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OPTIMIZING AGRONOMIC-NITROGEN USE EFFICIENCY OF MAIZE PRODUCTION IN TANZANIA

Augustine O. Iraoya[1*], Aida C. Isinika[2], and Tiri G. D[3]
[1*] Department of Agricultural Economics and Agribusiness, Sokoine University of Agriculture, Tanzania.
[2]Institute of Continuing Education, Sokoine University of Agriculture, Tanzania
[3]Department of Agricultural Economics , Federal University, Dutsin-Ma
[*]Corresponding Author's e-mail: iraoyaaustine@gmail.com

Abstract:

This study aimed at assessing different production functions for maize production in Tanzania. The maize yield performance, and agronomic – nitrogen use efficiency (AE) were evaluated under 6 rates of nitrogen (N) and water (W). Computations made for maize yield and AE shows that (i), the maximum potential maize yield increases with irrigation. (ii) less amount of fertilizer is needed to produce a unit of maize in the presence of high irrigation. Specifically, the maximum maize yield at 50 kg/ha of N is 6200 kg/ha and requires irrigation of 400mm, whereas at 100 kg/ha of N, the maximum yield is 5700 kg/ha and given 300mm of irrigation. Given the decrease in the fertilizer use efficiency, it implies that it is not plausible for farmers to apply optimum dose of nitrogen where there is water shortage. Moreover, two models, which are the quadratic function and the Mitscherlich-Baule function were fitted and compared based on a combination of agricultural, econometric and bioeconomic properties of the production process. The Mitscherlich-Baule function proved the best fit model. Results of the regression analysis shows that maize yield response to nitrogen (N) and water (W) exhibits diminishing returns. This suggests that when an extra unit of these input is added to the production process, less and less addition is observed in the total output. Based on the findings of this empirical study, it is plausible to recommend that farmers in the study area should be careful in applying the recommended dose of N where water is limited, because maize yield efficiency would not be maximized.

Keywords: Maize, Fertilizer, Production functions, Tanzania.

INTRODUCTION

Maize is one of the most important food crop in Tanzania and the most cultivated cereal crop, grown over 45 per cent of Tanzania total arable land (Baijukya *et al.*, 2020). Estimates by FAOSTAT (2019) shows that maize accounts for about 50 per cent of rural household income in Tanzania. Despite the importance of maize in the Tanzania economy, there is frequent maize crop failure due to soil fertility decline, poor agronomic practices (Kadigi *et al.* 2020; Baijukya *et al.*, 2020) and delayed sowing, which results from periodic droughts (Xiong and Tarnavsky, 2020). Such crop failure heightens the food security challenges in Tanzania (Kansal and Nyamsha, 2021; Kadigi *et al.* 2020) To address these biophysical challenges, precise irrigation and precise fertilizer application is highly recommended (Kansal and Nyamsha, 2021; Adu *et al.*, 2018)

In spite of the highly recommended increased fertilizer use in Africa, Liverpool-Tasie *et al.*, (2017) argued against the conventional wisdom and emphasized that low marginal physical product, among other factors significantly reduce the profitability of fertilizer use. Thus, in the absence of data driven evidence for informed decision making, farmers would tend to practice over-irrigation and over-fertilization in a bid to maximize productivity. Consequently, there will be decreased use efficiency of irrigation and fertilizer and as well as reduced economic efficiency (Zou *et al.*, 2020). Therefore, precise irrigation and increased accuracy of crop yield estimates is crucial in efficiency maximization and planning adaptation strategies aimed at achieving food security in the face of climate change.

Estimating yield response to nutrients facilitates an understanding of the technical relationship (production function) or input–output relationships in crop production (Shen, et al., 2020; Jha *et al.*, 2019). The nexus between inputs and output is better understood through an empirical estimate of agricultural production function. Moreover, the agricultural production function helps in determining the appropriate increase in output that can be derived from different levels of resource use (Shen, *et al.*, 2020).

