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# Effects of Nitrogen and Carbon Application on Maize Output in Ntcheu and Dedza Districts of Central Malawi

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## Abstract

This paper uses a translog stochastic frontier model to estimate the relationship between maize yield and an interplay of soil carbon, soil nitrogen and inorganic nitrogen fertilizer using plot-level data collected from smallholder farmers in Dedza and Ntcheu Districts of Malawi in 2013/2014 growing season. One of the covariates in the model is nitrogen applied to a plot from inorganic fertilizers. Farmer use of nitrogen is influenced through participation in a non-random targeted Farm Inputs Subsidy Program (FISP) of the Malawi Government. A control function approach is therefore applied to correct for possible endogeneity of participation in the FISP.Results show that inorganic nitrogen fertilizer has significant positive effect on maize output whereas an increase in soil carbon is associated with low maize output but interaction between soil carbon and soil nitrogen as well as with inorganic nitrogen significantly increases maize output. These results seem to be linked to Carbon to Nitrogen (C:N) ratio in the soil. The accumulation of C beyond the optimal C:N ratio is known to reduce rate of decomposition, nutrient cycling, shoot: root ratio and biomass in grasses including maize. Under such circumstances, increasing nitrogen brings the C:N ratio to beneficial levels. The results further show that inorganic nitrogen is a substitute to labour, seed and land. The substitution relationship suggests that improvements in inorganic nitrogen require reduction in labour, seed use and land. It has further been shown that only 45.03% of the plots have marginal value cost ratios of greater than one which shows that considerable number of plots are not profitable. For 66.20% of the plots, applied inorganic nitrogen fertilizer exceeds optimal levels signifying suboptimal use of the input. The results suggest that inorganic nitrogen is profitable at low levels of application which is largely due to prevailing high nitrogen-maize price ratio. The prominent issue for policy consideration from these results is that soils in Malawi are depleted of nitrogen leading to unfavorably high C:N ratios which negatively impact maize production. Given that nitrogen-maize price ratio is already high in Malawi, farmers will need programs that enhance their access to nitrogen fertilizers at low prices for nitrogen fertilizer application to be profitable. Such programs need to be implemented simultaneously with a package of intensification practices that fix and retain nitrogen in the soil.

**Keywords:** Inorganic nitrogen, Soil carbon, Soil nitrogen, Translog stochastic frontier model, Control function approach
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## 1. Introduction

It is widely believed that sustainable agricultural productivity growth in sub-Saharan Africa will require much greater usage of inorganic fertilizer and improved seed, along with management practices that maintain and improve soil fertility (Snapp *et al*., 2014, Chianu *et al*., 2012). Nevertheless, limited use of nutrient inputs, gaseous losses, soil erosion and the general soil land degradation in the region present a fundamental food production challenge (Muyayabantu *et al*., 2012). Thus, meeting food demand for the growing population has remained an integral part of research and development agenda in the region.

In Malawi, maize is grown on 70% of smallholder land and is primarily for consumption, with only 15% sold on the market (MoAFS, 2011; Jayne *et al*., 2010). Land holdings are very small, with over 80% below one hectare of land, and are continuing to fragment due to population growth, sub-divisions, and conversion of farmland to housing and other uses. In this environment, agricultural productivity growth will require greater concentration of inputs and soil-augmenting practices to achieve sustainable increases in productivity (Chirwa, 2005; Katengeza *et al*., 2012; Smale, 1995).

Efficient use of fertilizer potentially enhances agricultural productivity (Dittoh *et al*., 2012) but in Malawi its gainful use is hindered by diverse factors. For instance, high retail fertilizer prices have excluded most poor smallholder farmers from accessing inorganic fertilizers (IFDC, 2013). Furthermore, despite the country having heterogeneous biophysical and ecological conditions, fertilizer application rates for various crops are based on generalized recommendation (Mutegi *et al*., 2015). Such factors limit potential of farmers to optimize crop production even if inorganic fertilizer is used.

To improve smallholder maize yields, the Malawi Government has been implementing various forms of fertilizer subsidy programs for over two decades. It is however not clear whether current levels of fertilizer use can be sustained without continued subsidization. The evidence is mixed but some studies show that smallholder farmers get highly variable crop response to fertilizer application, which points to varying profitability of fertilizer across farm households and limited demand for fertilizer when obtained at commercial market prices (Snapp *et al*., 2014; Dorward *et al*., 2008). Evidence from the crop science and agronomy literature indicates that crop response to fertilizer (and hence its profitability) depends on soil characteristics that are highly influenced by the continuous adoption of integrated soil fertility management practices (Snapp *et al*., 2014).

To guide policy decisions in a backdrop of fertilizer use challenges, there is growing need to understand how productivity relates to soil nutrients and nutrients supplied through application of inorganic fertilizers. However, a gap in empirical evidence exists on such yield-input relationship with respect to maize and other key food security crops in Malawi. Studies have focused on general effects of subsidy fertilizer on yield (Ricker-Gilbert *et al*., 2009; Chibwana *et al*., 2014; Holden, 2013) or on the general effect of fertilizer input on yield within a production frontier framework (Tchale, 2009; Tchale and Sauer, 2007; Simwaka *et al*., 2013).

As Whitbread *et al*. (2013) noted, few studies have examined maize yield responses to nitrogen under farmer managed conditions. This paper presents an assessment of the effect of soil carbon, nitrogen, both from inorganic fertilizer sources and from the soil (soil nitrogen), and the interaction effect of carbon and nitrogen on maize yield. Analysis follows control function approach to address the endogeneity of nitrogen from subsidized fertilizer input. Estimation of a stochastic production frontier within an econometric framework that controls for endogeneity, is a first application to the assessment of the effects of nutrient use on maize yield in Malawi.

The rest of paper is organized as follows: Section 2 presents a review of literature on maize productivity. A theoretical model, which is the basis of the analytical model for the study, is covered in Section 3. Section 4 outlines the empirical model, while Section 5 describes the data. The results of the analysis are presented in Section 6 before presenting conclusion and recommendations in Section 7.

