Maximizing Net Returns to Financially Constrained Fertilizer Use

J. A. Jansen, C. S. Wortmann,* M. A. Stockton, and C. K. Kaizzi

ABSTRACT

Financial constraints commonly limit fertilizer use by smallholder farmers as they strive to maximize net returns on their investments. Fifteen crop–nutrient response functions, including six crops, were derived from the results of 80 trials conducted in Uganda. The net return to nutrient application for typical fertilizer use costs and grain prices in Uganda was greatest for a small amount of N applied to dry bean (*Phaseolus vulgaris* L.), followed by N applied to rice (*Oryza* spp.), P applied to groundnut (*Arachis hypogaea* L.) and soybean [*Glycine max* (L.) Merr.], and then N applied to maize (*Zea mays* L.) and grain sorghum [*Sorghum bicolor* (L.) Moench]. Net returns were less for the remaining nine response functions. The Uganda Fertilizer Optimization Tool was developed for Uganda to maximize net returns to fertilizer use for finance-limited crop management. It considers the area of each crop to be planted, fertilizer costs, expected grain value, and the money available for investment. The tool optimizes across response functions to provide the crop–nutrient–rate combinations expected to maximize net returns. In an example with 1 ha each of the above six crops and US$170 available for fertilizer use, the optimized net return was US$1918 compared with US$676 and US$804 for US$170 of fertilizer applied to maize and rice, respectively, at rates to maximize net returns per hectare. This approach to fertilizer use of maximizing net returns on investment can gradually enable much increased fertilizer use because of the relatively high returns on investment compared with traditional fertilizer use recommendations.

The yields of cereal and legume crops produced for food security and market have not increased significantly in much of sub-Saharan Africa since the 1980s, partly due to low or declining soil fertility (Sanchez et al., 1996; Muchena et al., 2005). Fertilizer use by financially constrained farmers has not increased substantially. The cost of fertilizer use per kilogram applied is often two to six times higher in sub-Saharan Africa than in the United States or Europe due to higher transportation costs, market inefficiencies, importation costs, and other expenses (Vlek, 1990; Sanchez, 2002). The lack of credit and agricultural subsidies commonly makes conditions even worse for financially constrained farmers (Heisey and Mwangi, 1996).

Excessively high fertilizer expenses lead to unfavorable fertilizer use costs to grain price ratios (CP) and low net returns to fertilizer use. Financially constrained farmers need large returns on their relatively small investment to justify the expense of fertilizer use. A guideline used in evaluating the potential for the adoption of practices by financially constrained farmers is the need for a 100% net return on investment (CIMMYT, 1988, p. 34–35; Wortmann and Ssali, 2001). Excessively high nutrient costs and severely constrained budgets require that such farmers strive to maximize their net returns on their small investment in fertilizer subject to the availability of financial resources.

Curvilinear response functions relating crop yield response to applied nutrients estimate the increase in yield with nutrient application. The crop response to applied nutrients is a gradually decreasing marginal increase in yield with increased rate of application until a maximum yield, or the point where one or more other constraints prevail over the nutrient deficiency, beyond which an increased application rate does not result in increased yield. At low rates of application, the response is steep, with relatively great change in yield per unit of nutrient applied (Fig. 1). The change in yield per unit applied diminishes as the maximum or plateau yield is approached. Once the plateau is reached, additional nutrient application does not result in additional yield.

Three approaches to the determination of nutrient application rates can be considered (Fig. 1):

1. The response functions can be used to determine the nutrient application rate to achieve a targeted percentage, for example 98%, of the maximum yield per hectare.
2. If the CP is considered, the application rate required to maximize net returns per hectare resulting from application of a fertilizer nutrient, a common goal with financially unconstrained fertilizer use, can be determined. This rate is often called the *economically optimal rate* (Dobermann et al., 2011) or the rate of maximum net returns to fertilizer use, where the additional fertilizer cost equals the

J.A. Jansen and C.S. Wortmann, Dep. of Agronomy and Horticulture, Univ. of Nebraska, Lincoln, NE 68583; M.A. Stockton, Dep. of Agricultural Economics, Univ. of Nebraska, Lincoln, NE 68583; and C.K. Kaizzi, National Agricultural Research Laboratories–Kawanda, P.O. Box 7065, Kampala, Uganda. Received 27 Oct. 2012.*Corresponding author (cwortmann2@unl.edu).

