0.06	***
Number of observations	5,099	2,746	

Notes: [a] *, **, *** indicate that the means of the two groups are statistically different at the 10, 5, and 1% level, respectively; n.s. is not significant. [b] Median price in the district. [c] Takes the value 1 if the household owns a hopper, a seeder, a harrow, or a hoe, and 0 otherwise. [d] Takes the value 1 if the household head believes that the soil of his/her parcel is of low quality, and 0 otherwise.

The adoption of chemical fertilizers was more likely for household heads who were literate,

had better access to credit, and owned more livestock units, as well as a plough and some

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[12] The dummy variable describing plot status takes the value 1 if the plot was either borrowed or rented, and the value 0 if the plot belongs to the household (either because it was purchased, received as a gift, or inherited).

small agricultural machinery. Households who applied fertilizers on their plot benefited from lower fertilizer prices on average (the price shown in the table is the average of the median price of fertilizers in the district). Interestingly, the proportion of household heads who perceived the quality of their soil to be poor was higher for plots that did not receive any fertilizers.[13] This may reflect the fact that poor households which were often more likely to work on lower quality plots faced more constraints regarding access to fertilizers, either through difficult access to credit or difficult access (in terms of time, distance, and availability of products) to input markets. It may also be an indication that fertilizers are less profitable on lower quality soils (Marenya and Barrett, 2009a). Finally, those plots on which fertilizers were not applied were more affected by catastrophic climatic events such as droughts and floods.

Maize yields and the use of fertilizers vary significantly across the 13 regions (Table 2). Average yield varies by a factor of three: from a low of 655 kg/ha in Sahel to a high of 1,877 kg/ha in Hauts Bassins. The proportion of plots on which fertilizers were applied also varies significantly. In Sahel, where agriculture is less developed,[14] fertilizers were very rarely used (1% of the plots) while they were applied on 75% of the plots in Hauts Bassins. Average nitrogen application was in the range 15-40 kg/ha for most regions. Regional differences may be explained by differences in environmental conditions (weather, altitude, type of soil etc.) as well as by differences in terms of infrastructure, distance to markets and input suppliers, access to extension services and other information sources. For instance, both maize yields

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[13] The farmers were asked about their constraints on agricultural production, which include a shortage of land, the lack of technical knowledge, the poor quality of soils, climatic shocks and pest attacks. The indicator of soil quality is the household head's subjective evaluation of the quality of the soil: a binary indicator equal to one if the head evaluates the soil as poor.

[14] The Sahel region, which is situated in the extreme north of Burkina Faso, is relatively less suited to agricultural production. Nonetheless, livestock raising and agriculture remain the principal activities of the households who live in this part of the country.

and fertilizer use were particularly high in cotton producing regions such as Hauts Bassins, Cascades and Boucle du Mouhoun where access to fertilizer and extension services is easier.[15]

Table 2. Average maize yield and fertilizer use by region

Region	Obs.	Maize yield	Fertilizers used on plots	Nitrogen use[a]
		(kg/ha)		(kg/ha)
Boucle du Mouhoun	932	1,338	58%	37.1
Cascades	441	1,704	68%	26.6
Centre	174	1,030	21%	21.7
Centre Est	821	1,398	27%	33.1
Centre Nord	460	1,072	11%	14.5
Centre Ouest	593	1,396	47%	41.0
Centre Sud	640	1,222	29%	29.7
Est	906	1,425	17%	24.9
Hauts Bassins	851	1,877	75%	36.8
Nord	268	1,022	30%	17.2
Plateau Central	600	1,087	11%	23.0
Sahel	77	655	1%	9.4
Sud Ouest	1,082	842	18%	25.0

Note: [a] Average calculated over the plots which received some fertilizer.

5. Estimation methodology

Our purpose is to estimate a maize yield function and the yield response to nitrogen application. The local polynomial regression discussed above suggests a non-linear relationship between nitrogen application and maize yield, which calls for the use of a quadratic functional form (i.e., with the square of nitrogen application as one of the right-hand-side variables). There is also evidence in the literature that the marginal productivity of nitrogen may vary depending on plot characteristics such as soil quality (Marenya and Barrett, 2009a), so our yield function also includes interactions between nitrogen application and plot characteristics.

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[15] The diversion of cotton fertilizer to maize fields is a well-known phenomenon in Burkina Faso cotton producing areas (e.g. Schwartz, 2008).

Yield also depends directly on plot and household characteristics. Regarding a plot, we have information on its size, whether it was a pure maize plot or not, whether maize was grown on the plot the year before, whether the parcel was borrowed or rented, whether some external laborers were hired to work on the plot, and whether the plot had been affected by some catastrophic climatic events over which the farmer had no control (flood or drought). To control for households' heterogeneity, we use the number of livestock units (as a proxy for the use of inorganic fertilizers such as manure), the household's equipment (plough, small machinery), gender, age, and literacy of the household head, plus his/her perception of the soil quality. Finally we include regional dummies to control for varying climatic conditions and soil quality across the country. Regional dummies might also capture differences in access to information and extension services across regions.