## 2. Literature Review on Maize Productivity

In most soils, the use of inorganic nitrogen and phosphorus fertilizers as well as the application of organic fertilizers such as farm yard manure increase maize yield (Oad *et al*., 2014; Ademba, 2009; Ademba *et al*., 2015; Mutegi *et al*., 2012; Nasim *et al*., 2012). Applied nitrogen reduces the impacts of *Striga hermonthica* damage to maize yields (Ademba, 2009) and there is evidence that the combination of organic and inorganic fertilizers is superior to the application of organic or inorganic fertilizers separately (Mutegi *et al*., 2012).

Some studies have shown that inorganic fertilizers alone can improve maize yield (Jiang and Schulthess, 2005; Amin, 2011; Crista *et al*., 2014; Le Silva *et al*., 2006; Woldsenbet and Haileyesus 2016) while others have argued that the use of organic fertilizers alone is more superior in enhancing maize yields than inorganic fertilizers. Achieng *et al*. (2010) found that use of farm yard manure is the best bet for maize production on both Alfisols and Ultisols because there was no significant yield advantage from inorganics over farm yard manure. Supporting this argument, Okonmah (2009) and Boateng *et al*. (2006) observed that application of poultry manure increases maize yield.

Impact of fertilizers on maize yield is sometimes affected by location factors. In China, Gao *et al*. (2009) found different yield response rates between northeast, northcentral, and northwest regions with total macronutrient accumulation being higher in the northwest compared to the other two regions. Mugwira *et al*. (2007) evaluated the effects of manure and inorganic fertilizer on maize growth, yield, and nutrient uptake at Grasslands Research Station and Matiza in Chihota communal area from 1983/84 to 1988/89 as a part of a wider project on sandveld soils in Zimbabwe. The study concluded that feedlot manure was effective in correcting deficiencies of N, P, or Mg at the Grasslands. However, application of both manure and inorganic fertilizer had no significant effect on poor status of nutrients of soils at Matiza location.

Ajayi *et al*. (2005) assessed the effect of fertilizer tree fallows on maize yield in several trials. The study found that apart from increased maize yields, fertilizer tree fallows were more profitable than continuous maize cultivation without fertilizer. However, the fallows were less profitable than fully fertilized plots, especially when the fertilizer was subsidized. The fertilizer tree system is a low-cost investment that requires less labour over its full cycle than other land uses over the same period of time. The results suggested that lasting fertilizer tree fallow systems can generate lasting environmental impacts such as improved soil structure, increased carbon sequestration and reduced cutting of woodlands for fuelwood.

Mango *et al*. (2015) analyzed technical efficiency of maize production among smallholder farmers in Zimbabwe. The study found that maize output is positively influenced by inorganic fertilizers, seed quantity, the use of labour and area planted. The results also showed that the average efficiency of maize production could be improved by 35 percent through better use of existing resources and technology. Njenga (2013) studied the effect of fertilizer input subsidy on maize production in Wareng District, Kenya. The results indicated that an extra subsidized bag of fertilizer applied increased the number of maize bags produced per acre by 14.3 percent. Access to research and extension services, being a male farmer, access to credit, and use of improved seed (hybrids) increased maize productivity.

## 3. Theoretical Framework

Smallholder farmers make numerous input allocation decisions in maize production to maximize output given the available inputs and other constraints. The random utility principle underscores the choices farmers make in maize production. A farmer may fail to reach optimal production due to random shock, technical inefficiency or both. Kassie *et al.* (2014) observed that the agricultural production environment in sub-Saharan Africa, where smallholder farmers operate under uncertainty conditions, requires application of a stochastic production frontier to account for both technical inefficiency and random errors.

This paper takes the stochastic nature of agricultural production into account and applies a control function approach to correct for possible endogeneity of participation in the Malawi Farm Input Subsidy Program (FISP). This is important because the selection of FISP beneficiaries is not random but rather based on some defined criteria (Ricker-Gilbert and Jayne, 2009; Liverpool-Tasie, 2014; Darko and Ricker-Gilbert, 2013; Namonje-Kapembwa *et al*., 2017; Aloyce *et al*., 2014).

In a production function framework, consider a *k*th farmer who allocates conventional inputs, $x_k$, which along with other productivity shifters, $z_k$, affect maize output, $y_k$. This relationship in a stochastic production function is specified as:

$$y_k = f(x_k, z_k, \beta) + \varepsilon_k \text{ where } k = 1,2,\ldots n \text{ and } \varepsilon_k = v_k - \mu_k \tag{1}$$

In (1), $\beta$ is a vector of unknown parameters to be estimated. The composite error term, $\varepsilon_k$, captures unobservable characteristics that affect maize output and has two elements: a symmetrical two sided normally distributed disturbance term ($v_k$) reflecting the stochastic effects that cannot be controlled by a farmer; and an asymmetric non-negative error term ($\mu_k$) which is a one sided ($\mu_k \geq 0$) efficiency component for the *k*th farmer, thus $\varepsilon_k = v_k - \mu_k$ (Battese and Coelli, 1995).

Maize output response associated with additional use of an input is measured by the marginal product of the input which can be derived from (1) by taking partial derivative of $y_k$ with respect to $x_k$ as follows:

$$mp_{kj} = \frac{\partial y_k}{\partial x_{kj}} \tag{2}$$

where $mp_{kj}$ is marginal product of input *j* for a *k*th farmer and $x_{kj}$ is input *j* for a *k*th farmer.

