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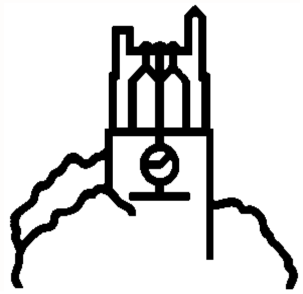
Maize Yield Response to Fertilizer under Differing Agro-Ecological Conditions in Burkina Faso

by

Veronique Theriault, Melinda Smale, and Hamza Haider



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EXECUTIVE SUMMARY

Achieving food security in Sub-Saharan Africa depends on raising the productivity of smallholder farmers, and in Burkina Faso, there is no option for enhancing crop productivity other than intensification. 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. Yet, as in other countries of Sub-Saharan Africa, the national agricultural research system formulated fertilizer recommendations during the 1970s and 1980s, but these did not, and still do not, take differing agro-ecologies into account. The heterogeneity of agro-ecological and soil conditions has led to a diversity of farming systems and cropping patterns. This heterogeneity, along with incomplete input markets, creates highly variable economic incentives for smallholder farmers.

Thus, there is a need to understand of farmers' incentives to use intensification strategies, including fertilizer. We use farm household survey data from Burkina Faso to examine how agro-ecological factors, measured at several scales of analysis (plot, village, and zone), affect the yield response of maize and the profitability of fertilizer use on maize. We focus on maize because it is the only dryland cereal with significant fertilizer use. We estimate the maize yield response function with a two-step procedure that combines correlated random effects with the control function approach in order to handle time-invariant unobserved heterogeneity and the endogeneity of fertilizer use. We then analyze the profitability of fertilizer use by calculating the marginal and average value-cost ratios based on coefficient estimates. We explore the sensitivity of profitability to different assumptions about maize price and fertilizer costs, including fertilizer subsidies and adjustments for transactions costs.

Results indicate that agro-ecological factors measured at the scale of plot, village and zone significantly affect maize productivity. The agronomic optimum lies outside the range of observed data, consistent with evidence of long-term nutrient depletion and suggesting that all maize plots would benefit from use of additional fertilizer. The marginal effect of nitrogen is stronger on less fertile soils and in the Sudano-Sahelian zone. At full market prices, fertilizer use is unprofitable, whereas it is profitable with the 50% fertilizer subsidy. However, transaction costs diminish the benefits of the subsidy. In some cases, fertilizer use is not profitable.

Findings underscore the need to be cautious when generalizing across regions or formulating policies based on findings from a single region. Policies that consider heterogeneity may be more effective in promoting sustainable input use by making it more profitable. As currently designed, the fertilizer subsidy program promotes maize, which is not well suited to all agro-ecologies in Burkina Faso. Programs targeted to a single crop may not be desirable, especially in the context of climate change. Although the subsidy enhances profitability (to the extent that it covers transactions costs), there may be more effective ways to make fertilizer more affordable to farmers, such as investments in road infrastructure and removing illicit tax collection.

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ACRONYMS

AVCR	Average Value Cost Ratio
CFA	Control Function Approach
CRE	Correlated Random Effects
DGESS	*Direction Générale des Études et des Statistiques Sectorielles*
EPA	Enquête Permanente Agricole (Continuous Farm Household Survey)
GPS	Global Positioning System
MASA	*Ministère de l'Agriculture et de la Sécurité alimentaire* (Ministry of Agriculture and Food Security)
MVCR	Marginal Value/Cost Ratio
OLS	ordinary Least Squares
TLU	Tropical Livestock Units

1. 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. 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, such as input subsidy programs, are implemented at the national scale with *blanket* recommendations that ignore 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 Africa, 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 (Reij, Tappan, and Smale 2009; Pretty, Toulmin, and Williams 2011). Recent analysis of satellite imagery confirms that between 2000 and 2013, the progression of agriculture has accelerated in Burkina Faso. 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 2016). To enhance crop productivity in Burkina Faso, there is no option other than intensification.

National agricultural research systems in Burkina Faso formulated fertilizer recommendations during the 1970s and 1980s, but these did not, and still do not, take differing rainfall regime or other aspects of growing conditions into account. 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 output markets. 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 is likely to lead to highly variable economic incentives for smallholder farmers.

These observations drive our central hypotheses that the response of maize yield to fertilizer in Burkina Faso, and thus the economic incentives for its use, 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.