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Abbreviations: CP, fertilizer cost/grain price ratio; MVI, marginal value of investment.

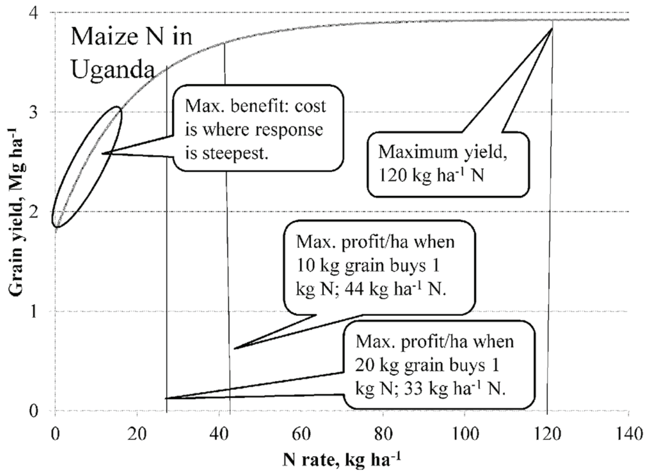

Fig. 1. Fertilizer rates can be determined from curvilinear yield response functions with the aim of (i) achieving maximum or some percentage of maximum yield, (ii) maximizing net returns per hectare due to fertilizer use in consideration of fertilizer cost relative to grain value; or (iii) maximizing net returns on a finance-constrained investment in fertilizer.

value of the increased yield. Beyond this point, net returns to additional fertilizer use diminishes even though yield continues to increase until the yield plateau is reached.

3. If the CP and the financial constraint of the farmer are considered, the nutrient application rate that maximizes net returns on the financially constrained investment in fertilizer use can be determined.

Distinguishing among these three approaches to the determination of nutrient application rates is important for maximizing profitability for financially constrained farmers.

Uganda farmers commonly have diverse cropping systems, with several crops likely to be responsive to applied nutrients (Wortmann and Eledu, 1999). The crop–nutrient combination, in addition to the rate of application, needs to be considered in maximizing net returns to financially constrained fertilizer use. Maximizing the net returns to a financially constrained fertilizer investment requires prioritizing crop–nutrient combinations according to net returns until the monetary investment is exhausted. Depending on the availability of financial resources, some crops may not receive fertilizer and others may receive only low application rates.

Fertilizer response functions were determined for 15 crop–nutrient combinations based on replicated field research across multiple site-seasons in Uganda including: maize (22 site-seasons); sorghum (11); upland rice (5); dry bean (12); groundnut or peanut (13); and soybean (17) (Kaizzi et al., 2012a, 2012b, 2012c). The sites represented the 1000- to 1900-m elevation zone with growing-season precipitation of >400 mm, soil sand content ranging from 25 to 70%, and an unrestricted rooting depth of >0.9 m. Responses were determined using asymptotic functions taking the form of an exponential rise to approach the maximum or plateau yield. The asymptotic function was $y = a - bc^n$, where y is yield (Mg ha^{-1}), a is the approximate maximum or plateau yield (Mg ha^{-1}), b is the gain in yield (Mg ha^{-1}) due to nutrient application, and c^n represents the shape of the response curve, where c is a curvature coefficient and n is the nutrient application rate (kg ha^{-1}). The grain yield response functions for N and P were significant for maize, sorghum, upland rice, and dry bean, and P and K response functions were significant for soybean and groundnut (Table 1). Although rate × site-season interactions occurred, variations in responses and economically optimal nutrient rates were not related to variations in grain yield, rainfall amount, soil test results, or the previous crop (Kaizzi et al., 2012a, 2012b, 2012c). Failure of the soil test results to account for a significant variation in the yield response to applied nutrients could be expected because yield in Uganda is constrained by diverse and often interacting biotic and abiotic factors in addition to an inadequate soil nutrient supply. Soil test values are often not predictive of yield response to applied N, and maize N recommendations across most of the U.S. Corn Belt are not made based on soil test information (Sawyer et al., 2006). Soil test P for the Uganda sites was ≤12 mg kg^{-1} by Mehlich 3 (Mehlich, 1984; Kaizzi et al., 2012a, 2012b, 2012c) and at levels with a high probability of response to applied P. Exchangeable K levels for the Uganda sites were ≥135 mg kg^{-1} and at levels with a low probability of yield response to applied K for the cereal crops, although there was a significant but small mean yield response for soybean and groundnut.

