1. Fertilizer Use Optimization: Principles and Approach

Kayuki C. Kaizzi[1] kckaizzi@gmail.com, Mohammed Beshir Mohammed[2] and Maman Nouri[3]

[1] National Agricultural Research Laboratories, P.O. Box 7065, Kampala, Uganda
[2] Arba Minch University, P.O. Box 21, Ethiopia
[3] Institut National de Recherche Agronomique du Niger, BP 240 Maradi, Niger

1.1 Introduction

Soils in sub-Saharan African (SSA) are degraded with low nutrient availability. This is partly a result of erosion, leaching and depletion through clearing and cultivation of the land with minimal use of external sources of nutrients (Stoorvogel et al., 1993; Bekunda et al., 1997). The rate of soil fertility decline depends on soil erosion, nutrient removal in harvests, the rate at which nutrients are returned to the soil through the use of both [inorganic] fertilizer and organic manures, and the rate of mineralization of soil mineral and organic matter nutrients.

The economic consequences of soil fertility/nutrient depletion are great with reduced farm production and food security. Economic growth is slowed at community, regional and national levels by reduced agricultural productivity and its economic multiplier effects. Lower farm employment and increased poverty may drive migration to urban areas where infrastructure and employment opportunities are inadequate (Homer-Dixon et al., 1993).

Fertilizer use in SSA countries is low, partly because farmers do not recognize adequate profit opportunity with acceptable risk. Unfortunately, most countries have blanket fertilizer use recommendations that too often fail to consider farmers' profit potential. Farmers who are financially well off can afford to apply fertilizers on all their farmland to maximize profit per hectare. Smallholders often have some financial ability to use fertilizer, but need high returns on their small investment. The high returns will often reduce the financial constraint, enabling them to invest more in fertilizer use in following seasons. Smallholders have a high opportunity cost for their money and a benefit-cost ratio of two within a six to 12 month period is often not sufficient to justify an investment; alternative use of the limited financial capacity may give better returns or better meet urgent needs.

Optimization of fertilizer use by smallholders refers in this chapter to the maximization of net returns on the farmers' investment achieved through the best choice of crop-nutrient-rate combinations. Making decisions on choice of crop to fertilize and the amount of each nutrient to apply, however, is very complex. Crop responses to applied nutrients needs to be considered in addition to the farmer's land allocation to different crops, the value of the produce, the costs of fertilizer use and the money available for fertilizer use.

1.2 What is optimization?

Optimization is the process of identifying solutions that minimize or maximize a function's value, where the function represents the investment required for the desired benefit (Kumar 2013). All optimization problems are constrained due to resource scarcity or costs, and the maximizing or minimizing of some objective function is always subject to one or more constraints.

Two common techniques of optimization are linear programming (LP) and non-linear programming. Linear programming is applied when the objective function f (the function that should be maximized or minimized) is linear and the constraints (resource limitations) are specified using only linear equalities and inequalities. Non-linear programming is applied when the objective function, the constraints, or both contain non-linear components. Other optimization techniques include integer stochastic programming, dynamic programming, hill climbing and simulated annealing (Kumar 2013).

Linear programming solves optimization problems where all the constraints as well as the objectives are expressed as a linear function using decision or activity variables and finite objective functions. The decision or activity variables refer to activities which are in competition with other variables for limited resources. For example, fertilizer purchase by a

Fertilizer Use Optimization in Sub-Saharan Africa (2017) Charles S. Wortmann and Keith Sones (eds). Published by CABI.

farmer may be at the expense of seed purchase, food expenditure, school fee payment or bicycle repair. Linear programming requires a single clearly defined, unambiguous finite objective function to be optimized that can be expressed as a linear function of the decision variables. For example, a farmer allocating a budget to fertilizer use may strive to maximize profit or production. Hence, the maximization of production/profit, or the minimization of loss for this specific farmer, are finite objective functions.

Constraints in linear programming are limitations on the available resources, such as availability of equipment, budget, managerial time or labour, production capacity and the market demand for the finished goods. Such limitations also occur with smallholders.

The maximization equation may take the form of net returns or profit resulting from decisions on different fertilizer uses (e.g. X_1 and X_2) and the LP optimization solves the values for X_1 and X_2 which maximize the objective function of high profit from fertilizer use (Figure 1.1). A limitation of linear programming is that both the objective and constrained functions must be linear and the coefficients for each function must be specified.

Linear programming was applied to develop fertilizer optimization tools (FOT) as a component of the fertilizer use optimization approach developed by the project Optimising Fertilizer Recommendations in Africa (OFRA). The FOTs are used to maximize the net returns of farmers from nutrient application, subject to budget constraints, fertilizer costs and produce values. National research teams of Burkina Faso, Ethiopia, Ghana, Kenya, Mali, Malawi, Mozambique, Niger, Nigeria, Rwanda, Tanzania, Uganda and Zambia collaborated in OFRA.

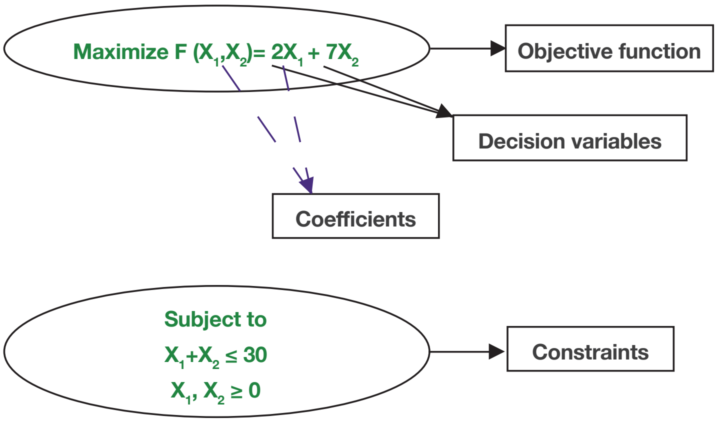


Figure 1.1: Schematic illustration of LP optimization.