Partial production elasticities of maize output with respect to the inputs can be computed as ratio of marginal product to average product and is defined as:

$$e_{kj} = \frac{\partial y_k}{\partial x_{kj}} * \frac{x_{kj}}{y_k} \tag{3}$$

where $e_{kj}$ is partial output elasticity of a *k*th farmer with respect to of input *j*. Elasticity of scales, *es,* which measures returns to scale of the technology can then be computed as the sum of all output elasticities as follows:

$$es = \sum e_{kj} \tag{4}$$

Technical similarity of factors of production in (1) can be measured by elasticity of substitution which captures degree to which one input can be substituted for another without changing quantity of maize output. Given that input $x_{kh}$ and input $x_{kq}$ are a subset of inputs *j* defined in (2) and (3), elasticity of substitution, $eos_{hq}$ of the two inputs is defined as:

$$eos_{hq} = \frac{\partial x_{kh}}{\partial x_{kq}} * \frac{x_{kq}}{x_{kh}} \tag{5}$$

where, the expression $\frac{\partial x_{kh}}{\partial x_{kq}}$ is marginal rate of technical substitution between input $x_{kh}$ and input $x_{kq}$.

Optimal level for each input in (1) can be determined as level of the input at the point where marginal value is equal to input cost. At this point, the marginal value–cost ratio is equal to one and a risk neutral farmer registers positive benefits from using the input (Liverpool-Tasie *et al*., 2017). For a *k*th farmer, marginal value–cost ratio of *j*th input is derived as follows:

$$mvcr_j = \frac{p_y}{p_j} * mp_{kj} \tag{6}$$

where $mvcr_j$ is marginal value–cost ratio, $p_y$ is price of maize, $p_j$ is price of an input and $mp_{kj}$ is marginal product of a given input as defined in (2).

Given the actual maize output, $y_k$, in (1), and the highest predicted maize output for the *k*th farmer given the available technology, $y_k^*$, the technical efficiency ($te_k$) of an individual farmer is computed as:

$$te_k = \frac{y_k}{y_k^*} = \frac{f(x_k, z_k, \beta)\exp(v_k - \mu_k)}{f(x_k, z_k, \beta)\exp(v_k)} = \exp(-\mu_k) \tag{7}$$

where parameters $x_k$, $z_k$, $\beta$, $v_k$ and $\mu_k$ are as defined in (1). $te_k$ has values between 0 and 1 and a farm is technically efficient when $te = 1$. Based on Battese and Coelli (1995), maize output gap in terms of technical inefficiency and its determinants is expressed as follows:

$$\mu_k = f(T_k, \delta) + \xi_k \tag{8}$$

where $T_k$ is a vector of covariates explaining technical inefficiency, $\delta$ is vector of unknown parameters to be estimated and $\xi_k$ is error term.

For consistent estimation of stochastic production frontier (Equation 1), the assumption that explanatory variables $x_k$ and $z_k$ are exogenously determined must hold (Amsler *et al.*, 2014). One of the covariates in this study is nitrogen from inorganic sources, which is accessed through participation in FISP thereby potentially violating this assumption. To correct for this endogeneity, a control function approach following Darko and Ricker-Gilbert (2013) and Namonje-Kapembwa *et al.* (2017) was employed.

The estimation procedure entailed inclusion of residuals computed from auxiliary model of participation among the factors explaining technical inefficiency in (8). A probit auxiliary model was used to analyze the two possible alternatives of either participating or not participating in FISP. The conditional probability, *Pr*, of the probit model, given binary outcome, *S*, for participation in FISP is as follows:

$$Pr(S_k = 1 \mid H) = f(H_k{}'\varphi) \tag{9}$$

where $H_k$ is a vector of explanatory variables including exclusion factors and covariates, $T_k$ is defined in (8) and $\varphi$ is a vector of parameters to be estimated. The model in (9) is non-linear and is estimated through maximum likelihood procedure as follows:

$$S_k = f(H_k{}'\varphi) + \in_k \tag{10}$$

where $\in_k$ is an error term with mean zero and independently and normally distributed. Computed residuals, $\Gamma_k$, from Equation (10) are included among explanatory variables in the inefficiency model to control for endogeneity. Thus, (8) is redefined as:

$$\mu_k = f(T_k, \Gamma_k, \delta) + \xi_k \tag{11}$$

Standard errors are adjusted for the two-step procedure through bootstrapping because the conventionally-calculated standard errors from the Step 2 estimation are incorrect (Bezu *et al.*, 2013; Amsler *et al.*, 2014).

## 4. The Empirical Model

A translog stochastic frontier model was specified to estimate the relationship between maize output and an interplay of soil carbon, soil nitrogen and inorganic nitrogen fertilizer. Unlike a linear production function, the translog production function flexibly measures interaction effects of inputs. Three functions were estimated using the maximum likelihood technique to analyze sensitivity of findings to model specification. Model 1 estimated equations (1) and (7) jointly without correcting for endogeneity of participating in FISP which is controlled in the other two models. Models 2 and 3 estimated (1) and (11) using conventionally-calculated and bootstrapped standard errors, respectively. The estimated frontier function is specified as:

$$lny_k = \beta_0 + \sum_{k=1}^{K} \beta_k \ln(x_k) + \frac{1}{2}\sum_{k}^{K-1}\sum_{i=k+1}^{K} \rho_{ki} \ln(x_k)\ln(x_i) + \sum_{w=1}^{W} \phi_w z_w + \varepsilon_k \tag{12}$$

where $y_k$ is maize output (kg) and $x_k$ constitutes the following conventional inputs: inorganic nitrogen fertilizer (kg), labour (labour-days), maize seed (kg) and farming plot (ha). Factors included in vector of productivity shifters, $z_w$, are soil nitrogen (%), soil active carbon (%), location dummies for Linthipe, Golomoti and Kandeu Extension Planning Areas, an interaction term for soil nitrogen and soil carbon, and an interaction term for inorganic nitrogen fertilizer and soil carbon. $\beta_k$, $\rho_{ki}$, and $\phi_w$ are parameters to be estimated for linear inputs, quadratic and interaction inputs, and other productivity shifters, respectively. The error term $\varepsilon_k$ is as defined in (1).