The general form of the yield function is the following:

$$y_{p,i} = f\left(N_{p,i}, \mathbf{x}_{p,i}, \mathbf{w}_i; \boldsymbol{\beta}\right) + \mu_{p,i} + \upsilon_i + \varepsilon_{p,i}, \tag{1}$$

where $y_{p,i}$ represents maize yield (in kg/ha) on plot p belonging to household i; $N_{p,i}$ is nitrogen application rate (kg/ha); $\mathbf{x}_{p,i}$ and $\mathbf{w}_i$ are vectors of observable covariates at the plot (p) and household (i) level respectively; $\boldsymbol{\beta}$ is the vector of unknown parameters; $\mu_{p,i}$ and υ_i represent plot- and household-specific unobservables; and $\varepsilon_{p,i}$ is an idiosyncractic error term with assumed mean zero.

Since our data are in a cross-sectional form, panel data techniques are not available to control for unobserved plot-specific effects $\mu_{p,i}$ (i.e., there is no way to separate $\mu_{p,i}$ from $\varepsilon_{p,i}$) and endogeneity bias might arise if some observable variables were correlated with the unobserved plot-specific effects. Unobservable plot characteristics, such as soil quality, plot

exposure or slope, are unobserved by the econometrician but known to the farmer. So we might expect these characteristics to have a direct influence on yield but also to influence the farmer's use of nitrogen. To control for the possible endogeneity of nitrogen application in the yield equation, we estimate an equation featuring nitrogen use ($N_{p,i}$) as the dependent variable simultaneously with the yield function:

$$
\begin{cases}
y_{p,i} = f\left(N_{p,i}, \mathbf{x}_{p,i}^{y}, \mathbf{w}_{i}^{y}; \boldsymbol{\beta}^{y}\right) + \upsilon_{i}^{y} + \varepsilon_{p,i}^{y} \\
N_{p,i} = g\left(\mathbf{x}_{p,i}^{N}, \mathbf{w}_{i}^{N}; \boldsymbol{\beta}^{N}\right) + \upsilon_{i}^{N} + \varepsilon_{p,i}^{N}
\end{cases}. \tag{2}
$$

We add superscripts y and N to differentiate the vectors of observable characteristics, unknown parameters, and error terms between the two equations. We have removed the unobservable plot characteristics $\mu_{p,i}$ from the equations in the system since they are not separable from the idiosyncratic error term.

The vector of exogenous variables in the nitrogen equation includes: plot size; plot location (whether in the plains or not); cultivation practices on the plot (whether this is a pure maize plot, and whether maize was grown the year before); plot status (borrowed or rented parcel); adverse climatic events (drought or flood) that affected the plot; the median price of fertilizers in the district;[16] total livestock units; the household's distance to market; gender, age, and literacy of household's head and his/her perception of soil quality; and regional dummies. Regional dummies in this model are used to control for possible infrastructure and input supply constraints since we do not have any precise information on the distance between the farm and the fertilizer suppliers. The price of fertilizers and the distance to market (a dummy variable taking the value 1 if the market is less than one hour away, and zero if not) play the role of identifying instruments in the nitrogen equation. Tests on the validity of these instruments are performed and discussed in the next section.

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[16] The district is another administrative unit, at a lower level than the province.

It might also be the case that some unobservable household characteristics, υ_i are correlated with both the dependent variables and observable plot characteristics. In the yield equation for example, an experienced and well-informed plot manager might have developed cultivation practices (intercropping, crop rotation) that have a direct influence on yields but also on his/her choice of nitrogen application. To control for possible correlations between unobservable household characteristics υ_i and some of the plot-specific observables $\mathbf{x}_{p,i}$, we follow the approach of Mundlak (1978) and Chamberlain (1980). We specify a linear relationship for the dependence between the unobserved household specific effects and the exogenous covariates as follows:

$$\upsilon_i = \psi + \overline{\mathbf{x}}_i \xi + a_i \tag{3}$$

where $\overline{\mathbf{x}}_i$ is the vector of household-specific mean plot characteristics (calculated over the plots owned by each household). We assume that $\overline{\mathbf{x}}_i$ allows us to control for the correlation between household unobserved specific effects and plot observable characteristics and that, conditional on $\overline{\mathbf{x}}_i$, the remaining error a_i can be assumed to be independent of $\mathbf{x}_{p,i}$. Mean plot characteristics will be informative only for households which own more than one plot (about 70% of the surveyed households). The same approach can be applied to both equations in the system.[17] Omitting the constant ψ which is embedded with the constant of the original models, the system is written as follows:

$$\begin{cases} y_{p,i} = f\left(N_{p,i}, \mathbf{x}_{p,i}^y, \mathbf{w}_i^y; \boldsymbol{\beta}^y\right) + \overline{N}_i \kappa + \overline{\mathbf{x}}_i^y \xi^y + a_i^Y + \varepsilon_{p,i}^y \\ N_{p,i} = g\left(\mathbf{x}_{p,i}^N, \mathbf{w}_i^N; \boldsymbol{\beta}^N\right) + \overline{\mathbf{x}}_i^N \xi^N + a_i^N + \varepsilon_{p,i}^N \end{cases}. \tag{4}$$

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[17] We also include the household-specific mean nitrogen application ($\overline{N}_i$) in the yield equation.