1.3 Fertilizer use optimization

Profit oriented recommendations for non-finance constrained fertilizer use commonly strive to maximize mean marginal rates of return across all cropland. Many smallholder farmers do not have the financial capacity to purchase enough fertilizer to maximize net returns per hectare to fertilizer use for all of their cropland. They need to maximize returns on their limited investment through choice of crop-nutrient-rates combinations with potential to achieve the highest marginal returns until the budgeted financial resources are exhausted (Jensen et al., 2013).

Crop nutrient response functions are essential to efficiently applying economics to fertilizer use decisions. These were determined from results of field research conducted across the 13 OFRA countries as asymptotic curvilinear-plateau functions taking the form of an exponential rise to a maximum or plateau yield. The asymptotic function is $Y = a - bc^n$, where Y is yield (t/ha), a is the maximum or plateau yield (t/ha) for application of a specific nutrient, b is the maximum gain in yield (t/ha) due to application of the nutrient, and c^n represents the shape of the quadratic response, where c is a curvature coefficient and n the nutrient application rate (kg/ha). Information available from locally conducted research was supplemented by geo-spatial transfer of response functions determined elsewhere under similar crop growing conditions, that is, in the same inference space (Chapter 2).

The response functions were then graphically displayed for each crop nutrient combination, such as for maize response to nitrogen (N) for growing conditions similar to those of the Transitional/Derived Savanna of Ghana and Nigeria (Figure 1.2). The legend identifies the source of the curves with a three letter country identifier followed by the research site's latitude and longitude (degrees). The results in this case were primarily from Ghana and Nigeria but also from Mali, Burkina Faso, Togo and even one case from eastern Tanzania.

A response function representing the median yield results across all N levels, displayed as the heavy green dashed line, was determined; median rather than mean results were used to reduce the influence of outlier responses. The response function for high yield maize (>3 t/ha),

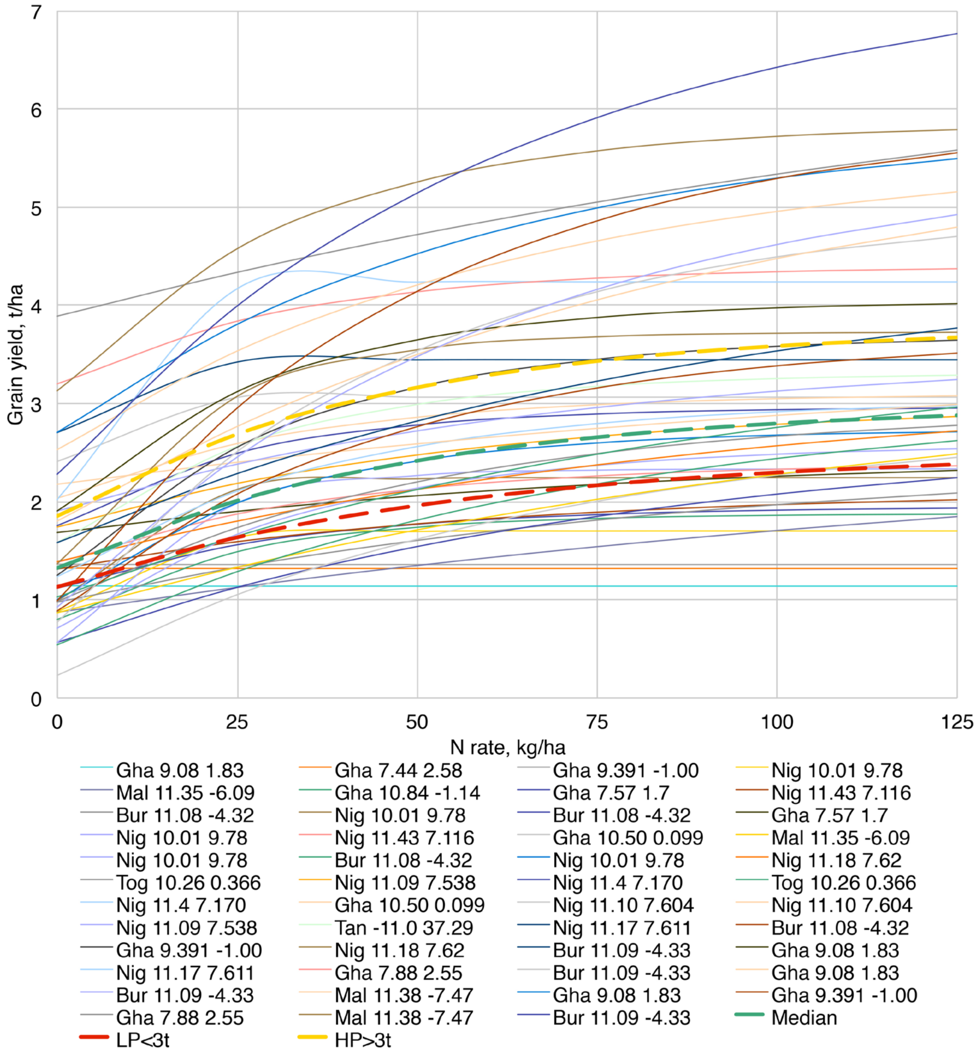


Figure 1.2: Maize nitrogen response functions available for determination of response functions for the Transitional/ Derived Savanna of Ghana and Nigeria.

represented by the heavy gold dashed line, was determined from functions with a coefficients >2.5 t/ha. The response function for low yield maize (<3 t/ha), represented by the heavy red dashed line, was determined from functions with a coefficients <3.5 t/ha. In most cases, available results from field research were not sufficient for determining high and low yield potential responses; in some cases responses were similar for high and low potential, and therefore only the median response was determined. Teams of national researchers considered these response functions, together with other information, such as current recommendations, and determined representative functions for each targeted crop-nutrient within an agro-ecological zone (AEZ).

1.4 Fertilizer optimization tools

Fertilizer optimization tools (FOTs) have been developed to assist farmers optimize profit from their fertilizer investments through best choice of fertilizer use options. Each FOT aims to provide optimized solutions given a farmer's agronomic and economic context.

