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Maize Yield Response to Fertilizer under Differing Agro-Ecological Conditions in Burkina Faso

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Introduction

Achieving food security in Sub-Saharan Africa depends crucially on raising the productivity of smallholder farmers—the cornerstone of most agricultural economies in that region (Hazell et al. 2007; Byerlee et al. 2009; Diao et al. 2012). Designing suitable policies to boost productivity while protecting natural resources depends on proper understanding of farmers' incentives to use intensification strategies, including fertilizer dosages. Underlying agro-ecological conditions shape the response of crop yield to fertilizer, which in turn affect economic incentives to use this relatively costly input. Yet, most of the agricultural policies to promote fertilizer use and increase productivity growth in Sub-Saharan Africa, such as input subsidy programs, are implemented at the national scale with "blanket" recommendations, ignoring the heterogeneity of rainfall and soil fertility across agro-ecologies (Kaizzi, Mohammed and Nouri 2017).

Poor drainage and limited availability of moisture constrain many of the soils in Sub-Saharan, along with spatial and temporal concentration of rainfall (Heisey and Mwangi 1997; Yanggen et al. 1998). The soils in the Sahel and Savanna of West Africa are old, deep and poor in soil organic matter, with low capacity to retain nutrients, while this region is also the most densely populated in the continent (Jones et al. 2013). The climatic vulnerability of West Africa , aggravated by high rates of population growth, has prompted major efforts by governments and farmers themselves to intensify production sustainably (Aune and Bationo 2008; Botoni and Reij, 2009; Reij, Tappan and Smale 2009; Pretty, Toulmin, and Williams 2011).

During the 1980s, in Burkina Faso, geographer Marchal (1985) described the decreasing productivity of cultivated land, the destruction of vegetation, and the expansion of cultivated land across soils that were marginal for agriculture. Recent analysis of satellite imagery confirms that between 2000 and 2013, the progression and agriculture has accelerated. Wooded savanna in the Sudanian zone of the country has been replaced entirely by rainfed crops, with natural landscapes throughout ceding to a mosaic of crops and fallows (CILSS 2017). To enhance crop productivity in Burkina Faso, there is no option other than intensification.

In Burkina Faso, as elsewhere in Sub-Saharan Africa, national agricultural research systems formulated fertilizer recommendations during the 1970s and 1980s, differing by rainfall regime but not other aspects of growing conditions (Ouattara et al. 2017). For some time, scientists working in Sub-Saharan Africa have recommended variable, as compared to uniform, fertilizer recommendations (e.g., Benson 1997). Although fertilizer is more widely available today than in the past, effective demand for inputs is often "sketchy" since it depends closely on farmer access to input and product markets (Sanginga et al. 2009). Titonnell et al. (2016) have argued for a new approach to precision farming in this region. Vanlauwe et al. (2010) and Kihara et al. (2016) explain that the heterogeneity of overall agro-ecological and soil conditions at regional, national, and local scales has led to diversity of farming systems, cropping patterns, soil management considerations, and input markets. This diversity leads to highly variable economic incentives for smallholder farmers.

These observations drive our central hypotheses that the response of maize yield to fertilizer, and more importantly, the profitability of fertilizer use on maize in Burkina Faso, vary by agro-ecological factors. We test these hypotheses by estimating a maize yield response function at the plot level with data collected during three cropping seasons (2009/10, 2010/11 and 2011/12) under the Continuous Farm Household Survey (*Enquête Permanente Agricole* (EPA). We test and control for endogeneity of fertilizer with a Control Function Approach

(CFA), employing Correlated Random Effects (CRE) to address time-invariant unobserved effects that may be related to household decision-making. We compare the robustness of the estimated marginal product of fertilizer while testing the effects of different sets of agro-ecological factors across econometric models. Agro-ecological conditions are indicated by a range of covariates, including climatic zone, soil quality, and plot characteristics such as presence of trees, fallow, soil and water conservation structures, location and slope. We then examine the profitability of fertilizer use by calculating the marginal and average value-cost ratios based on the estimated coefficients.

We focus on maize for two reasons. First, the EPA data demonstrate that fertilizer use on maize is highest among dryland cereals grown in Burkina Faso. In 2011/12, the latest season for which data were available, over two-thirds of maize area during this time period benefited from at least some inorganic fertilizer. Comparable rates were only 16% of the national millet area and 13% for sorghum. Second, maize is known to be more responsive to fertilizer than these other cereals (Yanggen et al. 1998; Wortmann and Sones 2017). Both of these considerations are needed for variability in production response to nitrogen nutrients.

Our analysis contributes to a sparse regional literature on maize yield response to fertilizer that is estimated with data collected from farm households. In recent years, most similar analysis have been conducted in Eastern and Southern African countries (e.g. Marenya and Barrett 2009; Xu et al. 2009; Sheahan, Black, and Jayne 2013). Farming context and agro-ecological conditions are vastly different in the West African Sahel compared to these other regions. Studies by Koussoube and Nauges (2017) and Foltz, Aldama, and Laris (2012) on the effect of fertilizer use on maize yield in Burkina Faso and Mali represent exceptions, but neither of these controlled for variations over both time and space. Earlier research by Henao et al.

(1992), Kouka et al. (1994) and others analyzed agronomic optima using trial data from northern Ghana and Mali. A recent compendium summarizes agronomic research on fertilizer optimization across the continent, including Burkina Faso (Wortmann and Sones 2017).

Section 2 highlights pertinent features of the farming context in Burkina Faso. Methodology is summarized in Section 3, referring to recent, comparable studies. Findings are presented and discussed in Section 4. Section 5 concludes and draws policy recommendations.

Farming Context in Burkina Faso

Burkina Faso is an agrarian country, with 80% of its population depending on agriculture as source of livelihood and agriculture accounting for 35% of its gross domestic products (Kabore et al. 2013; World Data Bank 2014). Domestic production is dominated by non-irrigated cereal crops, which represent over 70% of total cultivated area (RCA 2012). Principal cereal crops include sorghum, pearl millet and maize, which are cultivated for both home consumption and domestic markets. Cereals play a vital role in the Burkinabe diet, especially for the poor, accounting for 60% of calorie intake (DGPER 2012).