Finally, to account for the fact that a large number of plots did not receive any chemical fertilizers, we follow Shonkwiler and Yen (1999). This implies estimating an augmented version of system (4):

$$\begin{cases} y_{p,i} = f\left(N_{p,i}, \mathbf{x}_{p,i}^y, \mathbf{w}_i^y; \boldsymbol{\beta}^y\right) + \bar{N}_i \kappa + \bar{\mathbf{x}}_i^y \xi^y + a_i^Y + \varepsilon_{p,i}^y \\ N_{p,i} = \Phi\left(\mathbf{z}_{p,i}' \boldsymbol{\alpha}\right)\left[g\left(\mathbf{x}_{p,i}^N, \mathbf{w}_i^N; \boldsymbol{\beta}^N\right) + \bar{\mathbf{x}}_i^N \xi^N\right] + \delta\phi\left(\mathbf{z}_{p,i}' \boldsymbol{\alpha}\right) + a_i^N + \zeta_{p,i}^N \end{cases} \tag{5}$$

where $\Phi(.)$ and $\phi(.)$ are the probability density function and cumulative distribution function of a univariate standard normal, respectively; $\mathbf{z}_{p,i}'$ represents the vector of exogenous variables in a probit model describing the decision whether or not to use chemical fertilizers on plot p; and $\boldsymbol{\alpha}$ is the corresponding vector of unknown parameters (for more details on the procedure, see Shonkwiler and Yen, 1999).[18] We include in $\mathbf{z}$ observable characteristics of the plot (size, whether or not this is a pure maize plot, whether the parcel has been borrowed or rented), household characteristics (gender, age, and literacy of the household's head, soil quality perception, number of livestock units, distance to market, and fertilizer price), and regional dummies. We use as the excluded instrument the household's access to credit (which is measured by a dummy variable taking the value 1 if the household had access to credit over the previous three years, and zero if not) since this has been identified as one of the important factors explaining the low uptake of modern input use in SSA.

The estimation of system (5) involves two steps. First, we estimate the probability that some chemical fertilizer is applied on each plot (a binary indicator) using maximum likelihood.[19] Then we use the estimated parameters to compute $\Phi\left(\mathbf{z}_{p,i}' \hat{\boldsymbol{\alpha}}\right)$ and $\phi\left(\mathbf{z}_{p,i}' \hat{\boldsymbol{\alpha}}\right)$. In the second

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[18] The term $\Phi\left(\mathbf{z}_{p,i}' \boldsymbol{\alpha}\right)\left[g\left(\mathbf{x}_{p,i}^N, \mathbf{w}_i^N; \boldsymbol{\beta}^N\right) + \bar{\mathbf{x}}_i^N \xi\right] + \delta\phi\left(\mathbf{z}_{p,i}' \boldsymbol{\alpha}\right)$ corresponds to the unconditional mean of nitrogen use per hectare.

[19] More precisely we estimate a random-effects probit model and include household-specific mean plot characteristics to control for unobserved household specific effects.

stage, the system in which $\Phi\left(\mathbf{z}'_{p,i}\hat{\boldsymbol{\alpha}}\right)$ and $\phi\left(\mathbf{z}'_{p,i}\hat{\boldsymbol{\alpha}}\right)$ are used in place of $\Phi\left(\mathbf{z}'_{p,i}\boldsymbol{\alpha}\right)$ and $\phi\left(\mathbf{z}'_{p,i}\boldsymbol{\alpha}\right)$ is estimated using three-stage least squares (3SLS). Because of the two-stage estimation, we bootstrap standard errors in the second stage.

For comparison purposes, we estimate the system of equations described in (5) controlling for farmer fixed effects. This implies losing around one-third of the original observations since only households who grew maize on multiple plots can be considered.[20] The fixed-effect approach allows us to account for household-unobserved specific factors such as personal skills and knowledge, history of fertilizer use that may impact nitrogen use as well as maize yield. This system is run as a test of robustness for the 3SLS estimates obtained using the full sample of plots (see Marenya and Barrett, 2009a, for use of a similar approach). Finally, we estimate the yield function (first equation in system (5)) using Ordinary Least Squares (OLS). If the OLS estimates differ significantly from the 3SLS estimates, then this will be evidence of endogeneity of the quantity of nitrogen used.

6. Estimation results

Maximum-likelihood estimation results of the first-stage probit model show that access to credit, market conditions (the price of fertilizers) and distance to market are important drivers of the decision to use fertilizers on a plot.[21] Access to credit, which is used as an excluded instrument, is highly significant and was found to increase the probability to use fertilizers.[22] Lower fertilizer prices and a shorter distance to the market (less than one hour walking time) encourage fertilizers adoption. Fertilizers were also more likely to be used on larger plots and

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[20] We do not consider here the possible selection issue of farmers holding multiple plots.

[21] Estimation results of the first-stage probit model are not shown here but are available on request.

[22] Access to credit is assumed to influence only the decision to use fertilizers but not the quantity of fertilizers used. The correlation between access to credit and per hectare nitrogen use is indeed low (less than 0.1).

on pure maize plots. Households' characteristics do matter in the adoption of chemical fertilizers: we find that young and literate male heads were more likely to apply nitrogen on their maize plots.[23] Finally, regional dummies are significant, which may reflect differences in the availability of subsidized fertilizers across regions.