Thus, one vital key in agricultural and production economics modelling is to accurately represent the crop production or yield function. Emphasis is therefore laid on estimation of different functional forms in applied agricultural and environmental economics (Foster, and Brozovic, 2018). This task is complicated by the growing number of available functional forms, however available selection criteria pertaining to mathematical, statistical, and economic properties are used as guide in selecting appropriate functional form(s) in the course of building the model (Babazadeh, 2021; Popp *et al.*, 2018).

Given this premise, the motivation for this study is to provide evidence from novel crop production function analysis, how crop yields correlate with variable irrigation water input. This understanding is crucial in advancing the frontier of production function analysis and evaluation the production and welfare outcome of variations in irrigation water.

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LITERATURE REVIEW

Just like other crops, maize is faced with periods of water stress in its growth cycle. This period of water stress, coupled with low soil fertility as well as little or no fertilizer application, limits maize from maximizing its growth and yield potential. This assertion was confirmed by Kadigi *et al.* (2020) and Laudien *et al.* (2020) who project that maize sub-sector in Tanzania could continue experiencing a significant decrease in yields and net returns, if proper alternatives are not employed.

The prevailing system of maize production under rainfed agriculture is associated with low yields and little profit for maize farmers (Durodola and Mourad, 2020; Luhunga, 2017). This consequently affects the food security of the farmers and the nation (Thosmas, 2020), even though maize is Tanzania's most important food crop, grown by 3.5 million farming households (60%), and accounting for 40% of calories consumed (Kadigi *et al.*, 2020; Laudien *et al.*, 2020). Among the critical factors that limits maize yield in Tanzania is climate change, water scarcity and declining soil fertility (Kadigi et al., 2020).

Moreover, these consequences are complicated by a limited understanding of how irrigation and fertilization affect maize yield and as well as a biased estimation of the maize yield function. Given this premise, the need for assessment of the combined effect of water supply and fertilizer input on maize productivity in Tanzania cannot be overemphasized. Novel production function models are becoming significant tools in accurate estimation of the water needs of crops, as well as the yield response of crops to water supply in form of irrigation (Popp *et al.*, 2018; Babazadeh *et al.*, 2021). Knowledge products or outcomes of these modeling is crucial for evidence-based decision making by farmers, extension agents and policy makers.

Empirical literature such as Shen *et al.* (2020) which analyzed crop water production functions for winter wheat with drip fertigation in the North China plain shows that accurate production function is key to estimating how crop yields respond to variable irrigation water inputs and determine the value for irrigation water. Similarly, Giuliani *et al.* (2016), as well as Foster, and Brozovic, 2018) opined that estimates of crop-water production functions are critical in farm economic models to evaluate how future variations in water availability due to climate change, will affect agricultural production and welfare outcomes.

Furthermore, studies by Popp *et al.* (2018), Foster, and Brozovic (2018) and Babazadeh *et al.* (2021), establish the necessity of crop-water production functions, which are essential econometric tools for quantifying effects of water scarcity and climate change on agricultural production. Following Popp *et al.* (2018), and Babazadeh *et al.* (2021), this study utilized the quadratic and Mitscherlich-Baule production function to estimate maize-irrigation production function in Tanzania. This is aimed at emphasizing accurate choice and use of production functions in estimating crop yield.

Key Economic Properties of Selected Models (Production Functions)

According to Hu and Du (2018), the quadratic functional form has mathematically compliant properties, and easy estimation process, which is plausible for explaining crop yield response to nitrogen fertilizer and water use. The function is composed of additive input factors, the squared values of the factors, as well as an interaction term. The additional interaction term clarifies the interdependence of input factors. (Babazadeh, 2021). Moreover, the function accommodates a decline in yield beyond a given threshold of fertilizer application (Frederick *et al.*.2015)

The Mitscherlich-Baule production function permits factor substitution and a growth plateau (i.e. maximum yield) in line with von Liebig's "Law of the Minimum" this makes it preferable for use in an economic model (Babazadeh, 2021).

The input factors in the Mitscherlich-Baule production function are continuous and exhibits positive marginal productivities. This implies that the function allows for factor substitution unlike the classical von Liebig. The isoquants are not right-angled, meaning that unlike the von Liebig function, the Mitscherlich-Baule production function does not exhibit linear limitations in terms of factor input (Kadigi *et al.*, 2020).