Following Abdulai *et al.* (2013), all conventional input variables used in the analysis were mean-centered. Inorganic nitrogen fertilizer had zero values in some observations due to non-use of the input as such their corresponding log transformed values were undefined. Following Battese (1997), such zero values were replaced by unities and a dummy variable for fertilizer use was introduced in vector $z_w$ to correct for bias arising from substitution of the zero values and thereby obtain correct parameter estimates. This approach allows estimation of a production function from which elasticities of inputs with true zero values can be derived. Inorganic fertilizer quantities were converted to milligram before replacing the zeros to ensure that the imputed values are not very close to or exceed any reported quantity. The model was estimated using the converted values but interpretation is in kilogram for it is a commonly used unit of measurement for fertilizer in Malawi.

From the estimated production function, the partial elasticity of production, $e_{kj}$, derived from (12) is given in (13). Elasticity of scale was accordingly derived as sum of all partial output elasticities.

$$e_{kj} = \frac{\partial \ln y_k}{\partial \ln x_{kj}} = \beta_j + \sum\nolimits_{i=1}^{n} \beta_{ji} \ln\left(x_j\right) \qquad (13)$$

Elasticity of substitution for a pair of inputs measures the curvature of an isoquant. According to Stern (2008), Allen-Uzawa Elasticity of Substitution is the most commonly used and is adopted in this study. The Allen-Uzawa elasticities of substitution is derived from (12) as follows:

$$aue_{hq} = \frac{\sum x_h \left(\frac{\partial y_k}{\partial x_{kh}}\right)}{x_h x_q} * \frac{\left|H_{hq}\right|}{H} \qquad (14)$$

where $aue_{hq}$ is Allen-Uzawa Partial elasticity of substitution between inputs $h$ and $q$, $H_{hq}$ is the cofactor determinant of Hessian matrix for inputs $h$ and $q$, and $H$ is the border determinant of the Hessian matrix.

Marginal products, $mp_{kj}$, with respect to input quantities are derived from (12) based on the output elasticities in (13) as follows:

$$mp_{kj} = \frac{y_k}{x_{kj}} * \frac{\partial \ln y_k}{\partial x_{kj}} = \frac{y_k}{x_{kj}} * \left(\beta_j + \sum\nolimits_{i=1}^{n} \beta_{ji} \ln\left(x_j\right)\right) \qquad (15)$$

The marginal product of inorganic nitrogen fertilizer was used to determine the marginal value–cost ratio of the input. The point at which the ratio is equal to one was also computed accordingly.

Theoretical consistency with production theory requires fulfillment of monotonicity and quasi-concavity conditions for all inputs. For monotonicity condition to be satisfied, marginal product should be positive which implies positive partial production elasticities as well. Quasi-concavity condition is attained for negative semidefinite hessian matrix denoting that the leading principal minors of odd order are negative and of even order are positive. In practice a translog production function does not globally meet the two conditions but the model is assumed to behave appropriately if wide enough regions in input space satisfy the two regularity conditions (Corbo and Meller, 1979).

Translog loses its flexibility if concavity restrictions are imposed globally and hence restrictions are imposed at a particular reference point (Baum and Linz, 2009). Henningsen and Henning (2009) noted that attainment of a quasi-concave production function in practice may be deficient of a technical rational because of two factors. First, inputs are not perfectly divisible and production activities are not independently applicable as quasi-concavity conditions assume. Second, a household or a firm may maximize output given inputs rather than maximizing profits.

The inefficiency term in the translog production function is assumed to be independently distributed and follow an exponential distribution with mean, $\mu$, and variance, $\sigma_u^2$. An inefficiency model as defined in (11) was estimated as follows:

$$\mu_k = \delta_0 + \sum\nolimits_{h=1}^{H} \delta_h T_k + \delta_r \Gamma \qquad (16)$$

where covariates in vector $T_k$ are proportion of productive female household members, children under ten years of age, dummy for marital status, dummy for hired labour, remittances received by a household, ownership of bicycle, ownership of phone, head managed plot, spouse managed plot, perceived plot fertility and years of farming on a plot. The factor, $\Gamma$, is a generalized residual from probit auxiliary model as identified in (10). All covariates in (16) were included in the probit plus two exclusion variables: dummies for permanence of residence over last 12 months and distance to fertilizer market.

## 5. Data and Variable Description

The analysis utilized plot-level data collected from smallholder farmers in Dedza and Ntcheu Districts of Malawi in the 2013/2014 growing season. The data was collected within the catchment area of Africa Rising Project which was being implemented to promote use of Integrated Soil Fertility Management (ISFM) practices. The two districts of Dedza and Ntcheu fall within semi-arid to sub-humid tropical agro-ecological zones. Their soils are predominantly sandy loam, well drained, moderately fertile and acidic, and prone to soil erosion. The average annual rainfall varies between 700 and 1100 mm and is mainly received from December to March with some minor rainfall in November and April. Maize-based production systems are dominant in the two districts.

A structured questionnaire was used to purposefully collect data from households taking into account differences in the ecological zones following a stratified random sampling procedure. The survey targeted Mtakataka, Linthipe and Golomoti Extension Planning Areas (EPAs) of Dedza District, and Kandeu and Nsipe EPAs of Ntcheu District. The survey generated rich data on cropping systems, input usage, and household socio-economic characteristics. This paper focuses on plots with maize. Observations with other main crops were therefore dropped. Likewise, observations with missing or invalid data were also dropped, resulting in a total of 213 observations used for the analysis.

In estimating the translog production frontier model, harvesting labour was excluded from the analysis because it does not directly affect crop productivity. Liu (2006) noted that inclusion of environmental factors may control biases in the production frontier. For this reason, soil carbon and soil nitrogen, the two factors with direct link to the study's objective, were included in the analysis to represent environmental factors while locational dummies were included as proxies for spatial agro-climatic differences (Mignouna *et al.*, 2010; Tchale, 2009).