The Burkinabe land cover has changed drastically over the last decades. In 1975, about 15% of the land was under cultivation, compared to 39% in 2013 (Tappan, 2014). In acreage terms, this represents a 159% change in less than 40 years. Maize is among the crops that has seen the most significant increases in cultivated areas. From 1970-1974 to 2009-2013, cultivated areas of maize increased by more than 700% (~ 95,000 ha to 775,000 ha). Although maize yields have increased over the last decades, they still remain low with an average of 1.6 tons per hectare (FAO, 2014). Most of the increase in maize production has come from an expansion in arable land rather than through cropping intensity. Indeed, commercial fertilizer markets remain weak and overall use rates on dryland cereal crops, including maize, are but a fraction of the 50 kg/ha goal stated in the Abuja Declaration.

The use of inorganic fertilizers to increase productivity is the most commonly promoted practice in Sub-Saharan Africa, despite efforts to encourage the use of complementary practices designed to better manage soils and water or amend soils. An abundant literature exists on the positive impact of inorganic fertilizers on crop outputs, but where analyzed in depth for maize in Eastern and Southern Africa, much of this has come at the expense of state-managed subsidy schemes of questionable social return (see volume edited by Jayne and Rashid 2013; Liverpool-Tassie 2014). In many African countries, a large share of the agricultural budget has been allocated to subsidies on inorganic fertilizers as a way to boost production. This is also the case in Burkina Faso, where the government has implemented a program to facilitate access to fertilizer. Especially, the program provides financial support to the local cotton companies to purchase and distribute fertilizer on credit to cotton farmer cooperatives and subsidizes fertilizer for staple crops, such as maize and irrigated rice. Subsidized bags of 50kg of NPK and urea, available only for those three crops, are approximately a quarter cheaper than those purchased at full market value (Holtzman et al., 2011; IFDC, 2013) because of high transaction costs.

Officially, agro-ecological zones in Burkina Faso are constructed solely on the basis of rainfall isohyet (FAO 2001). There are three agro-ecological zones in Burkina Faso: 1) Sahelian; 2) Sudano-Sahelian; and 3) Sudanian (Bainville 2015; De Longueville et al. 2016). The Sahelian zone is characterized by low and erratic rainfall, averaging less than 600 mm annually. Millet and sorghum are the principal subsistence crops. Needing a minimum of 600mm of rainfall per year, maize is not a crop well-adapted to the Sahelian zone (CIRAD/GRET 2012). In the Sudano-Sahelian zone, average annual rainfall oscillates between 600 mm and 900 mm. With the additional rainfall, the Sudano-Sahelian zone is known for its production of maize and groundnut production as well as millet and sorghum. Precipitation is highest in the Sudanian zone, with an average of 900 mm to 1 200 per year. The Sudanian zone is the most suitable for agriculture. Perennial cultivation, cotton and cereal fields, including mil, sorghum, and maize, are all part of its landscape. Across the entire country, the rainy season lasts from three to six months, with the longest season in the Sudanian zone, and the shortest one in the Sahelian zone.

Ten different types of soils cover Burkina Faso. Yet, about 2/3 of the country is covered by soils that are iron-rich and low in organic matter content. Extensive areas of Plinthosols (i.e., iron-rich), occur in all zones (EU 1998; Jones et al. 2013; FAO 2014). Plinthosols are naturally poor in fertility and hardening occurs upon repeated dry and wet conditions (i.e., rainfall seasonality). The adoption of soil and water conservation practices is strongly encouraged to reduce erosion and ease farming activities on those soils. As rainfall increases, clay-rich soils, such as Lixisols, develop in the south part of the country (EU 1998). Deep sandy soils (i.e., Arenosols), which have low water and nutrient retention capacity, are mostly found in the Sahelian zone (FAO 2014).

Methodology

We first estimate a response function to measure the marginal effect of N nutrient kg/ha on maize yield while controlling for other covariate, also testing the hypothesis that the response depends on agro-ecological conditions at the scale of plot, village soil type and climatic zone. We then utilize the estimated coefficients to calculate the profitability of fertilizer use on maize in Burkina Faso across agro-ecologies.

Econometric strategy

Past literature on crop yield response to fertilizer, much of which involved agronomic analysis of trial data, demonstrates concern for choice of functional form (e.g., Cerrato and Blackmer 1990; Kouka 1994; Chambers and Lichtenberg 1996; Guan et al. 2006). Compared to the simplistic and popular Cobb-Douglas form, more flexible, polynomial approaches (e.g., Christensen et al. 1971) recognized the codependence of inputs in determining yield response (see discussions in Xu et al. 2009; Burke et al. 2017). Models with numerous interaction terms can generate important insights in a researcher-managed, experimental environment with controlled inputs. In the uncontrolled environment of household farm production, where many additional covariates must be considered, flexible forms such as the full quadratic or translog become computationally infeasible. Most recent analyses of maize yield response to fertilizer in Sub-Saharan Africa apply variations on quadratic models (Marenya and Barrett 2009; Xu et al. 2009; Sheahan et al. 2014; Burke et al. 2017). Our functional form most closely resembles that of Sheahan et al. (2014) and Burke et al. (2017), who include the quadratic term for nitrogen and interaction terms for main hypotheses of interest. In addition to a quadratic term for nitrogen, we specify interactions of nitrogen use with agro-ecological factors (i.e., zone, soils).

We start with the premise that yield (Y) on maize plot i from household j in time t is function of:

$$Yield_{ijt} = \alpha N_{ijt} + \beta X_{ijt} + U_{ijt}, \qquad i=1,\ldots.n, \quad j=1,\ldots..N, \text{ and } t=1\ldots..T \tag{1}$$

Where N_{ijt} is the nitrogen application rate and X_{ijt} represents a vector of other covariates. The error term U_{ijt} is composed of three parts: V_{ijt}, E_{ijt}, C_{ij}. Where E_{ijt} are random errors, V_{ijt} are unobserved characteristics that are correlated with nitrogen application, and C_{ij} are unobservable time-invariant characteristics.

There are plausible reasons to expect fertilizer application to be correlated with unobserved characteristics, such as plot manager's skills and agronomic conditions. To control for unobserved managerial skills, plot manager characteristics are included as proxies. Although we control for soil types, agro-ecological zones, and rainfall averages and variability at the village level, there are certainly some variations within a village, as Burke et al. (2017) highlighted. Not taking into account the presence of unobserved characteristics would lead to biased estimates and misleading reporting of the effect of nitrogen application on maize yields. For instance, plots with lower soil fertility may be more responsive to fertilizer (Sheahan et al. 2014) and, therefore, the omission of soil quality indicators would suggest stronger effect of nitrogen on maize yields than it is.