METHODOLOGY

Description of experimental plots

Filed experiments were conducted at the Sokoine University of Agriculture, Teaching and Research Farm. The field is located between latitude 6° 85’ S and longitude 37° 64’ E and at an elevation of 568 m above mean sea level, while the slope of the area is 4%. The climatic condition of the location is sub-humid, with a bimodal rainfall pattern and a mean monthly temperature range between 25 and 28°C. Lighter rainfalls are experienced from November to January with a peak in April, while heavy rains are experienced from March to May, with a peak in the month of April.

The soil of the experimental plot is characterized as sandy clay, moderately acidic with a soil pH of 5.7, low in nitrogen (0.04 to 0.14%), P that ranges from 7.7 to 8.3 mg $kg^{-}1$ and an exchangeable K of 0.7 cmol (+) $kg^{-}1$ (Uwiringiyimana *et al.*, 2020). This suggests that the fertility of the experimental plot is low.

Experimental design

The experimental design adopted was a Complete Randomized Block Design (CRBD). The CRDB consisted of six treatments in three replications. The experimental plots had a length of 7 m and a width of 6 m, with a plant spacing of 30 cm within a row and 90 cm between rows. One drip irrigation belt was fixed in the middle of the rows with a distance of 20 cm from each row, which was used to irrigate the maize plants. There were 6 treatments with 3 replicates each for a total of 18 experimental plots.

The P and K levels were kept constant at 100 kg/ha. Before sowing the maize, the whole amounts of P, K and 30% of N were applied. The remaining amount of N was apportioned to two doses, at different growth stages of the maize and applied through the irrigation system.

Derivation of the Response Models

Mitscherlich-Baule function

The specification of the Mitscherlich-Baule function as adapted from Frederick *et al*., (2015) and Beattie *et al*. (2009) is represented as;

$$Y = \beta 1[1 - \exp(-\beta 2(X1 - \beta 3)^{\beta 6})][1 - \exp(-\beta 4(X2 - \beta 5)^{\beta 7})] \quad . \quad . \quad . \quad (1)$$

Where $\beta 1$ = asymptotic yield plateau,
$\beta 2$ = residual level of nitrogen in the soil
$\beta 4$ = residual level of soil water,
if $\beta 1$, $\beta 2$, and $\beta 4 > 0$ it is strictly concave,
if $\beta 1$, $\beta 2$, $\beta 4$, $\beta 6$, and $\beta 7 > 0$ it is strictly quasi-concave.
$\beta 3$ and $\beta 5$ are the rate of variable at the X intercept,
When $\beta 6 = \beta 7 = 1$, it implies that only stage two of the production process is represented.
When $\beta 6$ lies between 0 and 1 ($0<\beta 6<1$) it implies that stage 1 and stage 2 of the production process is represented for input X1 while both stage and stage two of the production process is represented for input X2 when $\beta 7$ lies between 0 and 1 ($0<\beta 7<1$).

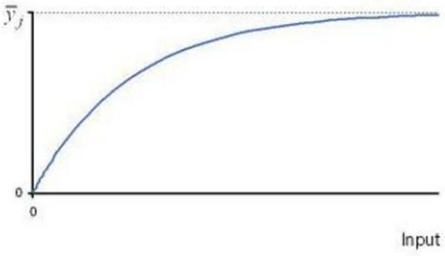

Figure 1

The curve can be derived as

$$\frac{dy}{dx} = (A-Y)C \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Equation (2) can be integrated such that we have;

$$\log (A-Y) = \log(A) - c_1B - cX \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where:

A = potential maximum yield.

Y = actual yield obtained in kg ha^{-1}.

$\frac{dy}{dx}$ = the rate at which yield increases (slope). This is dependent on the environment and the quantity of nutrient present.

X = quantity of added nutrient

B = the value of the soil test (kg/ha).

c1 = constant for B (i.e. efficiency of soil).

c = constant i.e., (efficiency of nutrients).
The idea of "half-way points" was developed by Baule in consonance with the identical relationship proposed by Mitscherlich. Baule opined that;

$Y = A - A(1/2)^{\#\ \text{Baule Units}}$ . . . . (4)

Y = actual yield.