Exclusion variables in the probit analysis were selected based on a principle underlined by similar studies that used sociopolitical and wealth indicators as instruments in relationships between subsidy fertilizer and production outcomes. For example, Aloyce *et al.* (2014) used length of residence in the village, accessibility to a village, and wealth situation of the household as exclusion variables when estimating an auxiliary model for subsidy fertilizer. Bezu *et al.* (2013) and Ricker-Gilbert and Jayne (2009) used number of years the household lived in the village and a member of parliament residing in the community as instruments that proxy social capital which may influence access to input subsidy. The instruments in this study are assumed to significantly correlate with access to subsidy fertilizer but not have direct influence on maize productivity. Validity of the instruments was tested using Durbin–Wu–Hausman test for endogeneity. Description of variables used in the analysis and their summary statistics are given in Table 1.

Table 1: Summary Statistics of the Variables Used in the Stochastic Production Frontier

| **Variable** | **Description** | **Mean** | **Std. Dev.** |
|---|---|---|---|
| Maize output | Maize output (kg) | 420.804 | 394.200 |
| Inorganic nitrogen fertilizer | Nitrogen from inorganic fertilizer (kg) | 26.048 | 68.656 |
| Labour | Household and hired labour (labour-days) | 52.634 | 40.120 |
| Seed | Amount of seed (kg) | 6.855 | 5.530 |
| Farming plot | Farm plot size (ha) | 0.224 | 0.189 |
| Soil carbon | Percentage carbon in the soil (%) | 1.296 | 0 .564 |
| Soil nitrogen | Percentage nitrogen in the soil (%) | 0.108 | 0.035 |
| Inorganic fertilizer use dummy | Dummy (1 = use of inorganic fertilizer, 0 = otherwise) | 0.709 | 0.455 |
| Linthipe | Dummy (1 = Linthipe EPA, 0 = otherwise) | 0.164 | 0 .371 |
| Kandeu | Dummy (1 = Kandeu EPA, 0 = otherwise) | 0.244 | 0 .431 |
| Golomoti | Dummy (1 = Golomoti EPA, 0 = otherwise) | 0.108 | 0.311 |

## 6. Results and Discussion

### *6.1 Diagnostic Test of the Model*

Adequacy of the translog production frontier in representing data was tested using a generalized likelihood-ratio (LR) test. The test was implemented under the null hypothesis that a Cobb Douglas model better fits the data compared to a translog production function. This was rejected (*Prob > chi2 = 0.0836*), signifying that the translog production frontier function represents the data. The null hypothesis that technical inefficiency effects are absent in the estimated model was also tested using LR test and was equally rejected (*Prob > chi2 = 5.328e-14*). Thus, there was no significant evidence supporting the choice of an average response function over a model which takes into account inefficiency effects in maize production.

Strict monotonicity and quasi-concavity were fulfilled for 86.85% and 85.92% of the sample points which suggests that the estimated model is largely consistent with theoretical assumptions underlining a typical production function. Breusch-Pagan test for heteroscedasticity showed that the null hypothesis that there is homoscedasticity cannot be rejected (*Prob > chi2 = 0.9350*). The mean Variance Inflation Factor of 9.27 gives an indication that multicollinearity is within tolerable levels. Durbin-Wu-Hausman test for endogeneity failed to reject a null hypothesis that use of subsidized fertilizer is endogenous in the production frontier (*Prob > chi2 = 0.0565*). Function control approach was accordingly employed to correct for the endogeneity. In this two-step estimation technique, generalized residuals from probit auxiliary model were included as regressors in the inefficiency model which was jointly estimated with the frontier model. Results of this analysis are not presented in this paper but are available from the author on request.

### *6.2 Econometric Results of the Translog Production Frontier*

The three estimated production functions are presented in Table 2. Results for model 1 were not adjusted for endogeneity of participating in FISP. Endogeneity was corrected in models 2 and 3 through control function approach but standard errors were bootstrapped only in model 3 at 1100 repetitions. Amsler *et al.* (2014) recommended bootstrapping standard errors in such two-step estimation. We present all the three models for comparison purposes. However, our discussion in this paper focuses on model 3 because its standard errors are bootstrapped. Effects of estimated parameters are consistent across the three models but significance levels vary. This suggests that results would be different if the study did not follow control function approach and standard errors were not bootstrapped.