Predicted net benefits associated with incremental fertilizer units applied differed for crop–nutrient combinations (Fig. 2). For each additional U.S. dollar per hectare invested, the resulting returns for that dollar investment is less than for the previous dollar, with a declining marginal effect per unit of additional marginal investment. Differences in declining marginal rates of return provide a basis for determining the crop–nutrient–rate

Table 1. Coefficients for crop–nutrient asymptotic response functions of grain yield (y, Mg ha^{-1}) determined for Uganda (sources: Kaizzi et al., 2012a, 2012b, 2012c; unpublished upland rice results, 2012) using the equation $y = a - bc^n$, where a is the yield at the asymptote (Mg ha^{-1}), b is the gain in yield (Mg ha^{-1}) due to nutrient application, and c^n represents the shape of the response curve, where c is a curvature coefficient and n is the nutrient application rate (kg ha^{-1}).

	Site	Nitrogen			Phosphorus			Potassium†		
Crop	seasons	*a*	*b*	*c*	*a*	b	c	a	b	c
Maize	22	3.92	2.14	0.948	3.98	0.377	0.809			
Grain sorghum	11	2.27	1.58	0.932	2.30	0.362	0.839			
Upland rice	5	3.67	2.40	0.958	3.79	0.556	0.947			
Dry bean	12	1.79	0.99	0.892	1.81	0.286	0.926			
Soybean	17				1.92	1.09	0.887	1.97	0.285	0.974
Groundnut	13				1.79	0.94	0.893	1.72	0.221	0.942

† Potassium effects were not significant for cereal crops or bean.

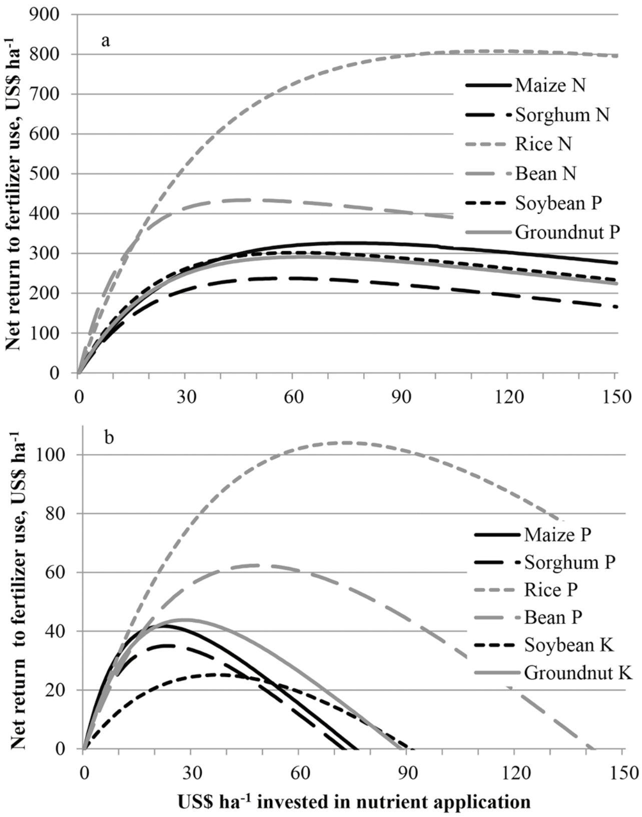

Fig. 2. Added net returns of each added unit invested in fertilizer for six crop–nutrient combinations with (a) relatively high and (b) relatively low net returns.

combinations that are expected to maximize net returns for a financially constrained investment in fertilizer use.