Unlike Sheahan et al. (2014), we also test and control for potential endogeneity by employing an instrumental variable technique. To be valid, the instrument must be sufficiently correlated with fertilizer application (inclusion restriction) and uncorrelated with the error term (exclusion restriction). After testing several of the instruments used in previous research on the topic, our strongest is the proportion of households in the commune that belong to cotton cooperatives[1]. Since commercial fertilizer markets are still underdeveloped in Burkina Faso, cotton cooperatives remain the primary source to access fertilizer (Theriault and Tschirley 2014), but membership is not uncorrelated with soil characteristics. In Burkina Faso, cotton is cultivated in rotation with dryland cereals, such as maize. Some fertilizer provided on credit by the local

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[1] Note that the instrument excludes the village where the household lives.

cotton companies is diverted from cotton to maize fields. In an effort to reduce fertilizer diversion, which is detrimental to cotton productivity, local cotton companies have recently provided fertilizer on credit for both cotton and maize crops (Theriault and Serra 2014).

Since we are interested in understanding how agro-ecological conditions affect fertilizer use and profitability, we specify and test a regression that includes interactions between nitrogen application rate and agro-ecological conditions (i.e., climatic zones and soil types). A control function approach is preferred to a 2SLS since it enables us to address not only unobserved heterogeneity in fertilizer use but also endogeneity, which can result from the interaction terms (Wooldridge 2010). In the first stage of the control function approach, the nitrogen application rate is regressed on the instrument and all other explanatory variables:

$$N_{ijt} = \pi Z_{ijt} + V_{ijt} + C_{ij} \qquad (2)$$

Where Z_{ijt} represents the set of covariates, including the instrument. Note that the instrument is uncorrelated with the error term. Endogeneity in nitrogen application arises when V_{ijt} is correlated with U_{ijt}, as follows:

$$U_{ijt} = \rho V_{ijt} + E_{ijt} + C_{ij} \qquad (3)$$

Where, ρ is the population regression coefficient. Then, equation (3) is substitute into equation (1) as follows:

$$Yield_{ijt} = \alpha N_{ijt} + \beta X_{ijt} + \rho V_{ijt} + E_{ijt}, + C_{ij} \qquad (4)$$

Although V_{ijt} is unobservable, we can rearrange equation (2) in order to estimate it:

$$\hat{V}_{ijt} = N_{ijt} - \pi Z_{ijt} - C_{ij} \qquad (5)$$

Finally, equation (5) is substituted into equation (4) to obtain the main specification (equation 6), using the predicted residual of the first stage as an explanatory variable to control for possible endogeneity.

$$\text{Yield}_{ijt} = \alpha N_{ijt} + \beta X_{ijt} + \rho \hat{V}_{ijt} + E_{ijt} + C_{ij}, \qquad (6)$$

We build on the work by Koussoubé and Nauges (2017) by applying the model to panel data, employing the Mundlak-Chamberlain device (a.k.a correlated random effects) to address time-invariant household heterogeneity. Unlike the fixed effects, the Mundlak-Chamberlain device allows us to recover the coefficients of important time-invariant explanatory variables. Under the Mundlak-Chamberlain device, the household unobserved time-invariant effects (C_{ij}) are correlated with the observed covariates (X_i), through the projection of those effects on the time average ($\overline{X}_i$) of covariates, as follows:

$$C_{ij} = \overline{X}_{ij}\delta + \alpha_i + \omega, \qquad \alpha_i \mid X_i \sim N(0, \sigma_\alpha^2) \qquad (7)$$

All standard errors are bootstrapped to take in account that maize yields of plots belonging to a same household may be correlated. With large sample size and high number of repetitions, the bootstrapping method provides valid estimates of variance estimates for statistical inference (Guan 2003).

Our emphasis, and a contribution of this analysis is that we test for agro-ecological factors measured at several scales of analysis (plot, village, zone), while controlling for a wide range of production inputs, plot manager characteristics and household characteristics. With the exception of seeds, few other production inputs were included in previous studies. Likewise, plot manager characteristics were often overlooked. We also depart from Koussoubé and Nauges (2017) by incorporating observed soil indicators and rainfall isohyets as zone criteria into our analysis. In contrast, they utilized farmer perception of soil fertility and included regional administrative dummies, which have little to do with agro-ecological conditions.

Profitability

To examine the profitability of fertilizer use, we first estimate the marginal product of N, which represents the change in expected maize yield with the use of an additional kilogram of N. The marginal product of N is obtained by taking partial derivative of expected yields conditional on X with respect to N.

To find the optimal quantity of nitrogen to apply from an agronomic view point, we set derivative equal to zero and solve for "N". Next, we examine marginal value/cost ratios (MVCRs)[2], which is the value of an increase in maize output association with the application of an additional kilogram of nitrogen divided by the price of one kilogram of nitrogen[3]. The general rule is that profit is maximized by applying the quantity of nitrogen at which marginal revenues equal marginal costs. Or, simply, when MVCR equals one.

We compute MVCRs under different fertilizer costs and farm gate prices for maize. An average low, mean, and high price value for maize is computed using monthly farm gate prices across the three crop years from INERA (2013). We also consider three different fertilizer costs: market price, official subsidized price, and transacted subsidized price. The subsidized fertilizer prices for urea and NPK are set at 270 FCFA/kg and 250 FCFA/kg, which is 50% below market prices (MAFAP 2013). As highlighted by Holtzman et al. (2011), high transaction costs, due in part to poor road infrastructure and illicit tax collection, increase fertilizer costs and thereby,

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[2] $E(MVCR_{ijt}) = E(MP_{ijt}) * P_{maize}/P_N$.

[3] As Xu et al. (2009), we use the price of urea and NPK and their nutrient content to estimate the price of nitrogen per kilogram. The amount of each fertilizer required for 1 kg is given by $0.46X + 0.15x = 1$. Solving for x, we get $x=1.63$. Therefore, 1 kg of nitrogen costs approximately 1.63 kg of each fertilizer, or $P_N = 1.63 (P_{urea} + P_{NPK})$.

reduce the overall subsidy at 28% and 23% of the market price for urea and NPK compared to the official 50% price reduction.