Estimation results for the maize yield equation are shown in Table 3. We report estimates obtained using 3SLS on the full sample of plots (7,845 observations), 3SLS with farmer fixed effects (3SLS-FE) on a sub-sample of plots (5,499 observations), and OLS (7,845 observations). We first comment on our preferred model, which is the system of equations estimated on the full sample using 3SLS.

Our findings confirm that yield is a non-linear (concave) function of nitrogen application and that the marginal productivity of nitrogen is lower on plots of lower quality (as measured by farmer's perception) as well as on plots which were planted with maize the year before. We discuss the maize response rate to nitrogen application in greater detail in the next section.

Cultivation practices have a direct impact on yield: in our sample, growing pure maize plots and growing maize on a plot which was planted with maize the year before are found to increase yield on average by 80 kg/ha and 114 kg/ha, respectively. Maize yield on a borrowed or rented parcel is significantly lower, by 133 kg/ha on average, possibly because such parcels are of lower quality or because plot managers put less effort on these plots compared to the plots that they own. As expected, catastrophic climatic events such as floods and droughts have a significant impact on yield, leading to an average loss of about 435 kg/ha.

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[23] We only consider the characteristics (gender, age, and literacy) of the household head and not those of the plot manager for two main reasons: 96% of the household heads and 93% of the plot managers are male in our sample and there is a high collinearity between characteristics of household heads and plot managers. Also, using characteristics of plot managers instead of those of household heads did not improve the overall model quality and entailed a loss of about 10% of the observations because information was missing for a number of plot managers.

Yield is found to be significantly larger (+100kg/ha) on larger plots. This result contradicts a number of previous studies which found evidence of an inverse relationship between size and productivity (for a review of earlier studies, see Holden and Fisher, 2013). The total number of livestock units has a positive effect on yield, which may reflect the household's use of manure as a substitute or complement to chemical fertilizers. Yield is also significantly higher on plots belonging to households who own small agricultural machinery; the marginal effect is estimated at 48 kg/ha.

The household head's socio-demographics (gender, age, literacy level) are not found to be significant in this model.[24] The variable measuring the household head's perception of land quality has the expected negative sign but is not significant, which may reflect an imperfect assessment of soil quality by the survey respondents. Finally, regional dummies reflect differences in yields across regions, with the highest average yields recorded in Hauts Bassins, Est, and Cascades (reference region: Sud Ouest), and the lowest yield recorded in Sahel.

The estimated coefficient of the main variable of interest, nitrogen per hectare, is significantly higher when endogeneity of nitrogen use is taken into account. In the two models featuring a system of equations (3SLS and 3SLS-FE), the estimated (direct) effect of nitrogen on maize yield is estimated at around 23 kg/ha, while the estimated effect is 7 kg/ha when the maize yield equation is estimated by OLS. This is an indication that nitrogen use may be endogenous in the yield equation and that not controlling for its endogeneity may lead to biased estimates of the maize yield response to nitrogen. Even if the 3SLS and 3SLS-FE

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[24] Plot manager characteristics, when used instead of household head characteristics, were not found significant. This finding should not be interpreted as evidence for similar yields on men and women's plots because of very few plots managed by women in our sample. An earlier study in Burkina Faso found higher yields on men's plots than on similar women's plots simultaneously planted with the same crop within the same household (Udry et al., 1995).

estimates are not directly comparable because they were obtained using different samples, they are found to be statistically equal in most cases, which increases the confidence in our preferred model (3SLS). Estimates of maize yield responses obtained using the three models are discussed in the next section. Under- and over-identification tests were performed in a two-stage least squares setting and confirmed the validity of the instruments for the quantity of fertilizers used: the price of fertilizers and the distance to the market.[25] The Cragg-Donald Wald F Statistic (101.51) also confirmed that our instruments passed the weak identification test.

Estimation results for the second equation of the system (featuring per hectare nitrogen use as the dependent variable) are shown in the Appendix (Table A1). We only report the 3SLS estimates obtained on the full sample of plots since the 3SLS-FE estimates are not statistically different for most variables. The quantity of nitrogen applied on a plot is found to be lower on larger plots and on plots that were planted with maize the year before. Plots that belonged to households which perceived their land as low quality received less nitrogen on average (almost significant at the 10% level). This may be explained by the cost of nitrogen outweighing the expected benefit from nitrogen application. As discussed above, the marginal productivity of nitrogen is significantly lower on low quality soils and using nitrogen on these soils may simply not be profitable (see Marenya and Barrett, 2009a, for related discussions on data from Kenya). Male heads were also found to apply more nitrogen than female heads.

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[25] The null hypothesis of the under-identification test is that the instruments are not valid in the sense that they are not correlated with the endogenous regressor. The null hypothesis of the over-identification test is that the instruments are valid, i.e., uncorrelated with the error term and correctly excluded from the estimated equation. We reject the null of under-identification (p-value = 0.000) and do not reject the null of over-identification (p-value = 0.30).