The FOTs use linear programming to determine, on average, the most profitable fertilizer use options specific for a farmer's context. The FOT optimizes solutions using the Solver© add-on (Frontline Systems Inc., Incline Village, NV, USA) of Microsoft Office Excel 2007 or later. The process stage of the FOT considers the farmer-specified constraints, pre-determined model constraints and the model's optimization function. The farmer-imposed constraints, or input data, include:

i) the intended land area to be planted and the expected commodity value at harvest for each crop to be planted (zero is entered for land area of crops that are not being considered);

ii) fertilizers available and the cost of using each fertilizer including purchase, delivery, application and interest costs; and

iii) the farmer's budget constraint, that is, the amount of money that the farmer has for fertilizer use, whether borrowed or saved.

The FOT is also constrained by the setting of maximum fertilizer and nutrient rates to avoid exceeding the range of inference for the underlying equations, such as in the cases where fertilizer is free or of very low cost.

The objective function of the FOTs, therefore, is to maximize net returns, that is, the difference of the total value gain from fertilizer use minus total cost of fertilizer use. This is subject to (Figure 1.3):

i) Total costs of fertilizer applied across all crops within the bounds of the available budget for fertilizer.

ii) Optimized allocations of fertilizer rates by type and crop, not exceeding the imposed constraints of maximum rates for different fertilizer types applied to each crop, but in excess of any imposed minimum rates, generally zero.

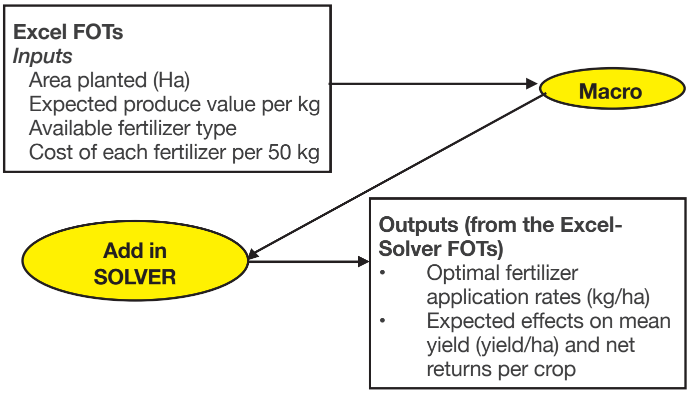


Figure 1.3: Fertilizer optimization process (Adapted from Jansen et al., 2013).

Since field research results follow Liebig's law of the minimum, the FOT often requires some N application before phosphorus (P) can be applied to cereals and bean, and some P application before potassium (K) can be applied. This is not always the case. For example, banana has similar mean yield responses to N or K application but less response to P. The FOTs do not consider other practices that affect soil nutrient supply, soil test results, or previous crop but these are considered in another step of the decision process. The FOT optimizes across crop nutrient response functions.

The FOT prototypes evolved, beginning with a six-crop and three possible nutrients version to a seven-crop and four possible nutrients version. The crops selected for a FOT varies according to importance by AEZ. The nutrients include N, P, K and either sulphur (S) or zinc (Zn). Another version includes maize-bean intercropping as one of the seven crops for which intercrop response is determined on a maize value equivalent basis. To date, 67 FOTs have been developed across the 13 countries (Table 1.1) and can be downloaded from the OFRA Tools page at http://agronomy.unl.edu/OFRA along with instructions (Kaizzi and Wortmann 2015).

1.5 Using the Excel FOT

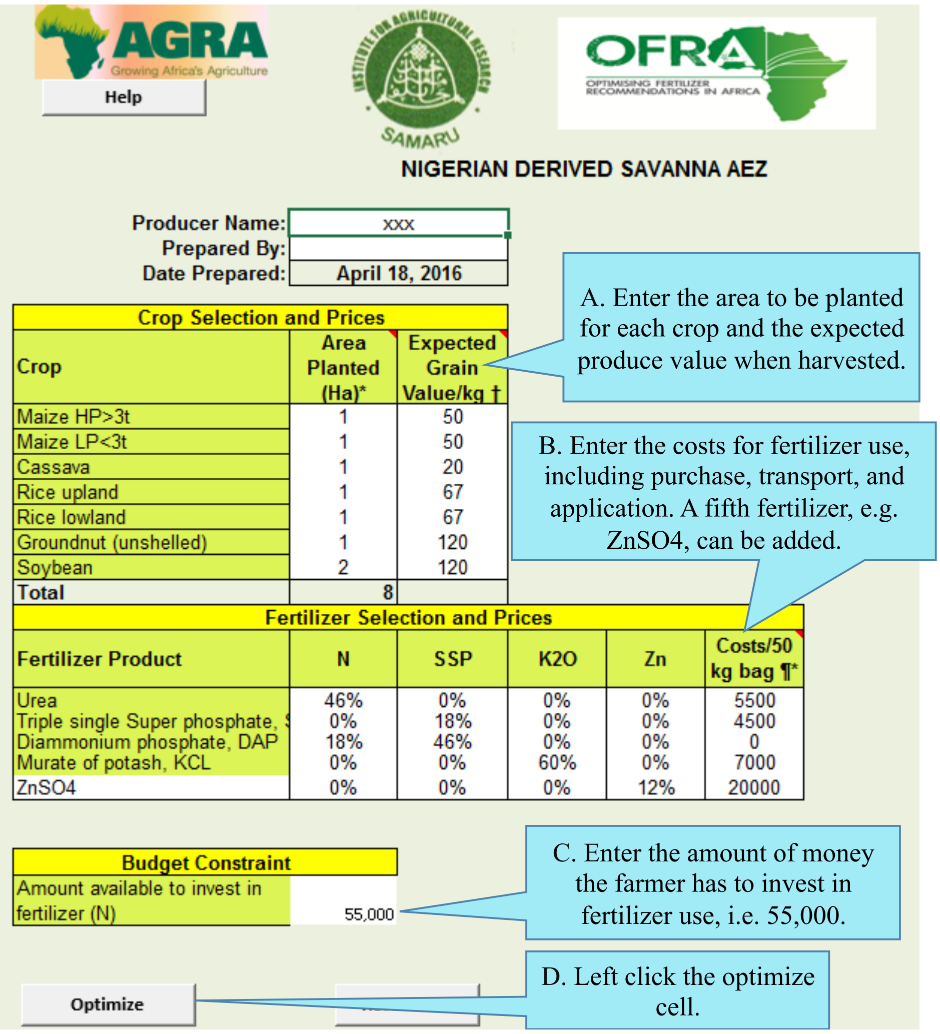
Use of the Excel FOT requires that the Solver add-in is engaged. If Solver is activated, it will appear under the Data tab, far to the right on the Quick Access Toolbar. The following steps to activating Solver are also available in the 'Help and Instructions' worksheet of FOTs and, in more detail, in Kaizzi and Wortmann (2015) at http://agronomy.unl.edu/OFRA.