The incentive to use fertilizer, in term of profitability, has been extensively examined through the average value cost ratio (AVCRs), which is calculated as $E(AVCR_{ijt})= E(AP_{ijt}) * (P_{maize} /P_{N})$, or the expected quantity of maize produced per unit of nitrogen, holding all other productive inputs fixed, times the maize-nitrogen price ratio. The average product of N is obtained by dividing the expected yield by N. Profitability has been considered low if the AVCR is less than two (Morris et al. 2007). When production or price risk is high, an AVCR ratio of three to four has been considered necessary to ensure profitability (Kelly 2006). In countries such as Burkina Faso, where maize production depends entirely on rainfall, a minimum AVCR of three may be essential to guarantee that the incentive to use fertilizer overcome any risk of production loss.

Data

Production, plot and household data are drawn from the Continuous Farm Household Survey (*Enquête Permanente Agricole* (EPA)) of Burkina Faso. The EPA is implemented by the General Research and Sectoral Statistics Department (*Direction Générale des Études et des Statistiques Sectorielles* (DGESS)) of the Ministry of Agriculture and Food Security (*Ministère de l'Agriculture et de la Sécurité alimentaire* (MASA)). The sampling frame for the EPA is based on the 2006 Population Census and is nationally representative, covering 571 villages, 45 provinces, 13 administrative regions, and three agro-ecological zones. In this analysis, we utilize data for 2009/10, 2010/11 and 2011/12 cropping seasons (three survey years). These are the last years for which fully cleaned data are available. After dropping households that were not continuously surveyed over the three-year period and those that did not cultivate maize, we are left with about 2,321 households out of 2,700.

As mentioned in Section 2, agro-ecological zones are defined on the basis of rainfall isohyets only in Burkina Faso. To construct more nuanced indicators of agro-ecological zones, GPS coordinates have been recorded for the village of each surveyed household. These coordinates were then linked to rainfall data from the National Oceanic and Atmospheric Administration’s Climate Prediction Center and to soils information from the European Union’s Soil Atlas of Africa. Each village was assigned to an agro-ecological zone based on its average rainfall history over the last decade. Virtually all maize plots are located in the Sudano-Sahelien (between the 600mm isohyet and 900mm isohyet) and Sudanian (above 900mm isohyet) zones[4]. The annual rainfall and coefficients of variation in total annual rainfall at the village level over the last three years are also computed. The GPS coordinates are used to identify the soil type at the village level. Following the Harmonized World Soil Database (HWSD FAO 1990, cited by Jones et al. 2013), the different soil types in our sample have been classified, based on their suitability for maize production, into three groups. The first groups include excellent soils: Cambisols, Luvisols, and Nitisols. The second group encompasses good soils: Vertisols and Regosols. The third group is composed of poor and marginal soils: Arenosols, Leptosols, Lixisols, Plinthosols, and Planosols (See Jones et al. 2013 for a detailed description of each soil type).

Variables

Table 1 provides the definitions of variables included in the yield response function with summary statistics. Yield ($Yield_{ijt}$) is calculated in kg per ha based on the crop harvested

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[4] Less than 1% of maize plots are located in the Sahelian zone (below 600mm isohyet).

from randomized yield subplots and physical measurements of area. The nitrogen application rate, N_{ijt}, is the nitrogen nutrient kilograms divided by the plot area (ha). Total nitrogen nutrient kilograms are calculated by multiplying the quantities of NPK and Urea by their nitrogen content (14% and 46%, respectively). The vector of other covariates, X_{ijt}, comprises other productive inputs, agroecological factors at plot-level and other scales of analysis, household and plot manager characteristics.

Plot characteristics include whether or not the maize crop has been intercropped with legumes, the presence of soil and water conservation structures (e.g., stone bunds or permeable dikes, half-moons or planting pits, living fences). Both of these are fairly infrequent in this farming system (12% and 13% of plots, respectively). Use of agroforestry, or the presence of trees in the plot, is more common. Mean fallow periods are long now (18 years), reflecting the transformation of this region to a continuously cropped system (CILSS 2016). The position of the plot in the toposequence (lowland, plain, slope), and its location within or outside the compound are also associated with soil types and length of cultivation. Area may capture productivity differences related to scale of production. Previous research in Burkina Faso has shown that whether plot production is managed collectively under the supervision of the head or managed individually by a household member influences productivity (Udry 1996; Kazianga and Wahhaj 2013). Rainfall, zone, and soils variables measured at a higher scale of analysis are defined above.

Other conventional production inputs include seed, manure, herbicide, pesticide, and raticide application rates per ha. Labor input is measured as the total number of adult person days per plot. Plot manager characteristics include the age of the manager (a proxy for human capital and seniority in the extended family household), whether or not the manager is the head of the

Table 1. Variable definitions and summary statistics

Variable	Definition	Mean	Max.	Min.	Std. Dev.
Yield	Maize yield (kg/ha)	1255	4200	40	756
N	Nitrogen application (nutrient kg/ha)	16	278	0	29
Plot characteristics					
Area	Plot area (ha)	0.5	17	0.001	0.9
Collective	1= collective plot	0.88	1	0	0.33
Tenure	1= secure rights (customary or formal) over the plot	0.61	1	0	0.48
Intercropping	1=there is intercropping of legumes and maize	0.18	1	0	0.38
SWC	1=There is presence of soil and water conservation structure on the plot	0.12	1	0	0.33
Fallow	Number of years since the plot was left fallow (years)	18	86	0	15
Trees	1=there are trees on the plot	0.59	1	0	0.49
Location	1= plot is located outside the household compound	0.37	1	0	0.48
Lowland	1= lowland plot	0.05	1	0	0.22
Slope	1= plot with a steep slope	0.06	1	0	0.24
Climatic zones and soil quality					
Rain	Total rainfall in the village (mm)	955	1294	447	182
CV	Coefficient of variation of rainfall in the village over the last three years (mm)	0.09	0.23	0.004	0.04
Excellent_soils	1= Cambisols, Luvisols, and Nitisols	0.21	1	0	0.41
Good_soils	1= Vertisols and Regosols	0.09	1	0	0.29
Sudanian	1= Sudanian zone	0.55	1	0	0.49
Other production inputs					
Seed	Seed application (kg/ha)	17	36000	0	374
Manure	Manure application (kg/ha)	454	657000	0	8425
Herbicide	Herbicide application (l/ha)	66	5000	0	248
Fungicide	Fungicide application (g/ha)	2.6	2000	0	31
Pesticide	Pesticide application (g/ha)	0.35	75	0	3.6
Raticide	Raticide application (g/ha)	1.2	500	0	13
Labor	Number of adult labor days worked on plot (person days)	5.1	156	0	7.7
Plot manager characteristics					
Age	Age of plot manager (years)	49	99	15	15
Head	1= plot manager is the household head	0.88	1	0	0.32
Credit	1= plot manager has had access to credit over the last 12 months	0.15	1	0	0.35
Extension	Number of years since the plot manager has received any extension services (years).Top-coded at 5 years	4.66	5	0	0.98
Household characteristics					
Size	Number of people in the household (persons)	11	88	1	7.3
Livestock	Number of livestock owned by the household- measured in tropical livestock units (ln TLU)	8.2	434	0	20
Landholding	Total land cultivated by the household (ha)	3.8	70	0.14	4.6
Income	Value of non-farm income at the household level (ln FCFA)	190	12190	0	574
Cotton	Number of cotton hectares cultivated at the household level (ha)	0.63	69	0	2.2