Table 3. Maize yield equation (3SLS, 3SLS-FE, and OLS estimates)

Maize yield (kg/ha)	3SLS Coef.[a]	Std.Err.[b]	3SLS-FE Coef.[a]	Std.Err.[b]	OLS Coef.[a]	Std.Err.
Constant	649.380***	84.352	-	-	706.237***	59.620
Plot characteristics						
Nitrogen application (kg/ha)	23.237***	5.131	22.855**	10.025	7.380***	1.087
Plot size (ha)	99.767***	13.397	129.538***	20.832	96.682***	15.394
Plot located in the plains	27.506	33.021	12.169	35.738	45.530	46.891
Pure maize crop	80.176***	28.926	84.848***	32.011	105.255***	38.126
Maize grown year before	113.792***	33.132	80.993**	31.583	44.123	30.849
Hired labor	68.012**	28.843	82.384***	27.751	80.640**	39.093
Borrowed or rented parcel	-133.191**	62.292	-130.592**	65.501	-160.221**	70.084
Drought or flood	-435.088***	34.467	-396.816***	41.082	-431.165***	54.811
Household characteristics						
Total livestock units	1.603*	0.845	-	-	1.450***	0.472
Household has a plough	33.125	20.954	-	-	41.327**	16.934
Household owns small machinery	48.187*	24.899	-	-	61.897***	17.804
Household head is a male	-49.410	57.834	-	-	-46.315	39.059
Age of household head	-0.285	0.676	-	-	-0.453	0.514
Household head is illiterate	26.229	23.451	-	-	15.099	16.849
Low soil quality (perception)	-16.881	22.138	-	-	-36.238**	17.942
Regional dummies						
Boucle du Mouhoun	110.330**	44.313	-	-	149.173***	32.838
Cascades	470.274***	66.977	-	-	497.412***	38.981
Centre	18.029	109.168	-	-	15.879	55.104
Centre Est	419.547***	41.538	-	-	425.685***	31.819
Centre Nord	204.941***	45.080	-	-	207.399***	38.450
Centre Ouest	200.745***	46.544	-	-	240.270***	35.515
Centre Sud	194.060***	44.194	-	-	202.908***	35.410
Est	474.677***	41.420	-	-	471.921***	30.972
Hauts Bassins	543.703***	50.066	-	-	605.461***	34.193
Nord	42.473	47.904	-	-	56.725	46.198
Plateau Central	72.039	47.581	-	-	66.414*	36.736
Sahel	-22.988	53.231	-	-	-16.809	77.011
Sud Ouest	-	-	-	-	-	-
Interactions						
Nitrogen x Nitrogen	-0.110***	0.021	-0.036**	0.015	-0.050***	0.007
Nitro. x Low quality soil	-3.436***	1.226	-	-	-1.483*	0.803
Nitro. x Maize year before	-2.814**	1.118	-0.221	1.012	-0.437	0.668
Mean plot characteristics						
(Mean) Nitrogen application	-4.684**	2.138	-	-	1.583*	0.772
(Mean) Plot size	-43.844**	20.852	-	-	-19.604	19.535
(Mean) Plot located in plains	6.531	49.946	-	-	-11.062	54.962
(Mean) Pure maize crop	139.708***	41.038	-	-	139.261***	44.802
(Mean) Maize year before	-20.160	37.736	-	-	-17.798	36.443
(Mean) Hired labor	53.736	40.814	-	-	46.984	44.487

(Mean) Borrowed or rented plot	213.813***	73.741	-	-	252.785***	74.116
(Mean) Drought or flood	-93.798**	45.505	-	-	-108.037*	61.847
Number of observations	7,845		5,499		7,845	

Note: [a] *, **, *** indicates significance at the 10, 5, and 1% levels, respectively. [b] Bootstrapped standard errors (1,000 replications). The bootstrapped standard errors have been clustered by household to account for within-household correlation of errors across plots.

The yield equation includes variables (apart from nitrogen application) that are choice variables for the farmer and may hence be endogenous. These include a dummy variable describing whether some external laborers had been hired to work on the plot, plot status (i.e., whether the plot is borrowed or rented), and plot size. Because of the difficulty to find appropriate instruments, we tested the robustness of the 3SLS estimates by re-estimating the system of equations after excluding each of these variables, one after the other. The results are qualitatively the same and the estimated maize yield response is not statistically different from the 3SLS coefficient reported in Table 3 (23.2).[26] Finally, about 8% of the plots were planted with improved maize seeds. This variable was not used since it was not found significant in any of the models. As a robustness check, we re-estimated the system of equations on the sub-sample of plots that were not planted with improved seeds (7,206 observations). Results are similar to those shown in Table 3 (the coefficient of the nitrogen application rate is estimated at 20.9).

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[26] The estimated coefficient for nitrogen application rate in the yield equation is 24.3 when the variable measuring hired labor is removed, 23.9 when plot status is removed, and 29.0 when plot size is excluded.

7. Marginal return and the profitability of fertilizers

Table 4 shows the maize yield response to nitrogen application calculated from the estimated coefficients of the three models (3SLS, 3SLS-FE, and OLS) at the mean of the sample, along with 95% confidence intervals (calculated using the bootstrapped standard errors in the case of the 3SLS and 3SLS-FE models).

Table 4. Estimated maize yield response (kg/ha) at the sample mean

Model	Mean	95% CI Lower bound	95% CI Upper bound
System of equations – 3SLS	19.0	10.8	27.3
System of equations – 3SLS-FE	22.3	3.1	41.5
Single yield equation – OLS	6.1	4.2	8.0

The maize yield response is estimated at 19 kg/ha in our preferred model (3SLS), varying between 11 and 27 kg/ha with a 95% level of confidence. This is in the range of previous estimates reported in the literature for other countries in SSA (Jayne and Rashid, 2013). The estimated yield response obtained using the OLS model is significantly biased downwards due to the lack of control for endogeneity of nitrogen use. The maize yield response calculated from the 3SLS-FE model is 22 kg/ha, closer to the 3SLS estimate, but less precise due to the lower number of observations.