A = potential maximum yield.

Baule Unit = quantity of nutrient required to scale-up the yield "one-half way" closer to the potential maximum yield.

Practically, it implies that the addition of one Baule unit of a nutrient could make yield to increase by 50%, while the addition of a second Baule unit could increase yield by 75%. Also, the addition of a third Baule unit of a nutrient could yield an increase of 87.5%. However, an exact value of the Baule unit depends on the nutrient in question, for nitrogen, 1 Baule unit is 223 pounds per acre (Weng *et al.*, 2020)

Specification of the quadratic production function

The quadratic function is stated as:
$y = a + bx + cx^2$ . . . . (5)

where,
a, b, and c = constants
$c \neq 0$.

The quadratic formula is given as

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

The quadratic function has a parabola graph, which is symmetric along its line of symmetry. The symmetry intercepts the parabola at a point called the vertex.
Example

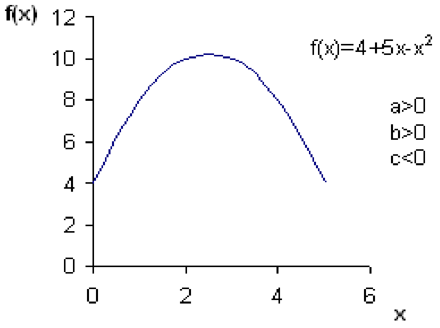

Figure 2: Graph of the quadratic function

The quadratic function for maize is stated as;
$Y = \alpha_0 + \alpha_1.N + \alpha_2.W + \alpha_3.N^2 + \alpha_4.W^2 + \alpha_5.N.W$ . . . . . (6)
Y = maize yield per acre,
N = quantity of nitrogen applied,
W = quantity of irrigation (water).
α_i's = parameter estimates
The quadratic function has the advantage of a second-order Taylor series approximation in relation nonlinear function. This implies that it is plausible for use in factors that are either complementary, competitive, as well as independent (Hu and Du, 2018).
The factors are considered to be complementary when $\alpha_5 > 0$,
The factors are said to be competitive if $\alpha_5 < 0$
The factors are independent if $\alpha_5 = 0$

Quadratic production functions allow outcomes at the second and third regions of production functions, but not at the first.

Data and Model Assessment

When choosing the right model for assessing the response of yield to input use, the combination of microeconomic, statistical, econometric, as well as agricultural or biological features of the production process should be considered (Frederick *et al*., 2015). This is the bases upon which the model chosen in this study are assessed. In order to model the combined effect of fertilizer use and irrigation on crop yield, maize yield data generated from varying rates of fertilizer (N) application (kg/ha) and varying amount of irrigation or Water (mm) were fitted (Table 1). Two prominent production functions (Quadratic and the Mitscherlich-Baule (M-B)) were employed and compared.

Table 1: Experimental treatments of maize.

Treatment	N application rate (kg/ha)	Irrigation volume ($m^3 ha^{-1}$)
1	10	1000
2	30	2000
3	40	3000
4	50	4000
5	60	5000
6	80	6000

Results and Discussions

Results of the analysis shows that the Mitscherlich-Baule model better explains the variation in maize yield than the quadratic model. Also, the Mitscherlich-Baule model gave the best fit for maize and confirms the inherent characteristics of the model which includes its ability to accommodate plateau characteristics which is in consonance with the biological or growth characteristics of maize. Other statistical results such as the correlation coefficients and signs of the coefficients also attest that nitrogen level, and irrigation amount are important variables to include in the functional forms

Graphical Analysis and Validation of Production Stages

Figures 1 and 2 represents the yield graph for each functional form fitted for a visual comparison. Although the inherent challenges of the data obtained could not give a perfect shape of the model. The curves are plotted across the range of fertilizer (nitrogen) and irrigation (water) applied. The predicted maximum maize yield and minimum fertilizer use are similar for both models. However, the M-B curve has a slope that is different to that of the quadratic function, this suggest that the choice of production function affects the optimal level of fertilizer input. Moreover, it implies that before giving advice to farmers, the choice of production function should be considered. The M-B function proved to be the best fit.