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 analyses 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. Studies by Koussoube and Nauges (2017) in Burkina Faso and Foltz, Aldana, and Laris (2012) in Mali represent exceptions, but neither of these controlled for variations over both time and space. Decades ago, Henao et al. (1992); Kouka, Jolly, and Henao (1995) 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).

2. FARMING CONTEXT IN BURKINA FASO

The Burkinabe land cover has changed drastically over the last decades. In 1975, about 15% of the land was under rainfed agriculture, compared to 39% in 2013—representing a 160% change in less than 40 years (CILSS 2016). 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 remain low with an average of 1.6 tons per hectare (FAO 2015). Most of the increase in maize production has come from an expansion in arable land rather than through cropping intensity. 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). 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 are available only for those three crops. Although the official subsidy rate is 50%, subsidized fertilizers are approximately a quarter cheaper than those purchased at full market value because of high transaction costs (Holtzman et al. 2013).

Officially, agro-ecological zones in Burkina Faso are constructed solely on the basis of rainfall isohyet, consisting of Sahelian, Sudano-Sahelianm, and Sudanian zones (Bainville 2016; De Longueville et al. 2016). The Sahelian zone has 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 millet, 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 but two-thirds of the area has soils that are iron-rich and low in organic matter content. Extensive areas of Plinthosols (i.e., iron-rich), occur in all zones (Jones et al. 2013; ESDAC 2014; FAO 2015). 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 southern part of the country (ESDAC 2014). Deep sandy soils (i.e., Arenosols), which have low water and nutrient retention capacity, are mostly found in the Sahelian zone (FAO 2015).

3. METHODOLOGY

3.1. 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., Chambers and Lichtenberg 1996; Guan et al. 2006). Compared to the simple and popular Cobb-Douglas form, more flexible, polynomial approaches recognize the codependence of inputs in determining yield response (see discussions in Xu et al. 2009; Burke, Jayne, and Black 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, Black, and Jayne 2013; Burke, Jayne, and Black 2017). Our functional form most closely resembles that of Sheahan, Black, and Jayne (2013) and Burke, Jayne, and Black (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.

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

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

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: $V_{ijt,}$ $E_{ijt,}$ and C_j. Where E_{ijt} are random errors, V_{ijt} are unobserved characteristics that are correlated with nitrogen application, and C_j 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 agro-ecological zones, soil types, and rainfall averages and variability at the village level, there are certainly some variations within a village, as Burke, Jayne, and Black (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, Black, and Jayne 2013) and, therefore, the omission of soil quality indicators could generate a positive bias in the effect of nitrogen on maize yields.

Unlike Sheahan, Black, and Jayne (2013), 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 correlated with soil characteristics. In Burkina Faso, cotton is cultivated in rotation with dryland cereals,

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

such as maize. Some fertilizer provided on credit by the local 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 (climatic zones and soil types). A control function approach is preferred to 2SLS, since it enables us to address endogeneity, which can result not only from N but also from the interaction terms in our specification (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:

$$N_{ijt} = \pi Z_{ijt} + V_{ijt} + C_j \tag{2}$$

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:

$$U_{ijt} = \rho V_{ijt} + E_{ijt} + C_j \tag{3}$$

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

$$\text{Yield}_{ijt} = \alpha N_{ijt} + \beta X_{ijt} + \rho V_{ijt} + E_{ijt}, + C_j \tag{4}$$

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

$$\hat{V}_{ijt} = N_{ijt} - \pi Z_{ijt} - C_j \tag{5}$$

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.

$$\text{Yield}_{ijt} = \alpha N_{ijt} + \beta X_{ijt} + \rho \hat{V}_{ijt} + E_{ijt} + C_j, \tag{6}$$

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

$$C_j = \overline{X}_j \delta + \alpha_j + \omega, \qquad \alpha_j \mid X_j \sim N(0, \sigma_\alpha^2) \tag{7}$$

All standard errors are bootstrapped to take into account the use of predicted values for V_{ijt} in the yield response estimation, also accommodating the fact 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 et al. 2006).

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 Koussoube 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.

3.2. Profitability

To examine the profitability of fertilizer use, we first obtain the marginal product of N by taking the partial derivative of expected yields conditional on X with respect to N in the regression equation. To find the optimal quantity of nitrogen to apply from an agronomic viewpoint, we set the derivative equal to zero and solve for N. Next, we examine the marginal value/cost ratio (MVCR),[2] which is the value of an increase in maize output that results from applying 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 MVCR equals one.