Source: Authors, based on EPA data (see text). Total n= 9,526 maize plots.

household (seniority), whether the plot manager had access to any credit in the 12 months preceding the survey, and the number of years since he or she has received any extension advice. Household characteristics include household size, livestock ownership measured in tropical livestock units, the farm size operated by the extended family household, household wealth computed as the value of non-farm income, and the number of cotton hectares cultivated, which proxies for the services and information received by the household from the formal cooperative system.

Results

Descriptive

Among the surveyed villages that cultivate maize, about 70% are located in the Sudano-Sahelien zone and the 30% remaining are in the Sudanian zone. Maize cultivation is more prominent in villages within the Sudanian zone, which accounts for approximately 4,200 maize plots distributed across 166 villages. In contrast, there are about 5,300 maize plots dispersed across 378 villages in the Sudano-Sahelien zone. About half of households apply some fertilizer on their maize plots, but only 40% of all maize plots do receive fertilizer. This suggests some disparities in fertilizer application within a household. Taking into account both fertilizer users and non-users, the unconditional mean of nitrogen application at the plot level is 16 kg/ha. In comparison, the conditional mean of nitrogen at the plot level, which considers the fertilizer users only, is twice as high at 38 kg/ha. Not controlling for other covariates, the average yield without fertilizer use is much lower at ~970 kg/ha compared to ~1314 kg/ha with fertilizer use.

Figures 1 and 2 show the probability density functions of maize yields between zones and across soil types, respectively. All distributions tend to be positively skewed, with a long right tail. Regardless of the agro-climatic zones and soil types, there is a small number of plots that are highly productive, with maize yields exceeding 2,000 kg/ha.

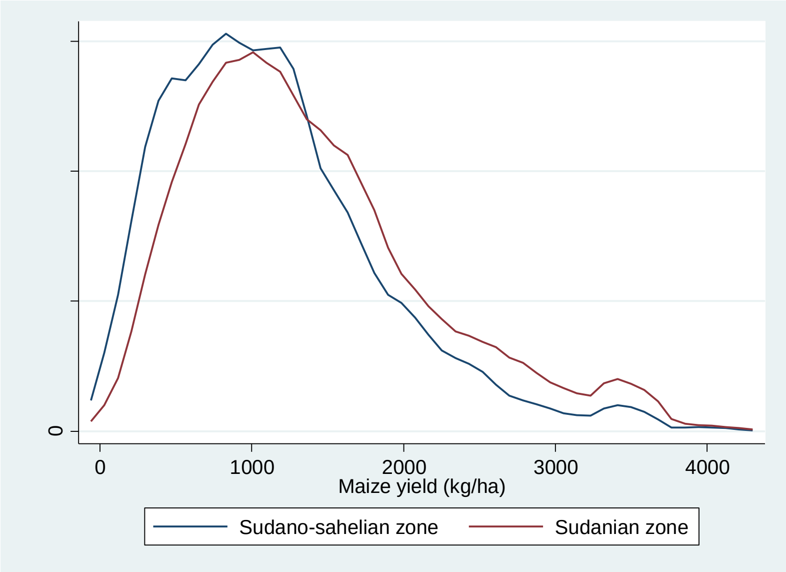

Figure 1. Probability density functions of maize yields between agro-climatic zones

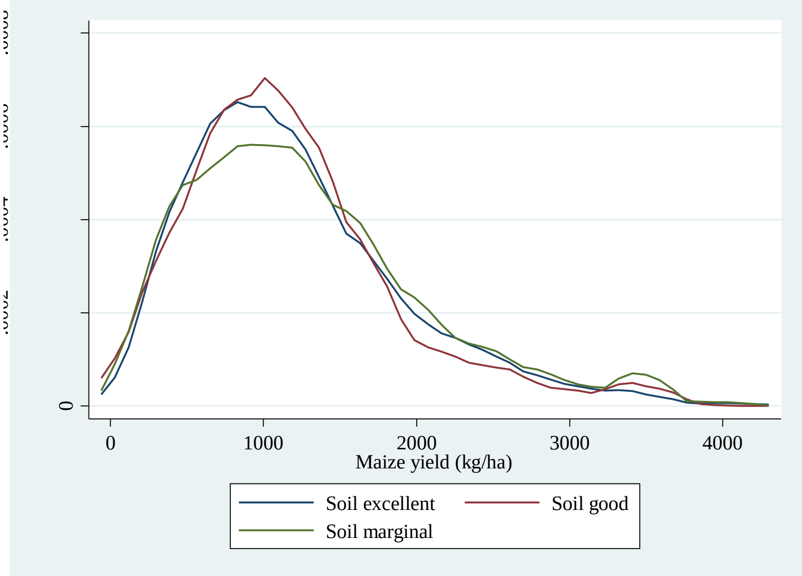

Figure 2. Probability density functions of maize yields across soil types

Maize Yield Response to Fertilizer

Model results are shown in Table 2. In column 1, we present the results of the CRE regression that treats nitrogen use as exogenous and excludes agro-ecological factors at a scale larger than plot. The results obtained with the same estimation approach, but including agro-ecological factors, is shown in column 2. Similarly, columns 3 and 4 report the findings of regressions that exclude and include agro-ecological factors, while also controlling for the potential endogeneity of nitrogen use. All models include a quadratic term for nitrogen to allow for diminishing marginal returns, and interactions of nitrogen with zone and soils, while controlling for other productive inputs, plot manager and household characteristics, and year effects in addition to household time-averages.