Table 2: Translog Stochastic Frontier Estimates

| **Variable** | **Model 1** | **Model 2** | **Model 3** |
|---|---|---|---|
| Log of inorganic nitrogen fertilizer | 0.1014**<br>(0.0464) | 0.1019**<br>(0.0463) | 0.1019*<br>(0.0596) |
| Log of labor | 0.1478*<br>(0.0799) | 0.1490*<br>(0.0799) | 0.1490*<br>(0.0882) |
| Log of seed | 0.1507*<br>(0.0840) | 0.1473*<br>(0.0827) | 0.1473<br>(0.0947) |
| Log of farming plot | 0.4125***<br>(0.0870) | 0.4159***<br>(0.0865) | 0.4159***<br>(0.1130) |
| Log of labor squared | -0.0203<br>(0.0598) | -0.0203<br>(0.0596) | -0.0203<br>(0.0722) |
| Log of seed squared | 0.0371<br>(0.0407) | 0.0378<br>(0.0408) | 0.0378<br>(0.0553) |
| Log of farming plot squared | -0.0832***<br>(0.0319) | -0.0837***<br>(0.0319) | -0.0837*<br>(0.0447) |
| Log of inorganic nitrogen fertilizer X log of labor | -0.0338<br>(0.0303) | -0.0353<br>(0.0302) | -0.0353<br>(0.0333) |
| Log of inorganic nitrogen fertilizer X log of farming plot | 0.0422*<br>(0.0255) | 0.0435*<br>(0.0255) | 0.0435<br>(0.0310) |
| Soil carbon | -0.6949**<br>(0.3440) | -0.6649*<br>(0.3424) | -0.6649*<br>(0.3882) |
| Soil nitrogen | -1.8860<br>(4.8461) | -2.3211<br>(4.8354) | -2.3211<br>(5.5347) |
| Soil nitrogen X soil carbon | 4.2179**<br>(1.7034) | 4.2537**<br>(1.7014) | 4.2537**<br>(1.8299) |
| Log of inorganic nitrogen fertilizer X log soil carbon | 0.0399**<br>(0.0177) | 0.0410**<br>(0.0177) | 0.0410**<br>(0.0204) |
| Inorganic fertilizer use | -1.2494***<br>(0.4287) | -1.2629***<br>(0.4280) | -1.2629**<br>(0.5589) |
| Linthipe | 0.5966***<br>(0.1475) | 0.5716***<br>(0.1455) | 0.5716***<br>(0.1985) |
| Kandeu | 0.2666**<br>(0.1048) | 0.2787***<br>(0.1052) | 0.2787<br>(0.1775) |
| Golomoti | 0.1083<br>(0.1374) | 0.0909<br>(0.1353) | 0.0909<br>(0.1816) |
| Intercept | 1.8868***<br>(0.4875) | 1.9123***<br>(0.4860) | 1.9123***<br>(0.6290) |
| *Sigma u* | *0.3594* | *0.3640* | |
| *Sigma v* | *0 .4864***<br>(0.0413)* | *0.4848***<br>(0.0385)* | *-1.4481*<br>(6.3156)* |
| *Wald chi2(17)* | *324.1700* | *323.0500* | *196.4200* |
| *Prob > chi2* | *0.0000* | *0.0000* | *0.0000* |
| *Log likelihood* | *187.7799* | *187.6960* | *187.6960* |
| *Number of observations* | *213* | *213* | *213* |
| **Model Tests** | | | |
| *Monotonicity* | *86.85%* | | |
| *Quasi-concavity* | *85.92%* | | |
| *Function Form test* | *chi2(6) = 9.72; Prob > chi2 = 0.0836* | | |
| *Inefficiency test* | *chi2(1) = 56.60; Prob > chi2 = 5.328e-14* | | |
| *Heteroscedasticity test* | *chi2(1) = 0.01; Prob > chi2 = 0.9350* | | |

| | |
|---|---|
| *Variance Inflation Factor* | *9.27* |
| *Endogeneity test* | *chi2( 1) = 3.64; Prob > chi2 = 0.0565* |

Standard errors in parentheses *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Among the conventional inputs, inorganic nitrogen fertilizer, labour and farming plot are significant factors that explain variation in maize output. The positive coefficient of inorganic nitrogen fertilizer signifies that the likelihood of having high maize output is greater for farmers using more of the input than those who do not. The results compare favorably with the findings of Dlamini *et al.* (2012) and Liverpool-Tasie (2017) who observed positive relationship between maize productivity and inorganic fertilizer in Swaziland and Nigeria, respectively. Majority of smallholder farmers in Malawi own small pieces of land which are largely nitrogen deficient (CARD, 2014). Nitrogen content on about 98.12 percent of farming plots in this study is below critical limit of 0.2 percent adopted in a study by Sagona *et al.* (2016) who analysed physiochemical properties of farming land in three districts of Southern Malawi. Intensified use of nitrogen fertilizer on such plots would present an option for maximizing maize production.

As expected a prior and consistent with Essilfie *et al.* (2011) and Ayinde *et al.* (2015), first order parameter estimate on labour is positive and significant at the 10% level. This implies that using more labour on a farming plot is associated with high maize yield than using less of it. Household labour is one of the key inputs readily available to resource constrained smallholder farmers who have limited access to purchased inputs. Households with adequate labour are able to meet timeliness in all field operations. Shortage of household labour therefore aggravates chronic production deficits among poor households, particularly those with farm sizes of up to 1 hectare who are perennial net food buyers (Devereux 1997; Jayne *et al*., 2010).

Coefficient of the first order term of farming plot is significant and positively associated with maize output whereas the quadratic term of the same has significant negative effects. Thus, increasing farming plot size would increase maize output to a point where further increase in farming plot size would reduce the output. The inverse relationship between farm size and maize productivity is reported in empirical work of many authors including Liverpool-Tasie *et al.* (2017). Such relationship is depicted in small farms in China purportedly attributable to use of more labour in place of capital inputs as scale of production increases with land size (Sheng *et al*., 2019). It was further noted by Restuccia and Santaeulàlia-Llopis (2017) that access to land by more productive farmers in Malawi is constrained by restrictive land markets as land is, to a greater extent, traditionally accessed through inheritance.

Contrary to findings of Matsumoto and Yamano (2009), soil carbon has a significant negative effect on maize output at the 10% level. Similar findings, however, were reported by Eschen *et al.* (2006) in Switzerland who found a reduction in shoot biomass in response to increasing levels of carbon in annual species than in perennial species. This was due to a reduction in shoot: root ratio in grasses in response to the addition of carbon that increased C:N ratio to unacceptable and possibly intolerable levels that impede crop productivity. For about 89.67 percent of the farming plots under the study, carbon content is above critical point of 0.7 percent required to support crop production as reported by Snapp (n.d.). This critical point appeared in more recent literature and is comparable to a critical value of 0.8 reported by Snapp (1998). With the low nitrogen content in the soil, C:N ratio may be high on most farming plots and therefore reducing carbon content would reduce the ratio to some tolerable levels that can boost maize production.

Unlike the coefficient on soil carbon, the interaction term of soil nitrogen and soil carbon is positive and significant as expected. This shows that the negative relationship between maize output and soil carbon may indeed be at low levels of soil nitrogen; maize output would increase as soil nitrogen content in the soil exceeds some threshold level and soil carbon simultaneously increases. The interaction between inorganic nitrogen fertilizer and soil carbon is significantly positive which shows that joint increase of the two factors would also increase maize output. In a study by Dong *et al.* (2012) in China, it was concluded that fertilizer application improves soil fertility by increasing carbon and nitrogen content in the soil with only slight increase in the C:N ratio. Our findings therefore appear to suggest that applied nitrogen fertilizer avails nitrogen in the soil to levels where maize output increases with an increase in soil carbon.