We compute MVCRs under various 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 (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). High transaction costs, due in part to poor road infrastructure and illicit tax collection, reduce the effective subsidy by 28% and 23% of the market price for urea and NPK compared to the official 50% price reduction (Holtzman et al. 2013).

The profitability incentive to use fertilizer has been examined frequently with the average value cost ratio (AVCR). The AVCR 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 2005). In countries such as Burkina Faso, where maize production is entirely rainfed, we propose a minimum AVCR of three.

3.3. 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. We utilize

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

[3] Like 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 $P_N = 1.63 (P_{urea} + P_{NPK})$.

data for 2009/10, 2010/11 and 2011/12 cropping seasons, which 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 have 2,321 households (out of 2,700) and 9,526 maize plots.

To construct more nuanced indicators of agro-ecological zones than rainfall isohyets, we linked Global Positioning System (GPS) coordinates for the village of each surveyed household 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 survey village was assigned to an official 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 were also computed. Following the Harmonized World Soil Database (Jones et al. 2013: 45), we used the GPS coordinates to identify the different soil types in our sample and classify them, based on their suitability for maize production, into three groups: 1) excellent (Cambisols, Luvisols, and Nitisols); 2) good (Vertisols and Regosols); 3) poor and marginal soils (Arenosols, Leptosols, Lixisols, Plinthosols, and Planosols). Details on soil types can be found in Jones et al. (2013).

3.4. Variables

Table 1 provides the definitions and summary statistics of variables included in the yield response function. Yield ($Yield_{ijt}$) is calculated in kg per ha based on the crop harvested 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 (15% and 46%, respectively). The vector of other covariates, X_{ijt}, comprises other productive inputs, agro-ecological factors at several scales of analysis as well as 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). These are fairly infrequent in this part of Burkina Faso (12% and 13% of plots, respectively). 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 included. Plot area is intended to 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, as defined in section 3.3 are included.

Other conventional production inputs encompass 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

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

capital and seniority in the household), whether or not the manager is the head of the household (seniority), whether the plot manager had access to any credit in the 12 months

Table 1. Variable Definitions and Summary Statistics

Variable	Definition	Mean	Max.	Min.	Std. Dev.
Yield	Maize yield (kg/ha)	1,255	4,200	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= intercropping of legumes and maize	0.18	1	0	0.38
SWC	1= soil and water conservation structure	0.12	1	0	0.33
Fallow	Number of years since fallow	18	86	0	15
Trees	1= trees (agroforestry)	0.59	1	0	0.49
Location	1= 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	1,294	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	36,000	0	374
Manure	Manure application (kg/ha)	454	657,000	0	8425
Herbicide	Herbicide application (l/ha)	66	5,000	0	248
Fungicide	Fungicide application (g/ha)	2.6	2,000	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 000’ FCFA)	190	12,190	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.

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, farm size, 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.

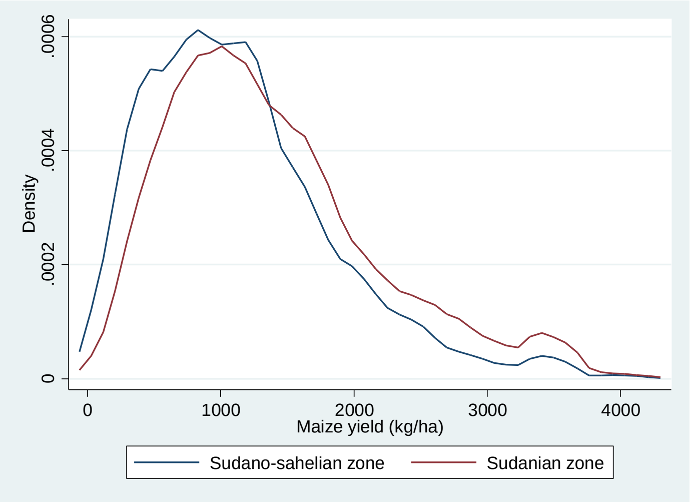
4. EMPIRICAL RESULTS

4.1. 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. Across years, only 40% of all maize plots were fertilized. Mean rates of nitrogen application at the plot level, including users and non-users, is 16 kg/ha. Not controlling for other covariates, the average yield without fertilizer use is ~970 kg/ha compared to ~1314 kg/ha with fertilizer use.