Selection of the crop–nutrient–rate combinations that are expected to maximize net returns is complex for the farmer who has diverse crops and fertilizer needs in excess of investment capacity. The objective of this research was to develop a user-friendly decision tool for optimization of the choice of crop–nutrient–rate combinations for maximization of net returns on finance-constrained fertilizer investment.

Features of the Uganda Fertilizer Optimization Tool

The Uganda Fertilizer Optimization Tool developed for financially constrained fertilizer use in Uganda maximizes net returns to fertilizer N, P, and K investments. The tool optimizes solutions using the Solver add-on (Frontline Systems Inc.) of Microsoft Office Excel 2007 or later and provides an output summary of the optimal crop–nutrient–rate combinations along with expected yield increases and net returns to investment (Fig. 3).

The process stage of the tool considers the farmer input data or farmer-specified constraints, predetermined model constraints, and the model's optimization mode (Fig. 3). The farmer-imposed constraints include: (i) the expected land area to be planted and the predicted value at harvest for maize, sorghum, upland rice, bean, soybean, and groundnut, with zero entered for the land area if the crop will not be planted; (ii) fertilizers available, including urea, triple superphosphate, diammonium phosphate, KCl, or another available product with its $N–P_2O_5–K_2O$ content specified; (iii) the cost of using each fertilizer, including purchase, interest, delivery, and application costs; and (iv) the farmer's budget constraint, or the amount of money available for fertilizer use whether borrowed or saved (Fig. 4a). The model is constrained to avoid exceeding the range of inference for the underlying equations, with maximum and minimum fertilizer amount limits imposed by the model for the 15 crop–nutrient response functions. Maximums prevent the amount of a specific nutrient recommended for a crop–nutrient function from exceeding the nutrient rate required for the yield response to plateau, a possibility with very low CP values below the range of inference of the equations. Minimum nutrient application rates of 0 kg ha^{-1} for all crop–nutrient response functions prevent a non-negativity constraint of the objective function. Finally, in accordance with research methodology to determine the relevant crop–nutrient response functions based on Liebig's law of the minimum, the tool requires some N application before P can be applied to cereals and bean, and some P application before K can be applied to soybean and groundnut. The tool does not consider factors that might affect the response to an applied nutrient such as expected yield or rainfall amount, soil test results, or previous crop because these did not have significant effects on the crop–nutrient responses (Kaizzi et al., 2012a, 2012b, 2012c); this is discussed below. The tool does not consider nutrients other than N, P, and K and only the above-mentioned six crops because adequate crop–nutrient response functions are not yet available, although these could be added once available.

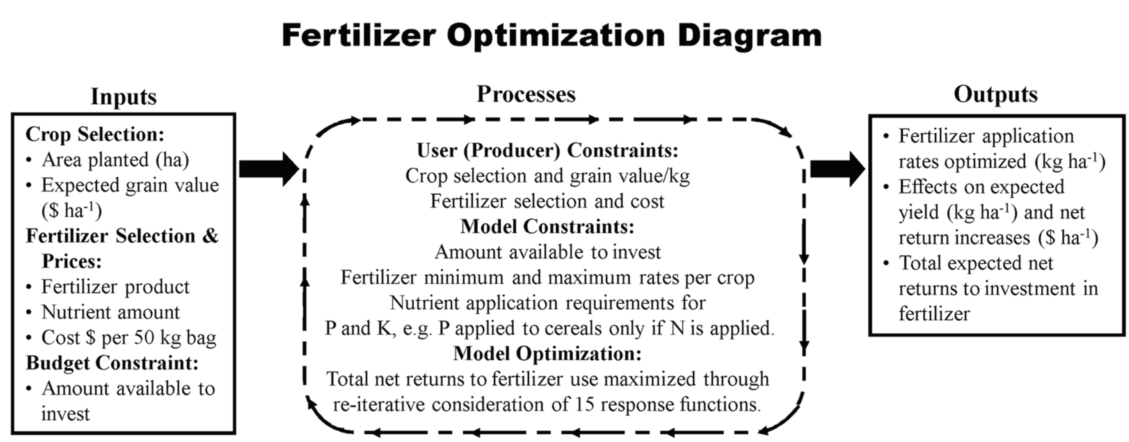

Fig. 3. Operational flow model of the Fertilizer Optimization Tool developed for Uganda.

