Fertilizer Intensification and Soil Fertility Impact on Maize Yield Response in Northern Ghana

by

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Abstract

Fertilizer use and intensity is low in Sub-Saharan Africa. Further, soil fertility has been declining over the years. These together have potentially been contributing to lower crop yields particularly for smallholder farmers. In this study we examine maize yield response to nitrogen in three Districts in Northern Ghana controlling for a number of covariates including soil fertility which have received less attention in the literature. Results show that soil fertility is crucial in increasing yields in Northern Ghana and increasing nitrogen per ha enhances maize yield up to a certain yield plateau beyond which further increases will not increase yields.

Keywords: nitrogen, maize yield, stochastic, fertilizer, Ghana

JEL Codes: Q12

Introduction

Most of the population in Sub-Saharan Africa (SSA) is rural where agriculture is the backbone and social fabric underpinning the livelihood of many households, millions of jobs and contributing a significant percentage to the Gross Domestic Product (GDP). For instance, agriculture contributed 30 percent to GDP and employed 42 percent of the total labor force in Ghana in 2010 (FAOSTAT 2014). Consequently, governments, international agencies, and researchers have been focusing more on growth in this sector as the oasis of hope for the majority of the smallholder farming population. However, agricultural productivity in SSA remains low and is falling farther behind other regions of the world (Fuglie and Rada (2012)). The low productivity growth is attributed to low education of the labor force, high rate of HIV/AIDS, armed conflicts, reliance on rainfed production rather than irrigation, and unfavorable economic policies experienced in most countries in SSA.

Although more than half of the developing countries (54 percent) have either met or are on track to achieving Millennium Development Goal 1 - eradicate extreme poverty and hunger by 2015, estimates from much of Sub-Saharan Africa (SSA) presents a gloomy picture (World Bank 2014). Partially expected to contribute in eradicating extreme poverty is growth in agricultural productivity. However, a seesaw trend has been observed in agricultural total factor productivity in SSA over the years and this warrants revisiting and attempting to answer the question of why there hasn't been consistent growth in agriculture as has been the case in other developing countries. Further, the abundant land in Africa (which include 60 percent of the global arable uncultivated land in the world (Asenso-Okyere and Jemaneh 2012)) necessitates research on how to increase agricultural productivity in SSA. Additionally, Asenso-Okyere and Jemaneh (2012) highlight that doubling cereal yields on the current millions of hectares cultivated by smallholder farmers would turn Africa into a major food surplus region. The question then is what has been and is the missing link.

A handful of studies have been conducted in East Africa examining the relationship between fertilizer use, soil fertility and yield. For example, Matsumoto and Yamano (2010) use a large household panel data and soil carbon content as an indicator of soil condition to investigate reasons for the low level of fertilizer application on farms in Kenya and Uganda. They find that soil carbon content has a significant positive effect on maize yield with a decreasing return on both of the seed types in Kenya. Marenya and Barrett (2007) study state-conditional fertilizer yield response on western Kenya using data from maize plots of smallholder farmers. They estimate the marginal returns to nitrogen fertilizer use and relate these estimates to soil organic carbon stocks using a switching regression model to determine the response of yield to applied nitrogen under two different systems indicating whether soil organic matter (SOM) or nitrogen (N) impose a greater limit on yields. They find a von Liebig-type association between soil organic matter (SOM) and maize yield response to nitrogen application. Low SOM commonly constrains the yield response to mineral fertilizer application.

Despite recognition in the previous literature of the impact of soil fertility to crop yield response to fertilizer inputs, e.g. Marenya and Barret (2009), many yield response studies have either omitted soil fertility or used proxies to capture the fertility status of farmers' plots. As a result or coincidentally, many fertilizer policies in SSA have generally ignored the importance of soil fertility in agricultural productivity (see e.g. Chapoto and Ragasa 2013; Sheahan et al. 2013; Xu et al. 2009; Sherlund et al. 2002). There are however a few exceptions which have included soil fertility in yield response analysis (see Ekbom et al. 2012; Marenya and Barrett 2007; Tittonell et al. 2008). As Sherlund et al. (2002) highlight, omission of soil fertility leads to biased estimates of the parameters describing the production frontier, overstating technical inefficiency and biased estimates of the correlates of true technical inefficiency.