As expected, the coefficient estimate of nitrogen application rate is positive and significant across the models, whereas its squared term is negative and significant, indicating that as nitrogen applicate rate increases, maize yield increases at a decreasing rate. However, the coefficients on N are very small in the models that assumes fertilizer use to be exogenous (2.9). The F-statistic of the first stage (F (6, 1846=34.28; Prob > F= 0.0000)) indicates that the instrument, cotton cooperative membership, is strongly correlated with the potentially endogenous variable, nitrogen application rate (coeff=18.44***). The exclusion restriction is also highly plausible because the proportion of households belonging to a cotton cooperative at the commune level is unlikely to affect maize yields at the plot level in our econometric specification. Therefore, the instrument is considered reliable and valid. The other diagnostic statistic that supports the endogeneity of fertilizer application is the high level of significance of the predicted residual of nitrogen applicate rate (coeff= -14.88, p-value=0.000) in the second stage regression of the CFA-CRE models.

Various agro-ecological indicators measured at the scale of the plot are statistically significant across the models. As expected, topography, size, and management type influence productivity. Intercropping, which involves cultivating maize with a legume, such as groundnut or cowpeas, on the same plot during the same growing season, negatively affects maize yield. This contrasts with previous studies that found a positive effect of intercropping on grain yields compared to sole cropping (Tsubo, Walker, and Ogindo, 2005; Fujita, Ofosu-Budu, and Ogata, 1992) but is aligned with the findings reported by Koussombe and Nauges (2017). Intercropping effects on yield potential are often more visible over time, and typically, yield measurements in intercropped plots do not adequately account for smaller areas dedicated to the main crop. As such, the yields of main crop are understated. The existence of soil and water conservation structures, such as stone bunds, half moon, and zai positively affect maize yields. This is consistent with previous research that showed that farmers cultivating in agro-ecological zones characterized by low rainfall and soil fertility have higher incentives to adopt these practice (Bandre and Batta 1998; Sawadogo and Janvier 2011). Moreover, Savadogo et al. (1998) argued that smallholder farmers cultivating commercial crops, such as maize, are more likely to adopt soil and water conservation practices.

Introducing agro-ecological factors at a scale larger than the plot does not have much effect on other coefficients in the models that treat fertilizers use exogenously (columns 1 v 2, although it is associated with a higher response to N in the models that control for endogeneity (columns 3 v 4). Focusing on the full model in column 4, we see that yields are significantly higher on soils considered to be excellent (i.e., Cambisols, Luvisols, and Nitisols) and good (i.e., Vertisols and Regosols) for maize production, compared to poor and marginal soils (i.e., Arenosols, Leptosols, Lixisols, Plinthosols, and Planosols). Although Koussombe and Nauge

(2017) did not find a statistically significant relationship between soil quality and maize yields, they measured soil quality in terms of the perception of the household head. Marenya and Barrett (2009) found that low soil organic matter limited the yield response of maize to mineral fertilizers.

Further, we find that the interaction terms between nitrogen application and soil types are statistically significant (column 4). Compared to good and excellent soils, maize production on poor and marginal soils benefit the most from an additional kilogram of nitrogen. No statistically significant yield differential is found between the Sudano-Sahelian and Sudanian zones. Yet, the interaction term between nitrogen application and agro-ecological zone is statistically significant. Maize production in the Sudano-Sahelian zone benefits the most from an additional kilogram of nitrogen. The negative sign on rainfall may be explained by the fact that it is the availability of moisture, rather than the amount of rainfall, that most determines yields. Moreover, a feature of the Sudano-Sahelian farming system is that rainfall is infrequent but heavy, accompanied by runoff and soil erosion—which is why farmers and research programs in this region have developed soil and water conservation structures to retain moisture and nutrients (Reij et al. 2009; CILSS 2016).

The estimated response rate in the full model (column 4) is in line with other estimates for maize based on data from farmers' fields in Sub-Saharan Africa. In their review, Yanggen et al. (1998) found response rates to be less robust in West Africa than in East and Southern Africa, with some under 15 kg/ha, most in the 10-15 kg/ha and few over 25 kg/ha. In Burkina Faso, Savadogo et al. (1994) estimated a marginal product of 25 kg/ha in maize when cultivated with animal traction, but standard errors were so large that the coefficient was not statistically significant. Using cross-sectional data for the crop year 2008, Koussoubé and Nauges (2017) estimated a response rate on maize of 19 kg/ha in Burkina Faso.

Estimated marginal products for nitrogen on maize in Kenya are considerably higher. In Western Kenya, Marenya and Barrett (2009) estimated a marginal product of 40-44 kg/ha and emphasized the heterogeneity in profitability among farms in their sample. Sheahan et al. (2014) reported marginal products that vary from 14 to 25 kg/ha among agro-ecological zones in Kenya, with the highest response rate in the least fertile zone where fertilizer use is lower and more recent. In Zambia, Xu et al. (2009) found response rates ranging from under 10 to 30 kg/ha in maize, with a median marginal product of 16 kg/ha. The lowest we found was that reported by Chapoto et al. (2015) at 9-10 kg/ha, also in Zambia.

With the exception of fertilizer, none of the productive inputs is statistically significant in the yield response function to nitrogen. This is not so surprising giving the low adoption and use rates of other productive inputs in Burkina Faso (Theriault, Smale, and Haider 2017). Some plot manager characteristics do affect maize yield response to nitrogen. Maize plots managed by household heads have significantly higher yields, which is consistent with previous studies (Kazianga and Wahhaj 2013). Like Guirkinger, Platteau and Goetghebuer (2015), we find lower yields on plots that are collectively managed compared to those individually managed on maize, which is a high value cereal in Burkina Faso. Interestingly, having access to credit last year and recently in contact with extension services negatively affect maize yields. Likewise, Xu et al. (2009) found that farmers receiving maize advice from extension agents had statistically significantly lower yields. These findings should be interpreted carefully. They do not indicate that credit and extension services are detrimental to productivity gains, since we do not know for sure whether credit was used for maize production and whether extension services were oriented