The impact of soil conditions on (marginal) maize yield response to nitrogen application is illustrated in Table 5. Using the 3SLS estimates, we derive the quantity of nitrogen that maximizes maize yield for different soil conditions, in particular soil quality and the type of crop grown the year before. Maize yield response is calculated based on the average use of nitrogen under different soil conditions. The quantity of nitrogen that maximizes maize yield is estimated at 78 kg/ha and the maize yield response at 14.2 kg/ha when the soil is of low quality and maize was grown on the plot the year before. With a high quality soil and when

the plot was not planted with maize the previous year, the nitrogen application that maximizes

maize yield is estimated at 106 kg/ha and maize yield response is 19.4 kg/ha.

Table 5. Nitrogen application that maximizes maize yield under different soil conditions (95% confidence interval is shown in brackets)

Low quality soil	Maize grown year before	Optimal N application (kg/ha)	Maize yield response (kg/ha)
yes	yes	78 [65;90]	14.2 [7.6;20.9]
yes	no	90 [74;107]	16.2 [8.5;24.0]
no	yes	93 [84;103]	16.9 [9.5;24.2]
no	no	106 [92;120]	19.4 [10.7;28.1]

We next assess the profitability of fertilizer use on the plots that received nitrogen (2,746

observations), by comparing the expected increase in revenue induced by the use of an extra

kilogram of nitrogen with its cost (Table 6). In order to lower the risk of measurement error

and possible endogeneity of household-specific prices, we use median prices in each of the 13

regions, for both maize and nitrogen. Nitrogen prices[27] were derived from the reported

quantity and value of fertilizer purchased by farmers. As sources of fertilizer include public

sources, non-governmental organizations and farmers' organizations, these reported fertilizer

prices may not fully reflect the market price of fertilizer. The average price of nitrogen was

1,355 CFA franc/kg (approximately 3 USD/kg) in our sample, with variations across regions

(from 1,255 CFA franc/kg in Boucle du Mouhoun to 1,888 CFA franc/kg in Centre Nord and

3,494 CFA franc/kg in Sahel). These values seem realistic in comparison to prices reported in

a recent World Bank report (Siri, 2013): without any subsidies, the price of nitrogen in

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[27] The price of 1 kg of nitrogen in urea is the price per tonne of urea divided by 460 as urea contains 46% nitrogen. The price of 1 kg of nitrogen in NPK is the price per tonne of NPK divided by 140 as the NPK fertilizers used in the study area contain 14% nitrogen.

Burkina Faso was estimated at 1,961 CFA franc/kg while the subsidized price was estimated at 1,156 CFA franc/kg. Except for the case of Sahel, the regional median prices observed on our sample are all within this range. The average selling price of maize, as reported by the farmers, was 109 CFA franc/kg (approximately 235 USD per ton), varying from 92 CFA franc/kg in the Cascades region to 134 CFA franc/kg in Centre Sud. While slightly lower, these prices are in line with the producer prices in the main markets reported by the National Office for Food Security Stock for the 2008/2009 production season (see Pale, 2010). Differences in prices between regions reflect in part the differences in maize production areas with the main maize growing regions having relatively lower maize selling prices. Moreover, trade between surplus areas and neighboring deficit areas may also explain these price differences.

Using the estimated marginal yield response, we calculate the marginal value cost ratio (MVCR) of applying nitrogen for each plot which received some fertilizers. In our sample, the average MVCR is 1.41 with significant variation across regions: it varies from 0.57 in Sahel to 1.99 in Centre Est. Fertilizers are found to be profitable on 90% of the plots if a threshold of 1 is used (which is in line with the behavior observed on our data since those plots actually received fertilizers). But a threshold of 1 does not take account of any transaction costs (including transportation costs), labor constraints, and risk premium if farmers are risk averse (adoption of fertilizers may increase financial risk and new adopters face uncertainty regarding the best use of the technology).[28] If we instead consider a threshold of 1.5 and 2 as is common in the literature (Jayne and Rashid, 2013; Sheahan et al., 2013), then fertilizers are found to be profitable on 36% and on 5% of the plots, respectively. Hence, if our model provides an adequate representation of farmers' behavior, then our results would

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[28] Wanzala-Mlobela et al. (2013) estimate that most farmers have to travel at least 30 km to buy fertilizers, which would translate into an extra 50 CFA franc per kg of nitrogen. This estimate is, of course, very rough since the distance to fertilizer suppliers may vary significantly across regions.

suggest that the threshold for those plots which received fertilizers was probably close to 1 (which may correspond to farmers who have low transactions costs and/or low risk aversion).