Behind this backdrop, this study examines the impact of nitrogen, controlling for the effect of soil fertility, on maize yield in Northern Ghana using developments in the recent literature – stochastic plateau function which has been noted as the most suitable response function for modeling crop yield response (Tumusiime et al. 2011; Tembo et al. 2008; Marenya and Barrett 2007). We analyze the linear stochastic plateau response function using maximum likelihood estimation following Brorsen (2013). Results show that a one kg increase in nitrogen per ha will result in yield increase of 9 kg per ha. The linear stochastic plateau results show that the expected yield plateau is 1503 kg per ha which is two times higher than the current average yield for the three Districts under study. Additionally, results show the important role of soil fertility in enhancing maize yield. Based on these results, we recommend soil fertility investment programs, improvement in availability, accessibility, and affordability of nitrogen fertilizer and the need to make fertilizer recommendations area specific rather than one cap fits all.

The rest of the paper is organized as follows. Section 2 briefly discusses fertilizer use and intensity of use in SSA. Section 3 describes the empirical approach and means of estimation. This is followed by section 4 which gives a brief overview of the data used. Section 4 presents the results and discussion. Section 5 concludes.

Fertilizer use and low intensity of use in SSA

Fertilizer use and low intensity has been cited as one of the main factors hindering agricultural productivity growth in SSA (e.g. FAO, 2005 and Fuglie and Rada 2013). For instance, Maatman et al. (2007) and Morris et al. (2007) note that fertilizer usage in SSA is the lowest in the world, estimated at only 8kg/ha in 2002 – 10% of the world's average. Yet much of the projected growth in crop production in SSA is anticipated to be a result of intensification in the form of yield increases (Druilhe and Barreiro-Hurlé 2012). Many reasons have been ascribed to this low intensity of fertilizer use which include lack of access to credit, lack of knowledge on fertilizer use and high prices of fertilizers (Gregory and Bumb 2006; Marenya and Barret 2009).

Compounding the consequences of limited fertilizer usage is the accelerated soil fertility loss faced by much of SSA as noted by Morris et al. (2007). This adds on to the plethora of challenges farmers in SSA are facing as they try to increase their productivity and curb food shortages. Further, fertility of soils in many smallholder farming systems in SSA differ significantly at the farm and landscape level leading to differences in crop productivity and crop response to additions of fertilizer and organic nutrient resources (Zingore et al. 2007). Marenya and Barret (2009) provide evidence which suggest that soil organic matter significantly influence the economic returns to fertilizer inputs in the production of maize in western Kenya thereby providing an opportunity to exploit the economic complementarities of these two resources. Earlier, Vanlauwe and Giller (2006) note that there is a growing acknowledgement for the need to combine the applications of chemical fertilizer and organic resources to simultaneously tackle short-term crop nutrient demands and long-term increase in soil organic matter in SSA.

The major challenge has been that efforts aimed at encouraging farmers to use fertilizers in SSA do not capture the differences in soil fertility across farmers' fields. Failure to capture this heterogeneity in soil fertility across fields consequently denigrates efforts being made in addressing fertilizer usage enigma. Like in other countries in SSA, Ghana continues to heavily rely on blanket fertilizer recommendation which is uniform across geographic locations and crops disregarding differences in soil fertility. However, there has been heightened calls in Ghana to ramp up efforts to design and implement fertilizer programs that recognize the spatial variability of soil fertility and climatic conditions.