As expected, non-use of inorganic nitrogen fertilizer is negatively associated with maize yield. One location dummy (Linthipe) has significant effect on maize output which suggests the importance of spatial biophysical and ecological factors in maize productivity.

### *6.2.1 Elasticities of the Estimated Function*

Partial production elasticities, elasticity of scale and elasticities of substitution computed from the estimated production function are presented in Table 3. Consistent with Essilfie *et al.* (2011) and Dlamini *et al.* (2012), mean partial production elasticities for all conventional inputs are less than one and therefore inelastic. It is shown that holding all other factors constant, a percentage increase in inorganic nitrogen fertilizer would increase maize output by about 0.15 percent while a percentage increase in labour, seed and farming plot would result in 0.27 percent, 0.13 percent and 0.30 percent increase in maize output, respectively. These findings suggest that increase in use of the inputs would still shift maize yield towards some optimal achievable levels.

Output elasticities for soil nitrogen and soil carbon are 3.19 and -0.34, respectively. This shows that a percentage increase in soil nitrogen would increase maize output by 3.19 percent whereas similar increase in soil carbon would reduce maize output by 0.34 percent. The output elasticity of soil carbon is unexpectedly negative possibly due to low levels of soil nitrogen relative to soil carbon. Empirical evidence from China suggests that soil organic matter decomposition rate is low when C:N ratio is high because nitrogen content is not sufficient to sustain the growing population of decomposition bacteria (Shi, 2017). Under such circumstance, application of nitrogen-rich materials such as inorganic nitrogen fertilizer tends to speed decomposition and reduce temporary loss of soil nitrogen to microbial biological activities (Miller, 2000).

Threshold level of soil nitrogen that would yield positive elasticity of soil carbon was estimated for each farming plot. Soil carbon content vary across farming plots with different biophysical properties. As such, soil nitrogen critical values may also differ across plots. It was shown that the elasticity of soil carbon would be positive if nitrogen content on a plot exceeds the average of 0.19 percent. Only 3.76 percent of the farming plots contain soil nitrogen that exceed their threshold level. The estimations are consistent with observation by Mutegi *et al.* (2015) who noted that nitrogen is a key limiting soil nutrient on most farming plots in Malawi.

Table 3: Distribution of Elasticities

| **Elasticity** | **Variable** | **Mean** | **Std. Dev.** |
|---|---|---|---|
| *Output Elasticity* | Inorganic Nitrogen fertilizer | 0.1492 | 0.0423 |
| | Labour | 0.2721 | 0.1617 |
| | Seed | 0.1351 | 0.0324 |
| | Farming plot | 0.3020 | 0.2021 |
| | Soil carbon | -0.3432 | 0.2209 |
| | Soil nitrogen | 3.1925 | 2.4002 |
| *Elasticity of Substitution* | Nitrogen fertilizer and labour | 3.1550 | 2.8099 |
| | Nitrogen fertilizer and seed | 3.2542 | 2.9785 |
| | Nitrogen fertilizer and Farming Plot | 1.4079 | 1.0978 |
| | Labour and seed | 1.4485 | 0.5997 |
| | Labour and Farming Plot | 0.6170 | 4.7382 |
| | Seed and Farming Plot | 4.2614 | 47.0968 |
| *Elasticity of Scale* | | 3.3860 | 2.5362 |
| *Soil Nitrogen Threshold Level that Yields Positive Elasticity of Carbon (%)* | | 0.1883 | 0.0435 |

The elasticity of scale is estimated at 3.39 which shows that the farmers in the two study districts of Malawi are producing at increasing returns to scale. The results also show that a percentage increase in each of the inputs would increase maize output by 4.64 percent. Oduntan *et al.* (2016) observed decreasing return to scale among maize-cowpea farmers in South West Nigeria while Bwala *et al.* (2015) observed returns to scale of 1.06 in North Central Nigeria in a production frontier that did not control for environmental factors.

Table 3 also presents partial elasticities of substitution for the conventional input pairs. According to Debertin (2012), if a production function has more than two inputs, it is possible for some pairs of the inputs to be substitutes and others complements. For complement pairs, the elasticity of substitution is negative and positive for substitutes. The elasticity of substitution of labour, seed and farming plot for inorganic nitrogen fertilizer are 3.16, 3.25 and 1.41, respectively. Elasticity of substitution of labour for seed is 1.45 which is higher than elasticity of substitution of labour for land (0.62). Elasticity of substitution of seed for land is 4.26 which shows that the two inputs have the highest substitutability of all conventional input combinations.

### *6.2.2 Profitability of Inorganic Nitrogen Fertilizer*

Estimation of the optimal inorganic nitrogen fertilizer requirements considered the marginal product (MP) derived from estimated translog function, average price of inorganic nitrogen fertilizer and market price of maize prevailing in the study area. Table 4 summaries the marginal products for the conventional farm inputs. The marginal product of inorganic nitrogen fertilizer is 7.98kg, implying that an additional kilogram of inorganic nitrogen fertilizer would yield an increase of 7.98kg in maize output, ceteris paribus. The marginal product falls within a range of 0.12 to 17.6 noted by Liverpool-Tasie *et al.* (2017) with respect to fertilizer in selected African studies. Marginal product of labour is estimated at 3.14 and of seed is 11.44 implying that a unit increase in labour and seed increases maize output by 3.14 kg and 11.44kg, respectively. The marginal products reported for seed and labour are comparable to the values estimated by Sauer and Tchale (2009) in Malawi. Land has the highest marginal product of 908.40 which shows that increasing farming plot by a hectare increases maize output by 908.40 kg.