a

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	June 19, 2012

Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Maize	0	0
Sorghum	0	0
Upland rice, paddy	0	0
Beans	0	0
Soybeans	0	0
Groundnuts, unshelled	0	0
Total hectares	**0**	

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

Budget Constraint	
Amount available to invest in fertilizer	0

b

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	Urea	TSP	DAP	KCL	xxx
Maize	0	0	0	0	0
Sorghum	0	0	0	0	0
Upland rice, paddy	0	0	0	0	0
Beans	0	0	0	0	0
Soybeans	0	0	0	0	0
Groundnuts, unshelled	0	0	0	0	0
Total	**0**	**0**	**0**	**0**	**0**

Expected Average Effects per Ha		
Crop	Yield Increases	Net Returns
Maize	0	0
Sorghum	0	0
Upland rice, paddy	0	0
Beans	0	0
Soybeans	0	0
Groundnuts, unshelled	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	0

Fig. 4. (a) User input interface and (b) output of the Fertilizer Optimization Tool developed for Uganda.

The reiterative process performed by the Fertilizer Optimization Tool using Microsoft Office Excel Solver version 7 or later iteratively searches for a solution that optimizes a specified mathematical function, often referred to as an objective function, subject to specified constraints. The objective function in this case is to maximize net returns to fertilizer use as the difference of added crop revenue and added fertilizer costs, subject to farmer-input-imposed constraints and the internal constraints of the tool. The 15 crop–nutrient response functions (Table 1) are combined with fertilizer use costs and expected crop values to estimate the expected net income given investment limitations until the financial resource is exhausted. It selects the crop–nutrient–rate combinations that deliver the highest net return on investment by relating to a circular reference where each combination must satisfy all constraints imposed by the user and the tool. The tool achieves the objective function of maximizing the total expected net returns to fertilizer use by determining the optimal combination of crop–nutrient–rate subject to the budget and response-function constraints. The costs for the total amount of fertilizer recommended cannot exceed the financial resources available for investment.

Once the optimal crop–nutrient–rate combinations have been determined, the results are displayed (Fig. 4b), including the optimized crop–fertilizer application rates for the 15 possible crop–nutrient combinations, the expected effects on yield and net returns to fertilizer use, and overall net returns. Each set of constraints imposed by the user delivers a unique, but optimized, solution based on attributes pertinent to the farmer's production and economic environment.

Application Examples

The Fertilizer Optimization Tool allows consideration of the area planted and the expected value of selected crops, the costs of fertilizer use, and the total budget available for investment in fertilizer use. These parameters vary with each specific smallholder's circumstances and preferences, and the resulting optimized solution is a unique result. The effect that the Fertilizer Optimization Tool has on the allocation of limited investments in fertilizer use, net returns per crop, and overall net returns is illustrated with a set of scenarios with varying monetary resources for fertilizer use, keeping all other input data constant.

The set of optimization scenarios evaluated had a land area of 1 ha planted for each of the six crops considered by the tool. Based on our observations, expected commodity values and fertilizer costs reflected those of 2011 in Uganda. Expected grain values were US\$0.20, 0.20, 0.40, 0.50, 0.35, and 0.40 kg^{-1} for maize, sorghum, rice, dry bean, soybean, and groundnut. The expected fertilizer nutrient costs were US\$1.5, 2.5, and 1.0 kg^{-1} for N, P, and K. Given these prices and expenses, a set of four scenarios involving budget constraints of US\$170, 340, 510, and 678 per farm were devised to reflect approximately 25, 50, 75, and 100%, respectively, of the total investment necessary to maximize the net returns to fertilizer use, or the 100% budget allowance, for the 6 ha of cropland.