Empirical approach

Similar to estimation of any production function, the choice of functional form is one of the challenges we have to deal with. There are several debates as to the appropriate functional form to use in estimating crop yield response. On one hand, some authors argue that crop yield response can be estimated as a smooth, concave production function, for example the quadratic functional form (e.g. Chapoto and Ragasa 2013; Boyer et al. 2013; Sheahan et al. 2013; Xu et al. 2009; Kouka, Jolly, and Henao 1995; Bullock and Bullock 1994; Berck and Helfand, 1990). On the other hand, some authors argue that the linear response and plateau (LRP) is the most suitable response function for modeling crop yield response (Tumusiime et al. 2011; Tembo et al. 2008; Paris 1992). Another functional form which has also been used is the translog or Cobb-Douglas production function (Matsumoto and Yamano 2009; Sherlund et al. 2002). The choice of the appropriate functional form therefore remains an empirical issue. We use two different functional forms namely linear stochastic response plateau (LSRP) and quadratic production function. In order to examine the consequences of omitting soil fertility, we estimate the production function with and without the soil fertility variables.

The yield Y on maize field *i* from household *j* at time *t* is a function of several vectors:

$$Y_{ijt} = f\left(\boldsymbol{X_{ijt}}, \boldsymbol{V_{ijt}}, \boldsymbol{Z_{ijt}}, \boldsymbol{\mu_{ijt}}\right) \qquad (1)$$

where $\boldsymbol{X_{ijt}}$ is a vector of inputs chosen by the household (including fertilizer) as well as agro-ecological conditions; $\boldsymbol{V_{ijt}}$ is a vector of household-level characteristics that likely influence yield such as level of education of head of household; $\boldsymbol{Z_{ijt}}$ is a vector of soil fertility characteristics such as carbon content; and $\boldsymbol{\mu_{ijt}}$ is the error term vector containing unobservable characteristics of the production system including both time constant c_j and truly random variables ε_{ijt}. We estimated this model using the linear stochastic response plateau and quadratic production functions as described below:

Linear stochastic response plateau (LSRP)

The LSRP function assumes plant yield increases linearly with additional application of a limiting input (e.g. nitrogen) until a yield plateau is reached. At this point, other factors become output-limiting, thus any additional application of the earlier limiting input (i.e. nitrogen) does not lead to yield increase (Boyer et al. 2013; Tembo et al. 2008; Berck and Helfand 1990). Berck and Helfand (1990) highlight that there is lack of complete substitution possibilities in the LSRP model and that there is the need for combinations of inputs for plant growth. However, several studies have modelled yield response using the linear response plateau model (e.g. Ackello-Ogutu et al. 1985; Cerrato and Blackmer 1990; Llewelyn and Featherstone 1997; Marenya and Barrett 2007). These studies among others have generally concluded that the LSRP model explain crop response to nitrogen better than polynomial specifications. The conventional linear response plateau (LRP) model developed by Berck and Helfand (1990) and Paris (1992) is specified as:

$$y_{ijt} = \min\left(\beta_0 + \beta_1 X_{ijt}, \mu\right) + \varepsilon_{ijt}, \quad (2)$$

where y_{it} is the maize yield (kg/ha) from the i^{th} plot in year t; β_0 and β_1 are the yield response parameters; X_{it} is the level of the limiting input; μ is the expected plateau yield parameter in kg/ha; and $\varepsilon_{itj} \sim N(0, \sigma_e^2\ )$ is the random error term.

Tembo et al. (2008) extended this conventional LRP by including normally distributed plateau and year random effects. The inclusion of a stochastic plateau in the LRP model has been found to be a better fit than a non-stochastic plateau (Tumusiime et al. 2011; Tembo et al. 2008; Kaitibie et al. 2003).Thus equation (2) is re-specified as:

$$y_{ijt} = \min\left(\beta_0 + \beta_1 X_{ijt}, \mu + v_t\right) + u_t + \varepsilon_{ijt}, \quad (3)$$

where v_t is the plateau random effect, u_t is the (intercept) year random effect and the other variables in equation (2) are the same as in equation (1).

Another specification would have been to include slope random effect or intercept random effect but as noted by Boyer et al. (2013), this will require additional years of data in order for the model to converge. Thus we do not include the slope random effects in our model given our dataset.