Table 6. Price of maize, nitrogen, and MVCR, by region

Region	Maize price CFA/kg	N price CFA/kg	MVCR	% plots MVCR≥1	% plots MVCR≥1.5	% plots MVCR≥2
Boucle du Mouhoun	93	1,255	1.29	90	19	0
Cascades	92	1,277	1.27	92	11	0
Centre	133	1,880	1.16	86	0	0
Centre Est	167	1,405	1.99	96	85	58
Centre Nord	102	1,888	0.97	57	0	0
Centre Ouest	117	1,335	1.49	92	55	0
Centre Sud	134	1,703	1.35	90	34	0
Est	115	1,355	1.52	94	62	0
Hauts Bassins	98	1,256	1.37	91	35	0
Nord	102	1,766	1.03	61	0	0
Plateau Central	117	1,504	1.35	92	29	0
Sahel	102	3,494	0.57	0	0	0
Sud Ouest	111	1,256	1.56	96	61	4
Overall (2,746 plots)	109	1,355	1.41	90	36	5

We now turn our attention to the plots on which fertilizers were not applied (5,099 observations). For each of these plots, we calculate a hypothetical MVCR under the assumption that the plot received a quantity of nitrogen which was equal to the average nitrogen application in the region. We assume that maize could be sold at the median regional price. For the price of nitrogen, we consider a range of prices varying from 2,000 CFA franc/kg (which corresponds roughly to the national unsubsidized price) to 1,000 CFA franc/kg (roughly the national subsidized price) and calculate, for each of these prices, the percentage of plots for which the MVCR is greater than 1, 1.5, and 2. Our findings are shown in Figure 3. The horizontal axis is the level of the subsidy that varies from 0 CFA franc/kg (unsubsidized price) to 1,000 CFA franc/kg. The vertical axis measures the percentage of plots on which fertilizers are found to be profitable depending on the chosen threshold. Without subsidization and with a threshold set at 1, fertilizers are found to be profitable on

43% of the plots. With a subsidy set at 1,000 CFA franc/kg, then fertilizers are profitable on all plots. If a threshold of 1.5 is considered instead, then a subsidy of 700 CFA franc/kg is necessary for fertilizers to be profitable on 50% of the plots but fertilizers would become profitable on 96% of the plots with a subsidy set at 1,000 CFA franc/kg. Finally, with a threshold set at 2, 43% of the plots would be profitable if the subsidy were set at 1,000 CFA franc/kg.
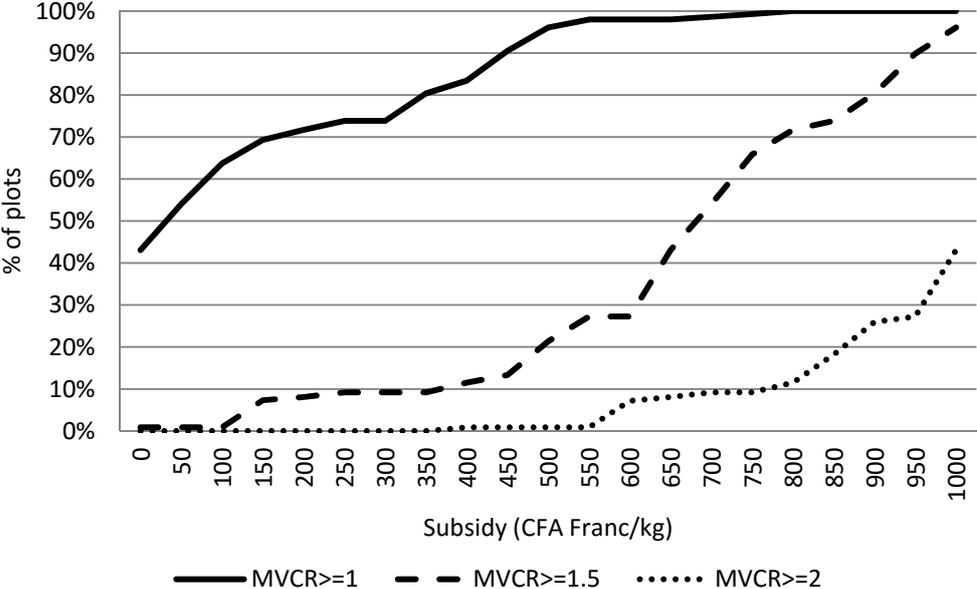

Figure 3. Percentage of plots for which MVCR is equal to or greater than 1, 1.5 and 2, as a function of the level of the subsidy (CFA franc/kg); reference (unsubsidized) price of N is 2,000 CFA franc/kg

We thus find that fertilizers should have been profitable for a number of plots which did not receive any fertilizers, under the current level of prices, even when the MVCR threshold is set at 1.5. This suggests that profitability (or lack of profitability) was not the main reason for farmers' low adoption of chemical fertilizers. There is anecdotal evidence that some farmers

were willing to use fertilizers but faced difficulties in accessing subsidized inputs (Wanzala-Mlobela et al., 2013): first, the demand from farmers was estimated at the district level and these estimates may be arbitrary and far from farmers' actual needs; second, the allocation of subsidized fertilizers across provinces might have been influenced by political and budgetary considerations; third, the amount of fertilizers allocated to each farmer might have differed from their actual demand if they were unable to present proof of their needs (based on evidence of crops planted and cultivated areas).

These figures still have to be interpreted with caution since calculations have been made in a partial equilibrium framework. That is, we ignored the possible response of fertilizer prices to an increase in fertilizer uptake. If fertilizer prices increase following an increase in fertilizers demand then part of the subsidy may become ineffective.