Table 2. Estimated Maize Yield Functions

Variable	CRE (1)	CRE (2)	CRE-CFA (3)	CRE-CFA (4)
N	2.93***	2.91***	17.31***	22.46***
	(0.739)	(0.886)	(3.81)	(4.55)
N*N	-0.013 ***	-0.014***	-0.015***	-0.016***
	(0.005)	(0.005)		(0.004)
Area	112.3***	110.0***	146.1***	183.7***
	(21.48)	(21.05)	(32.99)	(25.51)
Collective	-43.27	-31.85	-55.93*	-109.6**
	(38.67)	(38.41)	(31.59)	(44.92)
Tenure	-30.24	-27.97	-26.18	-4.039
	(23.86)	(23.77)	(25.68)	(23.52)
Intercropping	-219.91***	-235.24***	-148.11***	-155.9***
	(24.65)	(24.77)	(34.01)	(36.82)
SWC	61.25**	70.28**	72.82**	78.85**
	(28.50)	(28.76)	(31.23)	(30.95)
Fallow	0.732	1.049	0.321	1.215
	(0.719)	(0.716)	(0.768)	(0.761)
Trees	70.25***	62.58***	15.46	8.314
	(21.26)	(21.17)	(26.54)	(26.81)
Location	18.42	-1.576	-91.77**	-120.0***
	(26.11)	25.66	(39.38)	(40.07)
Lowland	95.82**	94.56**	264.77***	283.1***
	(45.98)	(45.83)	(51.92)	(57.19)
Slope	9.84	4.99	63.21	70.70*
	(38.39)	(38.39)	(43.35)	(42.90)
Rain		-0.086		-0.596***
		(0.154)		(0.199)
CV		291.80		-197.2
		(284.13)		(316.5)
Excellent soils		16.26		52.52*
		(33.90)		(28.93)
Good soils		178.75***		239.2***
		(39.20)		(37.32)
Sudanian zone		-198.46		-65.62
		(45.20)		(52.79)
N* Sudano-Sahelien zone		1.226***		1.441**
		(0.703)		(0.664)
N*excellent soils		-1.824**		-1.680**
		(0.703)		(0.724)
N* good soils		-3.124***		-2.096***
		(0.881)		(0.922)
Productive inputs	Included	Included	Included	Included
Plot manager characteristics	Included	Included	Included	Included
Household characteristics	Included	Included	Included	Included
Household time-averages	Included	Included	Included	Included
Crop years	Included	Included	Included	Included
Prob> chi2 =	0.0000	0.0000	0.0000	0.0000
R-squared =	0.1901	0.1998	0.1957	0.2112
Adj. R-squared =	0.1858	0.1947	0.1928	0.2048
N=	8871	8871	6974	6974

Source: As prepared by authors. Italics indicate that we controlled for production inputs, plot manager and household characteristics (see Table 1), household time averages, and crop years (2011 and 2012).

toward maize productivity. They indicate that plot manager characteristics do influence yields and, therefore, that there is a need to better control for them in yield response functions

4.3 Profitability of Fertilizer Use

Table 3 reports the partial effects of N at the sample means across acro-ecological conditions. The estimated average marginal product is 22kg/ha, with a 95% confidence interval ranging from 13 kg/ha to 31 kg/ha. This is slightly higher than previously estimated in Burkina Faso for earlier years (i.e., Koussombe and Nauges (2017) reported an estimate of 19 kg/ha) and overall consistent with earlier findings from the region (Yanggen et al. 1998). Holding everything else equal, we find that, in average, maize yield response to N is the highest on poor and marginal soils (~ 23 kg/ha) in the Sudano-sahelian zone and the lowest on good soils in the wetter Sudanian zone (~19 kg/ha). This contrasts with Koussombe and Nauges (2017)'s finding that soils with low fertility, as perceived by household heads, have lower yield response to N.

In Burkina Faso, agronomic research recommends to apply 50 kg/ha of urea and between 150 and 200 kg/ha of NPK on maize (Holtzman et al., 2013). Note that the recommended rates of fertilizer application remain the same, regardless of the agro-ecological conditions. It is in the Sudanian zone that the quantity of fertilizer N applied to plots (conditional application rate) is the closest to the recommended one. Yet, conditional application rates (excluding those that did not receive any fertilizer) fell short of the recommended rates nationwide. The gap is even more striking if we compare average unconditional application rates for all plots (including those that did not apply any fertilizer).

The findings regarding agronomical optimal rates of fertilizer application are interesting. In average, the agronomically optimal nitrogen application is 722 kg per hectare. This high value is mostly driven by the low nitrogen squared coefficient estimate (-0.02) in the yield response function. Using the nitrogen squared coefficient estimate from the 3SLS regression (-0.11), Kousoumbe and Nauges (2017), calculated that nitrogen application ranging from 77 to 106 kg/ha maximized yield. However, if they would have chosen the coefficient estimates on the squared terms from the 3SLS-FE (-0.03) or OLS (-0.05) regressions, their results would have had a similar order of magnitude. Using a quadratic production function, Chapoto et al. (2015) estimated a nitrogen-squared coefficient of -0.02, but did not report the agronomically optimal rate. Earlier research in sub-Saharan Africa estimated the net annual nutrient depletion at 22 kilogram of nitrogen per year (Stoorvogel, Smaling, and Jansseen, 1993) and a net loss of about 700 kilogram of nitrogen per hectare over a 30 year period (World Bank, 1996 cited by Gruhn, Goletti, and Yudelman 2000). Nutrient depletion can even reach 100 kg NPK/ha/ year in

Table 3. Average partial effect of nitrogen nutrient kg/ha by soil type and climatic zone

Agro-Ecological Conditions	Average Partial Effect of N (kg/ha)		Uncond. N (kg/ha)	Cond. N (kg/ha)	Agronomically Optimal N (kg/ha)
	Estimates	95% CI			
Sudano-sahelian zone	23	14-32	12	36	742
Sudanian zone	21	21-30	21	40	696
Poor/marginal soils	22	14-32	17	40	742
Good soils	20	10-29	8	27	638
Excellent soils	21	12-30	16	38	680
Sudano-sahelian & poor/marginal soils	23	14-32	12	39	762
Sudano-sahelian & good soils	20	11-29	8	25	658
Sudano-sahelien & excellent soils	21	12-31	16	35	700
Sudanian & poor/marginal soils	22	13-31	24	41	717
Sudanian & good soils	19	10-28	9	37	612
Sudanian & excellent soils	20	11-29	16	40	654
Average	22	13-31	16	38	722

Note: Partial effects are evaluated at the sample means, except for the dummy variable of interest, which takes a value of 0 or 1. The uniform recommended rate across all agroecological conditions is 45.5-53 N nutrient kg/ha.