However, Burke (2012) argues that the assumption used by the linear response stochastic plateau model and other von Liebig models that either the limiting factor of production is known, or, if unknown, is the same for all observations makes these models less appropriate to survey data as compared to test field data due to heterogeneity among households. Another shortcoming of the LRSP which has been noted in the literature is the assumption that the yield increases linearly up to the plateau and this should not be necessarily the case. As a remedy, other studies (e.g. Boyer et al. 2013; Tumusiime et al. 2011) have also estimated the quadratic stochastic response plateau (QSRP) function. Boyer et al. (2013) uses likelihood ratio test to compare the QRSP and the LRSP and they find no statistically significant difference between these models. They further note that since the quadratic terms in the QRSP were not significant, the LRSP fits the data well. Similarly, Tumusiime et al. (2011) compares QSRP and LRSP using Likelihood Dominance Criterion (LDC) and their results show that LRSP provides the best fit. Thus based on these findings, we use the LRSP function.

Following Tembo et al. (2008), optimal nitrogen – nitrogen used at the plateau, can be estimated from the LSRP as follows: assuming that the smallholder farmers want to maximize their expected profit,

$$E(\pi_{it}|N_{it}) = pE(y_{it}) - wN_{it} \qquad (4)$$

where p and w are output and input prices respectively, and $E(\pi_{it}|N_{it})$ is expected profit. Tembo argues that since we have plateau and year random effects in the LSRP, optimal nitrogen level has can be derived using theorems developed for Tobit models. Substituting for $E(y_{it})$ with equation (3), equation (4) becomes:

$$E(\pi_{it}|N_{it}) = p\left[(1-\theta)(\beta_0 + \beta_1 N_{it}) + \theta\left(\mu - \frac{\sigma_v \varphi}{\theta}\right)\right] - wN_{it} \qquad (5)$$

where $\theta = \theta[(\beta_0 + \beta_1 N_{it} - \mu)/\sigma_v]$ is the standard normal cumulative distribution and $\varphi = [\varphi(\beta_0 + \beta_1 N_{it} - \mu)/\sigma_v]$ is the standard normal probability density function. Differentiating with respect to N_{it} and solving

$$N_{it}^{*} = \frac{1}{\beta_1}(\mu - \beta_0 + \theta^{-1}\sigma_v) \qquad (6)$$

where $\theta^{-1} = \theta^{-1}(1 - \frac{w}{p\beta_1})$ is the inverse of the standard normal cumulative distribution function assuming that $\beta_1 \geq w/p$ or else zero N_{it} would be optimal. For full derivation of equation (6), we refer readers to Tembo et al. (2008). We estimated both equation (3) and equation (5) in order to get the optimal nitrogen at the plateau.

Quadratic production function

The quadratic form of the production function (equation 7) has been widely used for crop yield response to nutrient functions.

$$Y_{ijt} = \beta_0 + \beta_1 X_{ijt} + \beta_2 X_{ijt}^2 + \sum_{k=1}^{m} \gamma_k T_k + \varepsilon_{ijt}, \qquad (7)$$

where X_{ijt} are inputs and $\boldsymbol{T_k}$ is a vector of other control variables such as demographic and soil characteristics.

The quadratic production function assumes that increasing an input like fertilizer increases yield until a point is reached beyond which any further increase in that input leads to a decrease in yield (Ricker-Gilbert et al. 2009). According to Berck and Helfand (1990), the difference between the quadratic and the LRP is that the quadratic function permits substitution between inputs to plant growth. Many others who adopted this functional form have also cited its ability to permit zero inputs, capture temporal variability and concavity in the yield response curves (e.g. Chapoto and Ragasa 2013; Sheahan et al. 2013; Burke 2012; Xu et al. 2009; Traxler and Byerlee 1993; Kouka et al. 1995). Belanger et al. (2000) compared three statistical models namely quadratic, exponential, and square root to describe the yield response of potato to nitrogen fertilizer and concluded that the quadratic model fitted the data with less bias than the other two models.