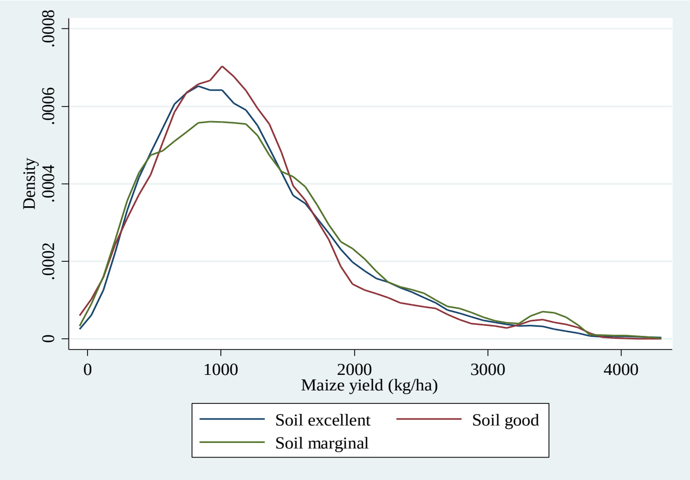
Figures 1 and 2 show the probability density functions of maize yields between zones and across soil types, respectively. All distributions tend to be positively skewed, with a long right tail. Regardless of the agro-climatic zones and soil types, there is a small number of plots that are highly productive,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

Figure 1. Probability Density Functions of Maize Yields between Agro-Climatic Zones



Source: Generated by the authors with the EPA dataset.

Figure 2. Probability Density Functions of Maize Yields across Soil Types



Source: Generated by the authors with the EPA dataset.

4.2. 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, are 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 control 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 (coefficient = 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 (coefficient = 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 (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. The presence of soil and water conservation structures positively affects 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 (Sawadogo and Kini 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 fertilizer 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 and good for maize production, compared to poor and marginal soils. In contrast, Koussombe and Nauge (2017) did not find a statistically significant relationship between soil quality and maize yields, but they measured soil quality in terms of the perception of the household head. 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.

Table 2. Maize Yield Function Estimation Results

Variable	CRE (1)	CRE (2)	CRE-CFA (3)	CRE-CFA (4)
N	2.93*** (0.739)	2.91***	17.31***	22.46***
		(0.886)	(3.81)	(4.55)
N*N	-0.013 ***	-0.014***	-0.015***	-0.016***
	(0.005)	(0.005)		(0.004)
Plot characteristics				
Area	112.3*** (21.48)	110.0***	146.1***	183.7***
		(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** (28.50)	70.28**	72.82** (31.23)	78.85**
		(28.76)		(30.95)
Fallow	0.732	1.049	0.321	1.215
	(0.719)	(0.716)	(0.768)	(0.761)
Trees	70.25*** (21.26)	62.58***	15.46	8.314
		(21.17)	(26.54)	(26.81)
Location	18.42	-1.576	-91.77** (39.38)	-120.0***
	(26.11)	25.66		(40.07)
Lowland	95.82** (45.98)	94.56**	264.77***	283.1***
		(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				
Plot manager characteristics		*(included)*		
Household characteristics				
Household time-averages				
Crop years				
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 these factors. Full analysis available from the authors.

No statistically significant yield differential is found between the Sudano-Sahelian and Sudanian zones, but 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. 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, Tappan, and Smale 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 eastern and southern Africa, with some under 15 kg/ha, most in the 10-15 kg/ha and few over 25 kg/ha. 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, Black, and Jayne (2013) 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.

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 given 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 yields. 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. Having access to credit last year and recently in contact with extension services was negatively associated with maize yields. Likewise, Somda et al. (2002) and Xu et al. (2009) found that farmers receiving advice from extension agents could be less likely to adopt organic manure and to get lower yields, respectively. 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 toward maize productivity. They do indicate that plot manager characteristics do influence yields and, therefore, that there is reason to 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. In Burkina Faso, agronomic research recommends 50 kg/ha of urea and between 150 and 200 kg/ha of NPK on maize (Holtzman et al. 2013), regardless of the agro-ecological conditions. The quantity of fertilizer N applied to plots (conditional on use) is the closest to recommendations in the Sudanian zone, but fell short nationwide. The gap is even more striking when we consider plots with no fertilizer applied.