1) Select the File tab on the Quick Access Toolbar
2) Select Options on File drop down menu
3) Select Add-Ins on the left hand side of the Excel Options window
4) In the Add-Ins drop down list, select the Solver Add-in options
5) Select Go
6) Select Solver Add-In again
7) Click OK

The data input panel of the FOT is shown in Figure 1.4. The user enters the estimated area to be planted and the expected value per kg of produce for each crop on farm at harvest considering the value of that saved for home consumption and that expected to be sold (A). The costs of using available fertilizers (B) and the amount of money the farmer has to invest in fertilizer use are entered (C). Click on the 'Optimize' cell to run the optimization (D). The output results are generated (Figure 1.5).

Table 1.1: Agro-ecological zones by country for which fertilizer optimization tools were developed

Burkina Faso		
Sahel Savanna	North Sudan Savanna	South Sudan Savanna
Ethiopia		
Cold-v. cold sub-Afro Alpine	Moist lowlands <9° latitude	Moist lowlands >9° latitude
Sub-moist lowlands <1000 m	Sub-moist lowlands >1000 m	Humid highland 1700-2200 m
Humid highland 2000-2700 m	Sub-humid highland 1700-2200 m	Sub-humid highland 2000-2700 m
Moist highland 1700-2200 m	Moist highland 2000-2700 m	Sub-moist highland 1700-2200 m
Sub-moist highland 2000-2700 m		
Ghana		
South Sudan Savanna	North Guinea Savanna	South Guinea Savanna
Derived/transitional Savanna		
Kenya		
Coastal	Eastern, above 1200 m	Eastern, below 1300 m
Central	Rift Valley, above 2000 m	Rift Valley, below 2200 m
Western, above 1400 m	Western, below 1600 m	
Malawi		
<900 m	900-1300 m	>1300 m
Mali		
Sahel Savanna	North Sudan Savanna	South Sudan Savanna
Mozambique		
<900 m	900-1300 m	>1300 m
Niger		
Sahel Savanna	North Sudan Savanna	
Nigeria		
Sahel Savanna	Sudan Savanna	North Guinea Savanna
South Guinea Savanna	Derived/transitional Savanna	Mid-altitude
Rwanda		
Northwestern	Eastern	Southern
Tanzania		
Northern	Lake >1300 m	Lake <1400 m
Eastern	Central	Western
Southern	Southern Highlands	
Uganda		
Eastern >1800 m	Eastern 1400-1800 m	Eastern <1400 m
North, Midwest	Central	Western Highlands: Ibanda, Bushenyi, Kyenjojo
Western Highlands: Kabale, Kisoro, Rukungiri,	Western Highlands >1800 m	
Zambia		
Zone I	Zone II	Zone III



NIGERIAN DERIVED SAVANNA AEZ

Producer Name: xxx
Prepared By:
Date Prepared: April 18, 2016

Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Maize HP>3t	1	50
Maize LP<3t	1	50
Cassava	1	20
Rice upland	1	67
Rice lowland	1	67
Groundnut (unshelled)	1	120
Soybean	2	120
Total	8	

Fertilizer Selection and Prices					
Fertilizer Product	N	SSP	K2O	Zn	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	5500
Triple single Super phosphate,	0%	18%	0%	0%	4500
Diammonium phosphate, DAP	18%	46%	0%	0%	0
Murate of potash, KCL	0%	0%	60%	0%	7000
ZnSO4	0%	0%	0%	12%	20000

Budget Constraint	
Amount available to invest in fertilizer (N)	55,000

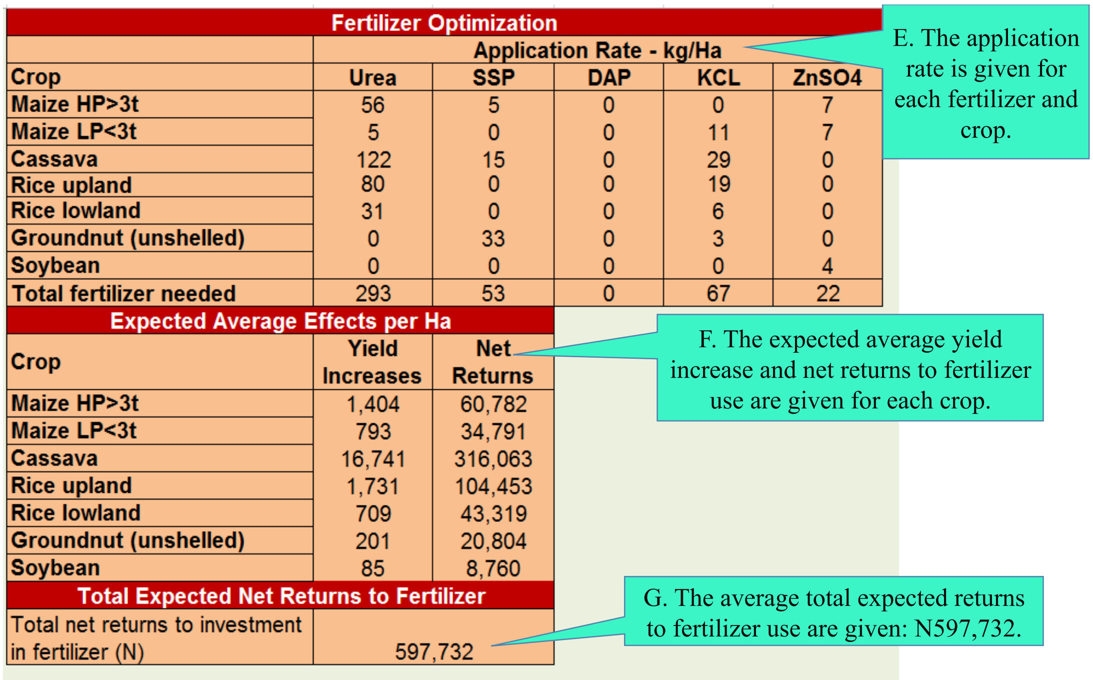
A. Enter the area to be planted for each crop and the expected produce value when harvested.