Table 2: Coefficient estimates of the Models

Variable	**OLS for Quadratic Function**	**OLS for Mitscherlich-Baule Function**
Intercept	1371.463	2277.001
α_1	54.012	59.337
	(14.677)	*(10.760)*
α_2	100.209	116.788
	(30.118)	*(28.951)*
α_3	-0.227	1.9424E+130
	(-0.097)	*(0.000)*
α_4	-0.010	5.2215E+173
	(-0.005)	*(0.000)*
α_5	0.050	NA
	(0.021)	
F-value	6.336	10.255
Adjusted R^2	0.572	0.698

All values are significant at the 95% level.

Numbers in parenthesis are standard errors.

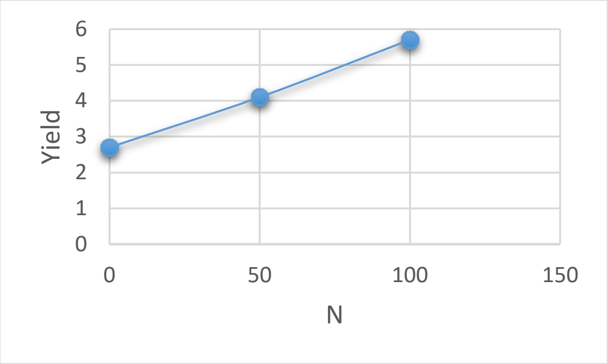

Figure 3a. Maize yield Quadratic

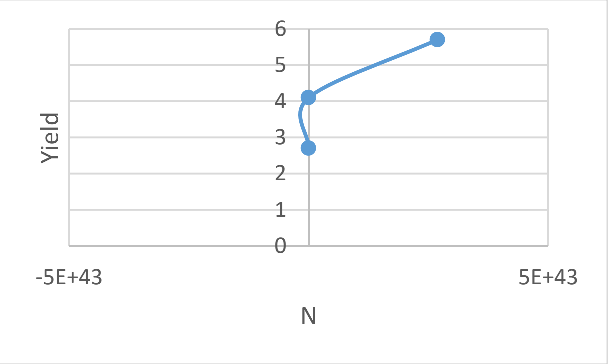

Figure 3b. Maize yield Mitscherlich-Baule.

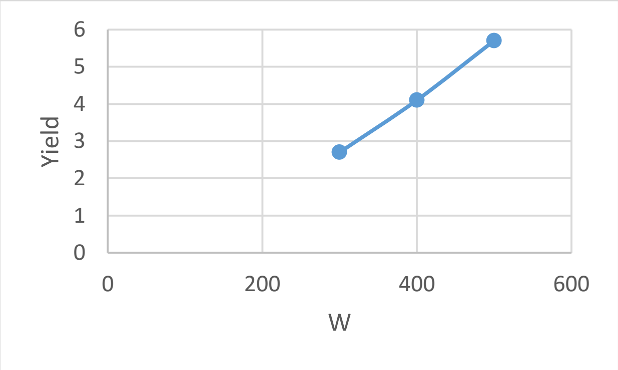

Figure 4a. Maize yield Quadratic

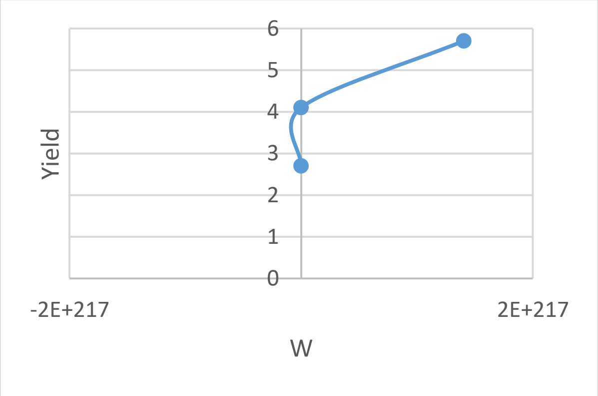

Figure 4b. Maize yield Mitscherlich-Baule.