8. Conclusion

In this article, we estimate the profitability of fertilizers for maize farmers in Burkina Faso, where a fertilizer subsidy program was launched in 2008 to foster fertilizer use and cereal production. Using data from 7,845 plots, we estimate the maize yield response to be around 19 kg/ha, in the range of previous estimates reported in the literature for other countries in SSA (Jayne and Rashid, 2013). Yield response to nitrogen is found to depend on soil characteristics, confirming earlier results by Marenya and Barrett (2009a) for Kenya. In particular, the maize yield response is found to be lower on lower quality soils and when maize was grown on the plot the year before. The average MVCR is estimated at 1.4 for the plots which received some fertilizers and the MVCR is found to be greater than 1 for 90% of these plots. There is, however, significant variation across regions, with MVCR varying from 0.57 in Sahel to 1.99 in Centre Est. This is mainly explained by regional differences in maize

and fertilizer prices, with some anecdotal evidence that differences in fertilizer prices were driven partly by unequal opportunities for farmers to access subsidized fertilizers.

Calculations made on plots which did not receive any fertilizers show that fertilizers should have been profitable on a number of plots at the current (2008) level of maize and fertilizer prices, even if an MVCR threshold greater than 1 is considered. This suggests that lack of, or low, profitability might not have been the main factor driving low uptake of fertilizers among maize growers in Burkina Faso. This result questions the efficiency of untargeted subsidies and point towards complementary or alternative policies to fertilizer subsidies. Access to credit was found to be among the most important factors explaining the adoption of chemical fertilizers, which confirms earlier findings that increasing the availability of credit is a prerequisite for increasing adoption of fertilizers among farmers in SSA (e.g., Croppenstedt et al., 2003; Moser and Barrett, 2006; Lambrecht et al., 2014). An inadequate supply of subsidized fertilizers was also reported and it appears essential for the government of Burkina Faso to put in place measures that guarantee farmers' actual needs for fertilizers are fulfilled. Policies that encourage adoption of soil conservation practices may also be beneficial and indirectly increase the uptake of fertilizers, since profitability is higher on soils of better quality. Furthermore, as shown in other contexts (e.g. Malawi) the question of alternative policies is especially relevant given the high costs of subsidy programs and the fiscal pressure putted on agricultural/national budgets (Druilhe and Barreiro-Hurlé, 2012; Wanzala-Mlobela et al., 2013).

The data used for this study were cross-sectional, which makes it more difficult to control for plot- and household-specific unobserved characteristics. However, our estimates were found to be robust when compared to estimates obtained using a fixed-effects model. Our results also show that not taking into account the endogeneity of nitrogen use in the yield equation may produce biased estimates of the maize yield response to nitrogen. One caveat of our

model is that it disregards uncertainty and assumes farmers' preferences are risk-neutral. Allowing for non-neutral risk preferences and being able to quantify the risk premium induced by the adoption of chemical fertilizers would bring additional insights into this subject. We hope to undertake research on these aspects in the near future.

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Appendix

Table A1. Nitrogen application equation – 3SLS estimation results (7,845 plots)

Nitrogen application equation	Coef.[a]	Std. Err.[b]	P>z
Constant	25.939***	3.267	0.000
Plot characteristics			
Plot size (ha)	-1.598***	0.526	0.002
Plot located in the plains (0/1)	4.706	3.473	0.175
Pure maize plot (0/1)	5.234	3.485	0.133
Maize grown year before (0/1)	-6.611***	2.079	0.001
Borrowed or rented plot (0/1)	-1.669	5.798	0.773
Drought or flood (0/1)	-1.515	5.443	0.781
Household characteristics			
Total livestock units	0.004	0.028	0.876
Fertilizer price (CFA franc/kg)	-0.012	0.022	0.595
Less than one hour to market (0/1)	3.321	2.180	0.128
Household head is a male (0/1)	8.772**	4.449	0.049
Age of the household head	-0.021	0.059	0.721
Household head is illiterate (0/1)	-0.281	1.622	0.862
Low soil quality (perception) (0/1)	-2.821	1.779	0.113
Regional dummies			
Boucle du Mouhoun	10.088	9.610	0.294
Cascades	2.966	9.716	0.760
Centre	-6.629	18.054	0.714
Centre Est	-0.989	11.017	0.928
Centre Nord	3.890	27.811	0.889
Centre Ouest	17.628	10.256	0.086
Centre Sud	11.948	12.642	0.345
Est	-2.199	10.881	0.840
Hauts Bassins	9.954	9.776	0.309
Nord	-17.700	12.016	0.141
Plateau Central	5.166	36.328	0.887
Sahel	289.020	1217.615	0.812
Sud Ouest	-0.773	10.545	0.942
Mean plot characteristics			
(Mean) Plot size	1.838**	0.857	0.032
(Mean) Plot located in the plains	-4.165	4.454	0.350
(Mean) Pure maize plot	8.741**	4.344	0.044
(Mean) Maize grown year before	-1.988	2.780	0.475
(Mean) Borrowed or rented plot	5.497	6.173	0.373
(Mean) Drought or flood	-7.980	7.111	0.262

Note: [a] *, **, *** indicates significance at the 10, 5, and 1% level, respectively. [b] Bootstrapped standard errors (1,000 replications). The bootstrapped standard errors have been clustered by household to account for within-household correlation of errors across plots.