B. Enter the costs for fertilizer use, including purchase, transport, and application. A fifth fertilizer, e.g. ZnSO4, can be added.

C. Enter the amount of money the farmer has to invest in fertilizer use, i.e. 55,000.

D. Left click the optimize cell.

Figure 1.4: The input panel of the OFRA Fertilizer Optimization Tool for the Derived Savanna of Nigeria.



Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	Urea	SSP	DAP	KCL	ZnSO4
Maize HP>3t	56	5	0	0	7
Maize LP<3t	5	0	0	11	7
Cassava	122	15	0	29	0
Rice upland	80	0	0	19	0
Rice lowland	31	0	0	6	0
Groundnut (unshelled)	0	33	0	3	0
Soybean	0	0	0	0	4
Total fertilizer needed	293	53	0	67	22

Expected Average Effects per Ha		
Crop	Yield Increases	Net Returns
Maize HP>3t	1,404	60,782
Maize LP<3t	793	34,791
Cassava	16,741	316,063
Rice upland	1,731	104,453
Rice lowland	709	43,319
Groundnut (unshelled)	201	20,804
Soybean	85	8,760

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer (N)	597,732

E. The application rate is given for each fertilizer and crop.

F. The expected average yield increase and net returns to fertilizer use are given for each crop.

G. The average total expected returns to fertilizer use are given: N597,732.

Figure 1.5: The output panel of the OFRA Fertilizer Optimization Tool for the Derived Savanna of Nigeria.

In this example, the farmer had Nigerian naira 55,000 to use on eight hectares for food crop production. The upper output panel (E) shows the fertilizer recommended for each crop given the financial constraints. The second panel (F) gives the average expected yield increase and net returns to fertilizer use for these levels of application. The third panel (G) gives the expected average total net returns to fertilizer use recommended in the FOT, that is, Naira 597,732.

Increasing the amount of money available for fertilizer use will increase the rates and expected net returns until the fertilizer rates are at the point where net return per hectare is maximized. Further increases in the budget allocation will not result in increased application rates as additional application would exceed the optimized rates and result in a loss of profit.

The current recommendation for high potential maize in the Derived Savanna of Nigeria is to apply 150, 33, and 65 kg/ha of N, P and K (Chapter 12). If the available Naira were used to fertilize maize at the recommended rate while using grain values and fertilizer use costs as in Fig. 1.4, the fertilizer would have been sufficient for 0.81 ha and the expected average net returns would have been Naira 35,013 and only 6% of returns with the optimized fertilizer use.

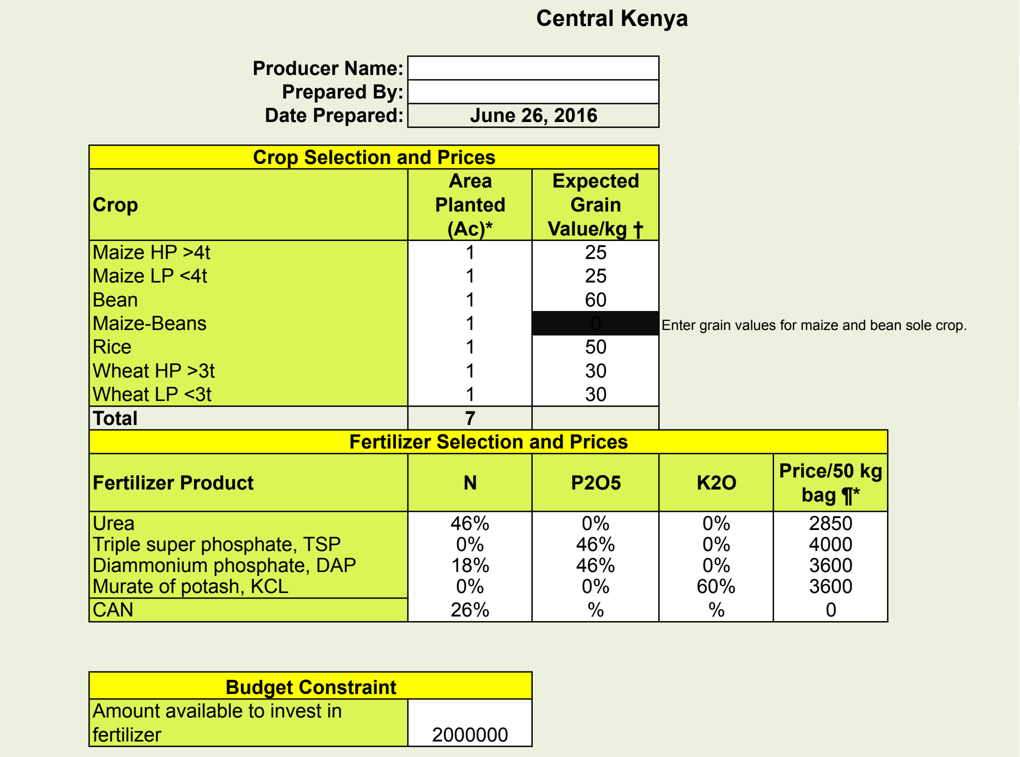
1.6 Paper versions of FOTs

The Excel Solver FOT requires a computer but easy to use AEZ-specific paper-based FOTs were developed for use when a computer is not available. The paper FOTs are updated annually or as needed due to major price and cost changes at national or regional levels. Some profit potential is sacrificed in decision making with the paper compared with the Excel FOT due to generalized input information and recommendations.

The paper FOT lists assumptions including available fertilizer and commodity values. It also provides guidelines for selecting the right product, rate, method and time of application, that is, the 4Rs of fertilizer use (http://www.nutrientstewardship.com/implement-4rs).