Data

This paper uses household-level panel survey data implemented by the Innovations for Poverty Action (IPA) in three districts (Savelugu-Nanton, Tamale Metropolitan and West Manprusi) in the Northern region of Ghana between 2009 and 2012. The initial sample was drawn from the Ghana Living Standards Survey 5 Plus (GLSS5+) survey data, a survey conducted from April to September 2008 by the Institute of Statistical, Social and Economic Research (ISSER) at the University of Ghana – Legon in collaboration with the Ghana Statistical Service. The GLSS5+ was a clustered representative random sample, with households randomly chosen based on a census of selected enumeration areas in the 23 Millennium Development Authority (MiDA) districts. From the GLSS5+ sample frame, IPA selected communities to undertake a survey "Examining Under Investment in Agriculture (EUI)" survey in these three districts. Map 1 shows the map of the study area. Though these districts are in the Northern region which is relatively dry due to their proximity to the Sahel and Sahara desserts (average rainfall of 700 mm during the years of the survey), agricultural production is the major absorbent of the economically active population. According to Ghana Ministry of Food and Agriculture, Statistics, Research and Information

Directorate (SRID 2011), the Northern region accounted for 9 percent of the total maize production in Ghana over the period 2006-2010.

Data collected include maize yield for the household, quantity and type of fertilizer used, quantity and type of seed used, soil characteristics – such as carbon content, cropping method – mono-cropping or intercropping, labor used (both family and hired), demographic characteristics such as age of household head and his/her education level. Additionally, data was also collected for method of ploughing – hand, bullock or tractor, rainfall, and value of livestock.

For soil characteristics, soil samples were collected from randomly selected household plots. A total of 2600 samples from 1040 households were collected but 1030 of these samples were discarded because they were soaked by rains before they could correctly be stored. With funding from the International Food Policy Research Institute (IFPRI), the remaining 1570 soil samples were sent to the Soil Research Institute of The Council for Scientific and Industrial Research (CSIR/SRI) for analysis. Map 2 shows the distribution of the soil samples in the three districts as well as the distribution of samples that were discarded. Most of the samples that were spoilt were collected in Savelugu-Nanton (79 percent), with 15 percent coming from Tamale. To ensure that the maps were more representative, in Tamale Metropolitan and Savelugu-Nanton, communities were selected where the sampling points were less sparse to show whether there was any significant variation in the selected soil parameters at a much lower geographic level (Maps 2). In addition, data from West Manprusi and the southern part of Savelugu-Nanton were used to show the variation of the soil fertility parameters for much larger geographic areas. In general, this study is based on 1570 samples from 270 plots in Tamale Metropolitan, 652 plots in West Manprusi, and 648 plots from Savelugu-Nanton.

Summary statistics are presented in Table 1. Average maize yield per ha was 624 kg against an average yield registered by the Ministry of Agriculture for the whole country in 2010 of 1,900kg per ha and an estimated achievable yield ranging from 2,500 to 4,000 kg per ha. There is variability in both yield and nitrogen application on average in the three districts as presented in Table 2. West Manprusi had the lowest average nitrogen application rate of 12 kg per ha corresponding to a yield of 513 kg per ha followed by Savalegu-Nanton with 17 kg per ha corresponding to a yield of 714 kg per ha and Tamale-Metropolitan has the highest nitrogen application rate of 19 kg per ha and a yield of 773 kg per ha.

Results

Maximum likelihood estimates of the LRP model estimated using SAS 9.2 PROC NLMIXED procedure are presented in Table 3. Estimates from the quadratic model are presented in Table 4. The first column is for the model which include soil characteristics measures and the second one is for the model without these soil characteristics measures.

For the LSRP model, four of the six parameters are significant at the 1% level. However, the plateau and year random effects are all insignificant indicating that the plateau is non-stochastic as has been assumed in some prior work. These results show that if zero nitrogen is applied the expected yield is 521 kg per ha and for each kg of nitrogen applied the yield will increase by 9 kg. The expected plateau yield is 1503 kg per ha with the optimal nitrogen equal to 110 kg per ha.