Table 4: Marginal Product of Inputs

| **Variable** | **Mean MP** | **Std. Dev.** |
|---|---|---|
| Nitrogen fertilizer | 7.9835 | 27.0209 |
| Labour | 3.1419 | 2.5738 |
| Seed | 11.4371 | 5.6413 |
| Farming Plot | 908.4046 | 844.6057 |

The market prices of fertilizer and maize as reported by farmers averaged MK1105.48/kg and MK65.93/kg, respectively (Table 5). This gives a high nitrogen-maize price ratio which is in conformity with observation by Edriss *et al.* (2004) that the ratio is high Malawi. Given the prices, marginal value cost ratio averaged 0.48 for all the plots. The marginal value cost ratio exceeds one on 45.03% of the plots which shows that use of inorganic nitrogen fertilizer is profitable for risk neutral farmers on these farming plots. However, the proportion of plots with marginal value cost ratios that exceed one may have been even lower if estimation had accounted for transaction and transport costs associated with fertilizer acquisition. The findings are consistent with observation by Snapp *et al.* (2014) that empirical evidence in Malawi reveals limited profitability or even negative profitability of fertilizer use at commercial price.

Table 5: Marginal Value Product as Ratio of Fertilizer Price

| **Nitrogen Price (MK/Kg)** | **Maize Price (MK/Kg)** | **Marginal Value Product as ratio of fertilizer price** | | **Plots MVPR> 1 (%)** |
|---|---|---|---|---|
| | | **Mean** | **Std. Dev.** | |
| 1105.48 | 65.93 | 0.4761 | 1.6115 | 45.03 |

Table 6 gives a summary of quantities of inorganic nitrogen fertilizer that optimize maize yield on different plots. Nitrogen fertilizer optimal level averaged 20.01kg for all the plots. About 66.20% of the plots uses inorganic nitrogen fertilizer beyond their respective optimal levels. For 29.11% of plots, observed inorganic nitrogen fertilizer levels are greater than their average optimal levels. Applying fertilizer beyond optimal levels signifies resource use inefficiencies and potential yield is not reached if applied fertilizer levels are below optimal levels (Amatya *et al.,* 2008). This shows that inorganic nitrogen is profitable at low levels of application for most plots. If levels of inorganic nitrogen fertilizer are higher than the optimal level, profitability will be eroded by high nitrogen-maize price ratio.

Table 6: Optimum Levels of Inorganic Nitrogen Fertilizer

| **Nitrogen fertilizer optimal level** | | **Plots exceeding their optimal level (%)** | **Plots exceeding average optimal level (%)** |
|---|---|---|---|
| **Mean** | **Std. Dev.** | | |
| 20.0090 | 110.6311 | 66.20 | 29.11 |

## 7. Conclusion and Recommendation

Farmers' efficient use of natural soil nitrogen and soil carbon as well as nutrients from other sources including inorganic nitrogen fertilizer application can elevate their potential to attain optimal maize output levels. This study has analyzed the effect of nitrogen and carbon on maize output. Both output effects of soil nitrogen and inorganic nitrogen fertilizer were analyzed alongside the effects of active carbon in the soil and other factors of production.

Results show that inorganic nitrogen fertilizer has significant positive effect on maize output whereas an increase in soil carbon is associated with lower maize output. It is further shown that interaction of soil nitrogen and soil carbon significantly increases maize output. These results seem to be linked to C:N ratio in the soil. If the C:N ratio is too high (high carbon), decomposition occurs slowly and the nitrogen content is not sufficient to sustain the growing population of decomposition bacteria. Thus, any addition of C makes matters worse by further increasing the ratio and this accumulation of C is known to reduce shoot: root ratio and biomass in grasses including maize. Under such circumstances, increasing nitrogen brings the C:N ratio to beneficial levels. Thus, farming practices that maintain appropriate C:N ratios would yield positive effect on maize output.

While for most farming plots (98.12%) nitrogen content is below the critical limit of 0.2 percent, carbon content on 89.67 percent of the farming plots exceeds critical limit of 0.7 percent. The C:N ratio may therefore indeed be high for most farming plots. It is hardly surprising that the average output elasticity of soil nitrogen is positive whereas that of soil carbon is negative. Increasing carbon content further in such scenario may raise the C:N ratio to even more intolerable levels. It has been shown that the output elasticity of carbon would have been positive if soil nitrogen was increased in the soil to an average of 0.19 percent. The output elasticity of inorganic nitrogen fertilizer is low (0.15), nevertheless, it suggests that increasing use of the input still shifts maize yield towards some optimal achievable levels. Estimated elasticities of substitution showed varying degree of substitutability between inorganic nitrogen fertilizer and other conventional inputs. The degree of substitutability is higher with respect to labour and seed than farming plot size. Nevertheless, this shows that increased use of inorganic nitrogen fertilizer can be accompanied by reduction in some inputs that farmers use for maize production.

The profitability of inorganic nitrogen fertilizer is shown to be dependent on marginal product of the fertilizer and the nitrogen-maize price ratio. At market price, 45.03 percent of farming plots have marginal value cost ratios that exceed one with respect to inorganic nitrogen fertilizer. Furthermore, it is shown that for 66.20 percent of farming plots, inorganic nitrogen fertilizer is used beyond optimal levels. Therefore, the use of inorganic nitrogen fertilizer has been shown to be profitable for some farmers but this is mainly at low levels of fertilizer application as high nitrogen-maize price ratio erodes profitability at high levels of fertilizer application.

As a key issue for recommendation, the study has shown that soils in the study area are depleted of nitrogen as compared to carbon leading to unfavorably high C:N ratios which impede maize production. Replenishing the soil with inorganic nitrogen fertilizer is one of the available options under such circumstance but its profitability is constrained by high nitrogen-maize price ratio. Farmers therefore need programs that enhance their access to inorganic nitrogen fertilizers at reasonable prices. Such programs can be implemented simultaneously with a package of intensified agricultural practices that fix and retain nitrogen in the soil.

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