For each fertilizer, the paper FOT provides guidance on how to calibrate or learn the rate of application; therefore, assumptions are made for readily available fertilizer measurement units (such as plastic bottles) and for crop row and plant spacing. The paper FOT considers three levels of farmer financial ability with corresponding fertilizer use guidelines.

Financial ability level 1 represents the most financially constrained who are able to use less than one-third of fertilizer applied to all cropland



Central Kenya

Producer Name:	
Prepared By:	
Date Prepared:	**June 26, 2016**

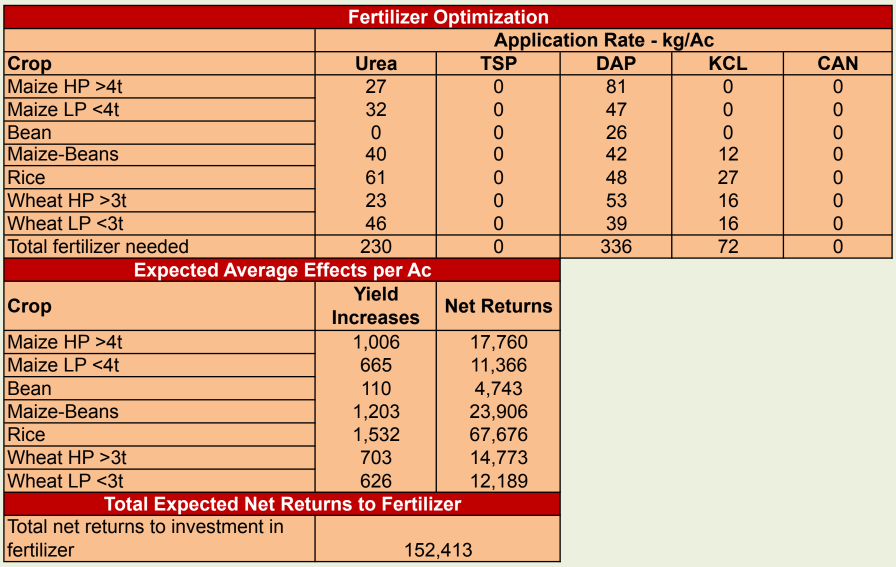
Crop Selection and Prices		
Crop	**Area Planted (Ac)***	**Expected Grain Value/kg †**
Maize HP >4t	1	25
Maize LP <4t	1	25
Bean	1	60
Maize-Beans	1	0
Rice	1	50
Wheat HP >3t	1	30
Wheat LP <3t	1	30
Total	**7**	

Enter grain values for maize and bean sole crop.

Fertilizer Selection and Prices				
Fertilizer Product	**N**	**P2O5**	**K2O**	**Price/50 kg bag ¶***
Urea	46%	0%	0%	2850
Triple super phosphate, TSP	0%	46%	0%	4000
Diammonium phosphate, DAP	18%	46%	0%	3600
Murate of potash, KCL	0%	0%	60%	3600
CAN	26%	%	%	0

Budget Constraint	
Amount available to invest in fertilizer	2000000

Figure 1.6: An FOT set up to determine the output for developing a paper FOT.



Fertilizer Optimization

	Application Rate - kg/Ac				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**CAN**
Maize HP >4t	27	0	81	0	0
Maize LP <4t	32	0	47	0	0
Bean	0	0	26	0	0
Maize-Beans	40	0	42	12	0
Rice	61	0	48	27	0
Wheat HP >3t	23	0	53	16	0
Wheat LP <3t	46	0	39	16	0
Total fertilizer needed	230	0	336	72	0

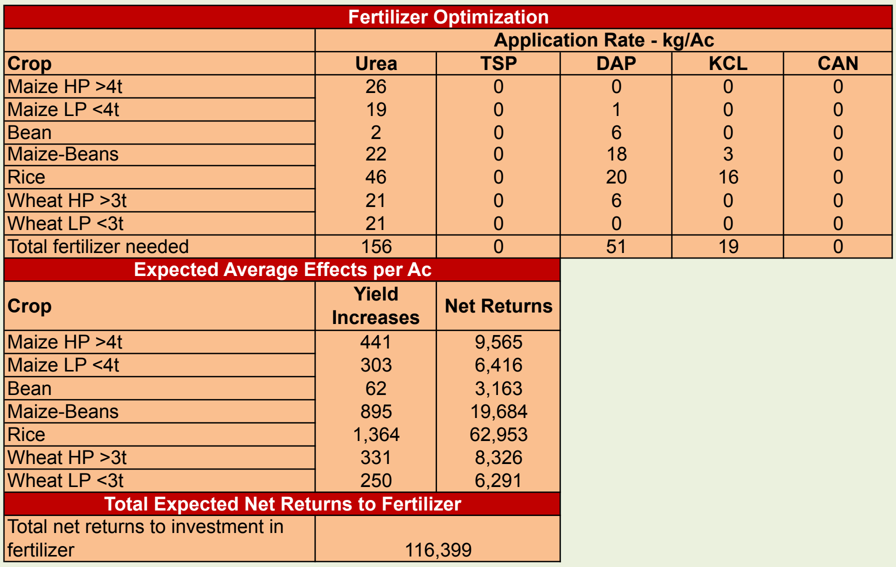
Expected Average Effects per Ac

Crop	Yield Increases	Net Returns
Maize HP >4t	1,006	17,760
Maize LP <4t	665	11,366
Bean	110	4,743
Maize-Beans	1,203	23,906
Rice	1,532	67,676
Wheat HP >3t	703	14,773
Wheat LP <3t	626	12,189

Total Expected Net Returns to Fertilizer

Total net returns to investment in fertilizer	152,413

Figure 1.7a: An FOT output for determining the recommended rates for financial ability level 3 in a paper FOT. This required Kenya Sh 41,936 for fertilizer costs.