Generally, estimates from the quadratic model have plausible and expected signs. Nitrogen, carbon content, method of plowing, weedicide application and value of livestock all have positive and statistically significant impact on maize yield. Our main variables of interest are nitrogen and soil fertility/characteristics. Estimate for nitrogen indicates that the marginal product of nitrogen (calculated at the data mean) is 9.94. Though both soil texture variables are insignificant (sandy soils and loamy coarse soils), carbon content is positive and statistically significant indicating that each additional percent of carbon content increases yield by 204.1 kg per ha. Regarding carbon content as a measure of soil fertility as in prior studies, this estimate highlight the critical role of soil fertility in increasing yields. Estimates for nitrogen with each of these soil variables are all insignificant and we drop them from the model. Examining other estimates, using mechanical plowing increases yield more than conventional plowing. The benefit from using mechanical plowing over conventional means is 118 kg per ha.

Total land cultivated and intercropping have expected negative and statistically significant impact on yield. The more cultivated land a household has, the higher the potential that the household may not be able to apply the required nutrients like nitrogen. That is, there is decreasing returns to cultivated land expansion. The negative impact of intercropping with other crops, which may not nitrogen fixing like legumes (e.g. beans), could be a result of those particular crops competing with maize for the applied nitrogen or any of the other limited nutrients already available in the field. Additionally, age of head of household is negative and statistically significant.

Comparing quadratic model estimates from the first model with all variables and the second one without the carbon content and soil texture variables, the results are generally similar both qualitatively and quantitatively.

Results reaffirm the critical role nitrogen plays in maize production in the Northern region in Ghana. These results further show that nitrogen application is yield enhancing to a certain point and any further increase, while other inputs are held constant, will not increase yield. Though estimates from models with and without soil fertility variables are similar, the high positive and statistically significant impact of carbon content on maize yield is worth noting. Additionally, cultivated land expansion negatively affects yield. Thus, policy framework should be focused on intensification of fertilizer usage and soil fertility enhancement rather than expanding cultivated land if maize yield is to be increased. Several pathways for the accomplishment of this goal exist which include removing bottlenecks in availability, affordability, and accessibility to nitrogen fertilizer. Given the higher gains from plowing using mechanical means, programs which enable households to have access to these mechanical methods such as renting these tractors and pay when they harvest could prove useful in increasing maize yield.

Conclusions

We investigate maize yield response to nitrogen in Northern Ghana using survey data on farming households in Savelugu-Nanton, Tamale Metropolitan and West Manprusi Districts. Ghana, like most of the countries in Sub-Saharan Africa, has a significant portion of its population engaged in smallholder agricultural production. However, most of these smallholder farmers/households have very low yields from maize production. Fertilizer use and intensity is very low at about 15 kg per ha on average in these three district. We use linear stochastic response plateau and quadratic functions to examine how maize yield responds to both nitrogen and soil fertility measures while controlling for soil management practices such as manure application, method of plowing – mechanical or conventional and demographic characteristics – age of head of household and education level of head of household among other covariates.

Results show that a one kg increase in nitrogen per ha will result in yield increase of 9 kg per ha. However, increase in cultivated land is counterproductive. The linear stochastic plateau results show that the expected yield plateau if 1503 kg per ha which however is below the average maize yield in Ghana but two times higher than the current average yield for these three Districts. Based on these results, we recommend policies aimed at helping these smallholder farmers to intensify their use of inputs such as nitrogen. This could be done by reducing barriers to access of nitrogen as well as educating these households the gains from intensifying nitrogen usage.