On average, the agronomically optimal nitrogen application is 722 kg per hectare—a high value that is 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 an order of magnitude similar to ours.

Earlier research in Sub-Saharan Africa provides an interpretation. Stoorvogel, Smaling, and Janssen (1993) found 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). Henao et al. (1992) reported that nutrient depletion could reach 100 kg NPK/ha/year in Burkina Faso and Mali. Our results suggest continuous soil fertility depletion in the maize farming system. With a maximum value of 278 kg/ha of nitrogen, the turning point at which an additional kilogram of nitrogen no longer benefits the crop, lies outside the range of the data.

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 and poor/marginal soils	23	14-32	12	39	762
Sudano-sahelian and good soils	20	11-29	8	25	658
Sudano-sahelian and excellent soils	21	12-31	16	35	700
Sudanian and poor/marginal soils	22	13-31	24	41	717
Sudanian and good soils	19	10-28	9	37	612
Sudanian and 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.

Table 4. Marginal and Average Value-Cost Ratio under Various 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

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

Table 4 reports the MVCRs and AVCRs under each scenario, using the expected marginal product (22.14 kg/ha) and expected average product (22.38 kg/ha), respectively. 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.

At full market prices, AVCRs are below 2, indicating that fertilizer use is unprofitable regardless of farm gate prices for maize. The ratios rise above 3 with an official price subsidy of 50%, despite low farm gate prices for maize. At the official subsidized price, incentives to use fertilizer are strong (above 2 but below 3), overcoming price and production risks. Transactions costs erode the apparent advantages of the subsidy, however.

The confidence intervals in Table 3 exhibit wide variation in the average partial effect of nitrogen (from 13 kg/ha to 31 kg/ha). Even under suitable agro-ecological conditions for maize and fertilizer subsidies, it is not always profitable to use fertilizer on all maize plots. Further, the minimum average product for fertilizer use to be profitable (AVCR=2) lies in some instances outside the 95% confidence intervals (analysis available from the authors).

5. CONCLUSIONS

Intensification strategies that aim to boost productivity while protecting natural resources have become central to agricultural growth, especially in the West African Sahel, where land resources are limited, and population pressures heavy. For the most part, agricultural policies have emphasized the use of inorganic fertilizer use through subsidy programs. Yet, little is known about how agro-ecological conditions on farms affect fertilizer use and profitability. Here, we have examined how agro-ecological factors measured at several scales of analysis (plot, village, and zone) affect maize yield response to fertilizer and economic incentives for use.

We find that maize yield response to nitrogen in Burkina Faso is ~22 kg/ha, which is within the range reported in the few other similar studies conducted in the region. Productivity, as well as the marginal effect of nitrogen, differs significantly according to soil fertility. The marginal effect of nitrogen is stronger on less fertile soils and in the Sudano-Sahelien 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 optimal application rate for nitrogen predicted by the response function lies outside the range of the data, indicating that the use of additional fertilizer would be agronomically beneficial on all maize plots. Nitrogen use rates are on average only 16 kg/ha.

As expected in an uncertain farming environment with poorly developed markets for fertilizer, plot managers apply fertilizer at lower than the profit-maximizing rate. We find that while fertilizer use is unprofitable at full market prices, it is, on average, profitable if we assume that farmers benefit fully from the 50% fertilizer subsidy. Transaction costs diminish the benefits of the subsidy, and we know these to be widespread and household-specific. This conclusion complements that of Kousoubé and Nauges (2017), who argue the need to overcome supply-side constraints.

Our findings have important policy implications, supporting research from field trials (e.g., Kihari et al. 2016) with analysis of farm 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 crop responses and economic incentives vary widely across agro-ecological conditions. Policies that consider heterogeneity may be more effective in promoting sustainable input use by making it more profitable. As currently designed, the fertilizer subsidy program promotes maize, which is not well suited to all agro-ecologies in Burkina Faso. Programs targeted to a single crop may not be desirable, especially in the context of climate change. Although the subsidy enhances profitability (to the extent that it covers transactions costs), there may be more effective ways to make fertilizer more affordable to farmers. For instance, investing in road infrastructure and removing illicit tax collection could lead to significant cut in transactions costs while freeing up resources from the agricultural budget to enable other services, such as research and development and extension.

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