Burkina Faso and Mali (Henao 1992). Our results suggest a continuous soil fertility depletion in maize farming system of Burkina Faso. In fact, with a maximum value of 278 kg/ha of nitrogen in the data, the turning point, at which an additional kilogram of nitrogen is not agronomically beneficial, is outside the range of the data.

Table 4 reports the MVCRs under each scenario, using the expected marginal product from Table 3 (22 kg/ha). Given the nature of farming in Burkina Faso, where crops depend entirely on rainfall, there is uncertainty in regards to the outcome of fertilizer use. Plot managers apply fertilizer at lower rates than those that would maximize profit, as evidenced by the MVCRs above 1.

Table 4. Marginal and Average Value-Cost Ratio under Different Prices

Scenarios	Fertilizer at market price		Subsidized fertilizer price		Subsidized fertilizer price + transaction costs	
	MVCR	AVCR	MVCR	AVCR	MVCR	AVCR
Low maize price	1.6	1.6	3.2	3.2	2.1	2.2
Average maize price	1.7	1.8	3.5	3.5	2.3	2.4
High maize price	1.9	2.0	3.9	3.9	2.6	2.6

Low, average, and high maize farm-gate prices are 123 FCFA/kg, 134 FCFA/kg, and 149 FCFA/kg, respectively.

Table 4 reports the AVCRs, using the expected average product of 22kg/ha.[5] At full market prices, AVCRs are below 2, which indicate that fertilizer use is not profitable regardless of farm-gate prices for maize. The ratios increase above 3 with an official price subsidy of 50%, even when the farm-gate price for maize is low. At the official subsidized price, incentives to use fertilizer is strong and overcome price and production risks. Once transaction costs are taken into consideration, the cut in fertilizer price is less than half and thereby, the incentives to use fertilizer are much lower. The AVCRs are above 2 but below 3.

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[5] The means of the marginal product (22.14) and average product (22.38) are comparable

The confidence intervals in Table 3 show the wide variation in average partial effect of nitrogen, indicating that even under suitable agro-ecological conditions for maize and governmental intervention- through the fertilizer subsidy program- fertilizer use is not always profitable for all. Table A1 shows the minimum average product for fertilizer use to be profitable (AVCR=2) under different price scenarios. In some instances, the minimum average product is beyond the 95% confidence intervals, indicating low incentive to use fertilizer.

Conclusions

Intensification strategies that aim to boost productivity while protecting natural resources have become central to agricultural growth, especially in Burkina Faso where food insecurity is prevalent. For most part, agricultural policies have targeted the promotion of inorganic fertilizer use, notably through subsidy programs. Yet, little is known on how agro-ecological conditions affect fertilizer use and profitability in the West African Sahel, including Burkina Faso. In this article, we address this gap in the literature by examining how agro-ecological factors, measured at several scales of analysis (plot, village, zone), affect the maize yield response to fertilizer as well as the economic incentives to use fertilizer. Using farm household survey data from Burkina Faso over three cropping seasons (2009/10 to 2011/12), we estimate a maize yield response function at the plot level through a Control Function Approach (CFA) in order to control for potential endogeneity issue in fertilizer use. We also employ the Correlated Random Effects (CRE) to address time-invariant unobserved effects that may be related to household decision-making. Then, we examine the profitability of fertilizer use by calculating the marginal and average value-cost ratios based on the estimated coefficients from the maize yield response function.

We find that maize yield response to nitrogen in Burkina Faso is ~22 kg/ha—within the range reported in other recent studies. As hypothesized, agro-ecological conditions significantly affect productivity. Good soil fertility positively influences maize yield, although the marginal effect of nitrogen nutrients is significantly greater on soils with lower fertility. After controlling for other covariates (especially soils), zone effects on maize productivity are not statistically significant. Yet, the marginal effect of nitrogen is greater in the Sudano-Sahelian zone than in the wetter Sudanian zone. Several agro-ecological characteristics of plots also prove to be important for maize productivity, including the presence of agroforestry, soil and water conservation structures, and location of the field in the lowlands, where nutrients and moisture more readily accumulate. The estimated optimal N rates are much larger than the maximum N application rates from the dataset, indicating that the use of additional kilograms of fertilizer would be agronomically beneficial on all maize plots.

As expected in an uncertain farming environment with poorly developed markets for fertilizer, plot managers apply fertilizer at lower than the profit-maximizing rate. Our results also show that fertilizer use is not profitable at full market prices, although it is profitable with a 50% fertilizer subsidy. However, if transaction costs in fertilizer supply are taken into account, the incentives to use fertilizer, even in the presence of the subsidy, remain low. This conclusion appears complementary to that of Kousoubé and Nauges (2017), who argue that need to overcome supply-side constraints.

Our findings have important policy implications, supporting research by Vanlauwe et al. (2010), Kihari et al. (2016), and others with household survey data. For example, policy makers need to be cautious when generalizing across regions or drawing policy recommendations from a single agro-ecological zone because economic incentives vary widely across and within a zone.

Policies that take heterogeneity into account may be more effective in promoting sustainable and profitable input use. As currently designed, the fertilizer subsidy program promotes maize, which is a crop not well-suited for all agro-ecologies in Burkina Faso (only for those above the 600mm isohyet). This raises question on the relevance of continuing with a crop targeted program, especially in the context of climate change. Moreover, the profitability analysis shows that the reduced costs of subsidized fertilizer increase their profitability, as it should. Yet, one wonder whether there are more effective and less costly ways to make fertilizer affordable to farmers. For instance, investing in road infrastructure and removing illicit tax collection could lead to significant cut in fertilizer costs while freeing up resources from the agricultural budget to enable other services, such as research and development and extension.

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Appendix

Table A1. Minimum Yield Response to Nitrogen Needed for Fertilizer Use to Be Profitable – AVCR=2

Scenario	Fertilizer at market price	Subsidized fertilizer price	Subsidized fertilizer price + transaction costs
Low maize farm-gate price	28	14	21
Average maize farm-gate price	25	13	19
High maize farm-gate price	23	11	17