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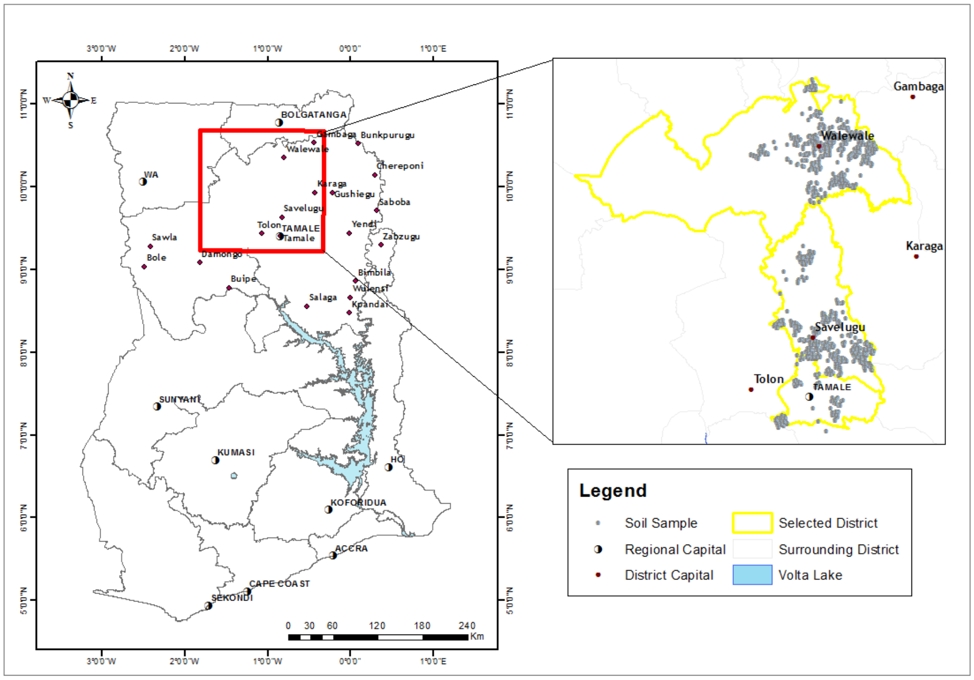
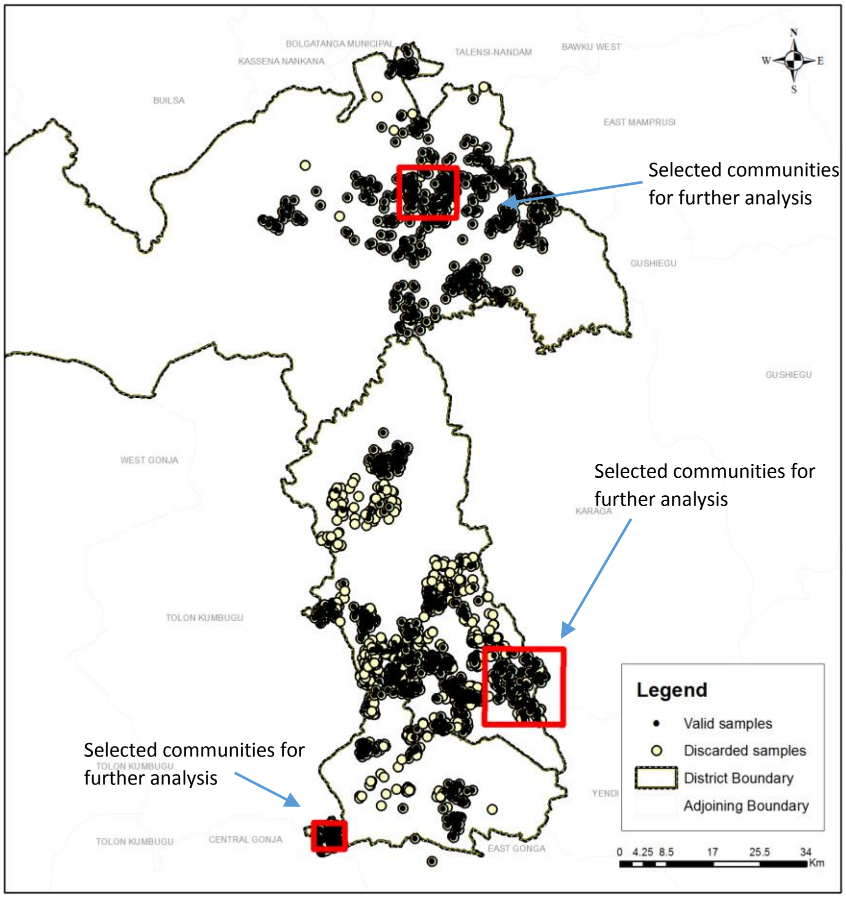
Map 1. Study Area