Fertilizer Optimization

	Application Rate - kg/Ac				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**CAN**
Maize HP >4t	26	0	0	0	0
Maize LP <4t	19	0	1	0	0
Bean	2	0	6	0	0
Maize-Beans	22	0	18	3	0
Rice	46	0	20	16	0
Wheat HP >3t	21	0	6	0	0
Wheat LP <3t	21	0	0	0	0
Total fertilizer needed	156	0	51	19	0

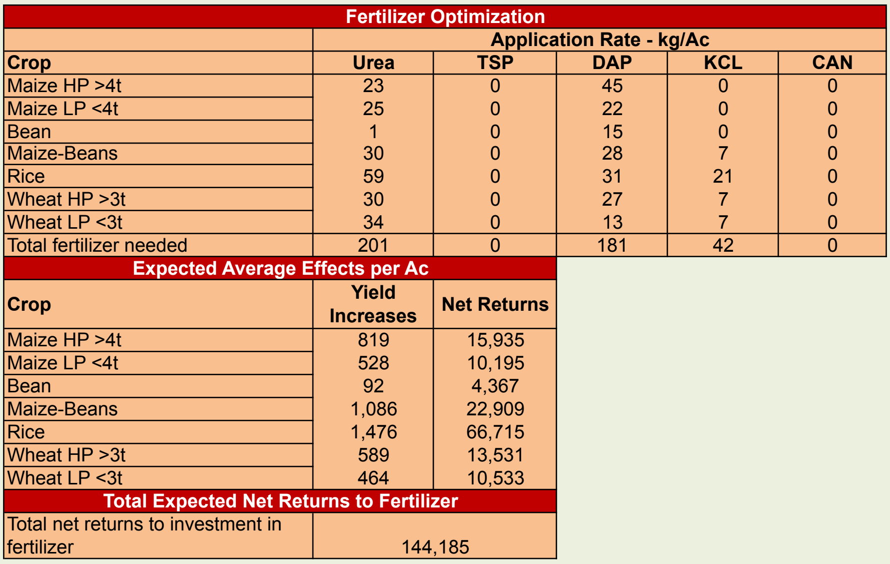
Expected Average Effects per Ac

Crop	Yield Increases	Net Returns
Maize HP >4t	441	9,565
Maize LP <4t	303	6,416
Bean	62	3,163
Maize-Beans	895	19,684
Rice	1,364	62,953
Wheat HP >3t	331	8,326
Wheat LP <3t	250	6,291

Total Expected Net Returns to Fertilizer

Total net returns to investment in fertilizer	116,399

Figure 1.7b: An FOT output for determining the recommended rates for financial ability level 1 in a paper FOT. This required Kenya Sh 13,979 for fertilizer costs.



Fertilizer Optimization

	Application Rate - kg/Ac				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**CAN**
Maize HP >4t	23	0	45	0	0
Maize LP <4t	25	0	22	0	0
Bean	1	0	15	0	0
Maize-Beans	30	0	28	7	0
Rice	59	0	31	21	0
Wheat HP >3t	30	0	27	7	0
Wheat LP <3t	34	0	13	7	0
Total fertilizer needed	201	0	181	42	0

Expected Average Effects per Ac

Crop	Yield Increases	Net Returns
Maize HP >4t	819	15,935
Maize LP <4t	528	10,195
Bean	92	4,367
Maize-Beans	1,086	22,909
Rice	1,476	66,715
Wheat HP >3t	589	13,531
Wheat LP <3t	464	10,533

Total Expected Net Returns to Fertilizer

Total net returns to investment in fertilizer	144,185

Figure 1.7c: An FOT output for determining the recommended rates for financial ability level 2 in a paper FOT. This required Kenya Sh 13,979 for fertilizer costs.

at the rate to maximize net returns to fertilizer use per hectare, also called the economically optimal rate (EOR). Financial ability level 2 represents the less financially constrained who are able to use less than two-thirds of the fertilizer applied to all cropland at EOR. Financial ability level 3 is for the farmer who can apply at EOR to at least some if not all cropland. Applying nutrients in excess of the financial ability level 3 is expected to result in declining profit.

The paper FOTs are developed and updated with the Excel FOT, with the Central Kenya FOT (Figure 1.6) as an example. 1) Using the Excel FOT, current information is entered for crop values (considering expected ‘farm-gate’ price and value if kept for home consumption) and fertilizer use costs (price plus costs of procurement and application). 2) Enter 1 acre or hectare for each crop. 3) Run the FOT using an excessive budget constraint to ensure the fertilizer recommendations are not finance constrained and therefore at EOR; in the example, the budget constraint is KSh 2,000,000 which is an excessive amount but the FOT will only use that needed for EOR. 4) Optimize.

From the output sheet (Figure 1.7a), get the ‘Total fertilizer needed’ and multiply the amount for each fertilizer by its cost for 50 kg. Total these to determine the amount of money required to apply fertilizers to one ac/ha for each crop at EOR. From the example, this gave a total cost of KSh 41,936. Keep a record of these fertilizer recommendations for each crop as these are the financial ability level 3 recommendations.

Keeping all of the other input data unchanged, optimize with a budget constraint of 1/3 the total needed, that is KSh 13,979, for the financial ability level 1 recommendations (Figure 1.7b). Repeat this for financial ability level 2 recommendations using KSh 27,597 (Figure 1.7c).

Use the three sets of fertilizer recommendations to construct the paper FOT (Table 1.2).

Determine your calibration measuring units and their volume. In the example from Central Kenya, the measuring units are a 5 ml water bottle lid and a water bottle cut to 4-cm height with an 80-ml volume. Both units are readily available in rural areas. These units with guidance enable a farmer to calibrate by eye and feel the rate of application but, beyond this initial and occasional verification calibration, actual application is likely to be by hand and not with the unit. Add other assumptions including plant spacing, fertilizer costs and produce values. Write the recommendations for each level of financial ability giving the product, rate, method, and time of application and the calibration guidelines, for example ‘Lowland rice: Broadcast with a 2 m width 22 kg DAP (cut bottle for 8.1 m) and 17 kg MOP (cut bottle for 9.1 m) at planting; broadcast apply 48 kg urea at panicle initiation (cut bottle for 2.1 m)’.

1.7 Conclusion

Optimization of fertilizer use is to maximize profit due to fertilizer use. This often means striving to apply fertilizer nutrients at rates for maximizing net returns per hectare due to fertilizer use, that is applying at EOR. However, smallholder farmers typically operate under severe financial constraint and need to obtain high returns on their often small investments in fertilizer use. Their capacity to apply fertilizer is typically for rates well under EOR so they need to apply crop-nutrient options that have high profit potential.