The F value shows that both models have predictive capabilities and significance. The adjusted R^2 shows that 57% and 69% of the observed variation in maize yield is jointly explained by irrigation and water using Quadratic and Mitscherlich-Baule functions respectively. However, according to Frederick *et al.* (2015), R^2 should not be used solely in comparing models because of bias in selecting model with best fit especially when assessing linear models against nonlinear model.

From the quadratic function we have;

$$Y = 1371.463 + 54.012N + 100.209W – 0.227N^2 – 0.010W^2 + 0.050NW \qquad (7)$$

Regression analysis of the quadratic model reveals that the maize yield response to nitrogen (N) and water (W) exhibits diminishing returns. This suggests that when an extra unit of these inputs is added to the production process, less and less addition is observed in the total output.

The partial derivative of equation (7) with respect to N leads to equation (8);

$$\frac{dy}{dN} = 54.012 - 0.454N \quad . \quad . \qquad (8)$$

Equation (8) suggests that when a farmer increases the quantity of fertilizer use indefinitely, it will not give an indefinite or proportionate increase in maize yield.

Moreover, the partial derivate of equation (7) with respect to W gives;

$$\frac{dy}{dW} = 100.209 – 0.020W \quad . \qquad (9)$$

Equation (9) reveals that total maize yield increases at a decreasing rate per unit increase in the amount of water. Adding water indefinitely will lead to yield reductions.

Furthermore, the positive interaction between nitrogen and water shows that the inputs are complement.

Maximum Yield

The yield response data revealed that (i), the maximum potential maize yield increases with irrigation. (ii) less amount of fertilizer is needed to produce a unit of maize in the presence of high irrigation. For example, the maximum maize yield at

50 kg/ha of N is 6200 kg/ha and requires irrigation of 400mm, whereas at 100 kg/ha of N, the maximum yield is 5700 kg/ha and given 300mm of irrigation. This implies a decrease in the fertilizer use efficiency and suggests that it is not plausible to apply the recommended or optimum dose of nitrogen where there is water shortage.

Isoquant

The curvature of the isoquant shows the amount of nitrogen fertilizer combined with a given amount of water (irrigation) to produce a unit maize yield. The greater the curvature of the isoquant, the greater the quantity of fertilizer required to substitute for reduced amount of irrigation. Moreover, the decrease in fertilizer use efficiency suggests that nitrogen fertilizer should not be assumed a perfect substitute for irrigation in maize production. Hence, the maximum potential maize yield could be achieve only when there is a correct combination of fertilizer use with relatively high level of precipitation or irrigation.

Returns to Scale

One inherent challenge in using the Mitscherlich-Baule function in the context of an optimizing economic model is that specifications with more than one input factor (e.g. nitrogen and water) exhibits increasing returns to scale. Consequently, recommendation on the bases of the Mitscherlich-Baule function could suggest application of inputs that exploits returns to scale. To correct for this, the study used a generalized form of the Mitscherlich-Baule function;

$$Yi = \beta_1 * (1-\exp(-\beta_2 (\beta_1+N_i)))^{\theta 1} * (1-\exp(-\beta_4 (\beta_5 + W_i)))^{\theta 2}$$

Thus the returns to scale is controlled by the sum $\theta 1 + \theta 2$

The quadratic function imposes constant returns to scale

CONCLUSION AND RECOMMENDATION

Conclusion

The empirical estimation and comparison production functions for maize yield found the Mitscherlich-Baule function best fit. This attest to past empirical literature in which flexible forms of production functions such as the Mitscherlich-Baule that has a growth plateau is recommended in analyzing maize yield. Based on the findings of this empirical study it is plausible to recommend that farmers in the study area should be very cautious when applying the recommended dose of N where water is limiting, because it could lead to losses or very little increase in maize yield. Moreover, recommendation on the bases of Mitscherlich-Baule function alone could be bias, thus researchers should endeavour to avoid this bias by applying a generalized form of the Mitscherlich-Baule model.

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