Source: EUI Survey 2011, Northern Ghana

Map 2: Distribution of Soil Samples in Study Districts



Source: EUI Survey, Northern Ghana 2011

Table 1. Summary Statistics

Variable	Mean	Standard Deviation	Minimum Value	Maximum Value
Maize harvested (kg/ha)	624.29	597.54	22.69	7260.73
Applied nitrogen (kg/ha)	14.45	30.80	0	408.42
Available phosphorous (kg/ha)	26.77	28.24	1.2	235.2
Soil PH	6.39	0.53	3.36	8.04
Plot size (ha)	2.42	2.13	0.20	28.28
Labor (total person-days used)	80.82	75.87	0	581
Carbon content (C) (% by weight)	0.91	0.49	0.16	3.81
Conventional plowing (=1)	0.08	0.27	0	1
Mechanical plowing (=1)	0.91	0.69	0	1
Sandysoils (=1)	0.25	0.43	0	1
Loamy coarse soils (=1)	0.50	0.50	0	1
Intercropping (=1)	0.58	0.49	0	1
Applied weedicide (=1)	0.14	0.34	0	1
Applied manure (=1)	0.22	0.42	0	1
Head of household age (HoH)	46.18	15.44	20	91
Education of HoH (years of education)	2.97	6.37	0	30
Value of livestock (Ghc - Ghananian Cedi)	1374.34	3782.95	0	67732.47

Table 2. Average Yield and Nitrogen Applied (kg/ha) by District

District	Maize harvested (kg/ha)	Applied nitrogen (kg/ha)
Savalegu-Nanton	714.85	16.59
Tamale Metropolitan	773.41	18.70
West-Manprusi	512.93	11.63

Table 3. Linear Response Plateau Model Estimates for Maize Yield (kg/ha) Response to Nitrogen

Parameter	LRSP Estimates
Intercept (b0)	521.34***
	(41.90)
Nitrogen (b1)	8.94***
	(1.41)
Plateau yield	1503.46***
	(238.76)
Plateau random effect	0.000322
	(2696.23)
Year random effect	16.71
	(29.35)
Random error term	3201.54***
	(195.89)
Optimal Nitrogen Level	109.93
-2 log likelihood	8395.2

Standard errors in parenthesis
*** $p<0.01$

Table 4. Estimates for the Quadratic Model

	Dependent Variable: Maize yield (kg/ha)	Dependent Variable: Maize yield (kg/ha)
	Quadratic Model With Soil variables	Quadratic Model Without Soil Variables
Nitrogen (kg/ha)	10.36***	9.399***
	(2.518)	(2.036)
Nitrogen squared	-0.0288***	-0.0262***
	(0.00687)	(0.00512)
Phosphorous (kg/ha)	-0.0321	
	(4.417)	
Phosphorous squared	-0.00344	
	(0.00983)	
Soil PH	-9.172	
	(44.62)	
Phosphorous*PH	0.0655	
	(0.651)	
Carbon content	204.1**	
	(102.9)	
Carbon squared	-41.21	
	(29.03)	
Sandy soils (=1)	-28.10	
	(75.85)	
Loamy coarse soils (=1)	-40.40	
	(75.41)	
Plot size	-52.11***	-48.91***
	(15.97)	(17.01)
Plot size squared	1.721***	1.567**
	(0.628)	(0.648)
Labor used	0.713	0.605
	(0.670)	(0.626)
Labor used squared	0.00116	0.00144
	(0.00170)	(0.00162)
Intercropping (=1)	-244.0***	-257.9***
	(61.15)	(55.65)
Applied weedicide (=1)	110.5	143.5**
	(70.04)	(66.62)
Applied manure (=1)	-35.92	-34.25
	(54.08)	(53.97)
Mechanical plowing (=1)	304.8***	293.2***
	(104.2)	(92.76)
Conventional plowing (=1)	186.7*	194.3*
	(104.8)	(99.87)
Head of household age (HoH)	-3.681***	-3.944***
	(1.240)	(1.212)

Education of HoH (1=no education)	3.463	3.436
	(5.008)	(4.918)
Value of livestock	0.0306*	0.0278*
	(0.0184)	(0.0168)
Intercept	435.9	531.3***
	(312.9)	(123.5)
Number of observations	530	537
R^2	0.30	0.29

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