Linear programming was used to develop fertilizer optimization tools (FOTs) that aid farmers in their choice of crop-nutrient-rate combinations likely to be most profitable given a budget constraint. Development and use of Excel and paper FOTs has been described.

Not addressed in this chapter is that optimization of fertilizer use needs to consider that other practices and field conditions affect nutrient availability. Therefore, FOT recommendations need to be adjusted for such practices as recent and past manure application, rotation with a legume, intercropping and use of a green manure crop. Soil test information should also be considered. Such practices are addressed in Chapter 3 and in the country chapters 4-16.

1.8 References

Bekunda MA, Bationo A, and Ssali H (1997) Soil fertility management in Africa. A review of selected research trials. In Buresh RJ, Sanchez PA and Calhoun F (eds) Replenishing soil fertility in Africa. SSSA Spec. Publ. 51 SSSA, Madison WI. p. 63–79.

Table 1.2: Kenya Central Fertilizer Use Optimizer: paper version, 2016

The below assumes:

- Calibration measurement is with: i) a 5 ml water bottle lid (lid) that holds about 3.5 g urea and 5.5 g DAP and MOP, ii) a 500 ml water bottle of 5 cm diameter cut to height of 4m (cut bottle) holds 80 ml, 56 g urea and 88 g DAP or MOP.
- It is assumed maize is planted with 75 cm, bean 50 cm, rice 25 cm and wheat 25 cm row spacing.
- It is assumed grain prices per kg (KSh): 25 maize, 60 bean, 50 rice and 30 wheat.
- It is assumed 50 kg of fertilizer costs (KSh): 2850 urea, 3600 DAP and 3600 MOP.
- Application rates are in kg/ac. Fertilizer rates < 10 kg/ac are not feasible for application.

Level 1 financial ability.	
Maize HP >4t	Band 29 kg urea as a top dress (lid for 0.4 m) at 6 WAP.
Maize LP <4t	Band 23 kg urea as a top dress (lid for 5 m) at 6 WAP.
Maize-Bean intercropping	Band 16 kg DAP (lid for 0.8 m) at planting; top dress 23 kg urea (lid for 0.5 m) at 6 WAP.
Lowland rice	Broadcast with a 2 m width 22 kg DAP (cut bottle for 8.1 m) and 17 kg MOP (cut bottle for 9.1 m) at planting; broadcast apply 48 kg urea at panicle initiation (cut bottle for 2.1 m).
Wheat HP>3t	Band 13 kg DAP (lid for 4.1 m) at planting; top dress by banding 24 kg urea at panicle initiation (lid for 1.7 m).
Wheat LP<3t	Band 28 kg urea at panicle initiation (lid for 1.5 m).
Level 2 financial ability.	
Maize HP >4t	Band 65 kg DAP (lid for 0.3 m) at planting; top dress 22 kg urea (lid for 0.6 m) at 6 WAP.
Maize LP <4t	Band 31 kg DAP (lid for 0.8 m) at planting; top dress 28 kg urea (lid for 0.5 m) at 6 WAP.
Bean	Band 19 kg DAP at planting (lid for 1.7 m).
Maize-Bean intercropping	Band 30 kg DAP (lid for 0.8 m) at planting; top dress 35 kg urea (lid for 0.4 m) at 6 WAP.
Lowland rice	Broadcast with a 2 m width 36 kg DAP (cut bottle for 4.6 m) and 23 kg MOP (cut bottle for 7 m) at planting; top dress 61 kg urea at panicle initiation (cut bottle for 1.6 m).
Wheat HP>3t	Band 36 kg DAP (lid for 1.8 m) and 10 kg MOP (lid for 6.8 m) at planting; top dress 30 kg urea at panicle initiation (lid for 1.3 m).
Wheat LP<3t	Band 22 kg DAP (lid for 3 m) and 10 kg MOP (lid for 6.8 m) at planting; top dress 38 kg urea at panicle initiation (lid for 1.0 m).
Level 3 financial ability (maximize profit per acre).	
Maize HP>4t	Band 81 kg DAP (lid for 0.3 m) at planting; top dress 27 kg urea (lid for 0.5 m) at 6 WAP.
Maize LP<4t	Band 47 kg DAP (lid for 0.5 m) at planting; top dress 32 kg urea (lid for 0.4 m) at 6 WAP.
Bean	Band 26 kg DAP at planting (lid for 1.3 m).
Maize-Bean intercropping	Band 38 kg DAP (lid for 0.6 m) at planting; top dress 42kg urea (lid for 0.3 m) at 6 WAP.
Lowland rice	Broadcast with a 2 m width 48 kg DAP (cut bottle for 3.5 m) and 27 kg MOP (cut bottle for 6.2 m) at planting; top dress 61 kg urea at panicle initiation (cut bottle for 2.4 m).
Wheat HP>3t	Band 53 kg DAP (lid for 1.2 m) and 16 kg MOP (lid for 4.2 m) at planting; top dress 23 kg urea at panicle initiation (lid for 1.7 m).
Wheat LP<3t	Band 39 kg DAP (lid for 1.7 m) and 17 kg MOP (lid for 4 m) at planting; top dress 46 kg urea at panicle initiation (lid for 0.9 m).

Homer-Dixon TF, Bountwell JH, and Rathfens GW (1993) Environmental change and violent conflict. Sci. Am. 268:16-23

Jansen J, Wortmann CS, Stockton MC, and Kaizzi CK (2013) Maximizing net returns to financially constrained fertilizer use. Agron. J. 105:573-578

Kaizzi KC and Wortmann CS (2015) Optimizing fertilizer use within an integrated soil fertility management framework: Fertilizer Optimizer Training Manual. http://agronomy.unl.edu/OFRA

Kumar N (2013) Optimization methods, historical development and model building. Banglore, India

Stoorvogel JJ, Smaling EMA, and Janssen BH (1993) Calculating soil nutrient balances in Africa at different Scales I. Supra-natural scale. Fert. Res. 35:227-235