The results of the scenario optimizations illustrate that the marginal value of investment (MVI) incrementally declined as the percentage of the full budget allowance increased, but the net returns per farm increased (Table 2). When constrained at 25% of the full budget allowance, the application of N to maize, grain sorghum, rice, and dry bean along with P to soybean and groundnut gave the highest marginal value, with a MVI of 10.9 and a net return to fertilizer use of US\$1918 per farm. Application rates were low and no nutrient was applied for nine of the crop–nutrient combinations, but the mean yield increase was 102% compared with no fertilizer applied. In comparison, investing US\$170 for fertilizer use to maximize net returns per hectare for maize and rice would have net returns of US\$676 and US\$804, respectively.

Application rates increased with a doubling of the budget to a mean of US\$56.67 ha^{-1}, or 50% of the full budget allowance, with an allocation to P applied to all crops and K applied to groundnut. The MVI was 6.94 and the net return to fertilizer use was US\$2430 per farm. The mean yield increase was 139% compared with no fertilizer applied.

With a budget constraint of 75% of the full budget allowance, or a mean of US\$85 ha^{-1}, rates were further increased and some P and K were allocated to grain sorghum and soybean, respectively. The MVI was 4.91 and the net return to fertilizer use was US\$2630 per farm. The mean yield increase was 159% compared with no fertilizer applied.

Table 2. The effects of fertilizer use decisions in Uganda on fertilizer nutrient allocation to crops and on net returns per investment and marginal value of investment (MVI).†

Crop	N	P	K	Fertilizer cost	Net return	MVI	Yield increase
	— kg ha^{-1} —			—— US\$ ha^{-1} ——		US\$ US\$$^{-1}$	kg ha^{-1}
US\$170 ha^{-1} invested, 25% of the amount needed to maximize net US\$ ha^{-1}							
Maize	18	0	0	26	235	8.93	1308
Grain sorghum	13	0	0	19	170	8.73	945
Rice	36	0	0	53	697	13.06	1875
Dry bean	16	0	0	24	392	16.20	832
Soybean	0	9	0	24	221	9.33	698
Groundnut	0	9	0	23	204	8.86	569
Overall mean					320	10.85	
US\$340 ha^{-1} invested, 50% of the amount needed to maximize net US\$ ha^{-1}							
Maize	31	4	0	56	331	5.86	1936
Grain sorghum	24	3	0	43	240	5.60	1416
Rice	53	9	0	101	836	8.24	2342
Dry bean	23	5	0	46	452	9.82	995
Soybean	0	16	0	41	276	6.73	907
Groundnut	0	17	13	55	296	5.39	870
Overall mean					405	6.94	
US\$510 ha^{-1} invested, 75% of the amount needed to maximize net US\$ ha^{-1}							
Maize	42	7	0	79	357	4.53	2179
Grain sorghum	31	6	0	63	264	4.20	1635
Rice	66	20	0	148	891	6.00	2599
Dry bean	27	13	0	73	483	6.63	1113
Soybean	0	22	23	77	313	4.06	1100
Groundnut	0	22	24	79	322	4.06	991
Overall mean					438	4.91	
US\$678 ha^{-1} invested, 100% of the amount needed to maximize net US\$ ha^{-1}							
Maize	46	10	0	93	362	3.90	2274
Grain sorghum	39	10	0	84	270	3.21	1768
Rice	79	32	0	197	903	4.59	2751
Dry bean	32	21	0	101	490	4.87	1182
Soybean	0	27	49	116	321	2.78	1220
Groundnut	0	28	36	105	328	3.13	1063
Overall mean					446	3.75	

† In this evaluation, the land area planted for each crop was 1 ha. The grain prices were US\$0.20, 0.20, 0.40, 0.50, 0.35, and 0.40 kg^{-1} for maize, sorghum, rice, dry bean, soybean, and groundnut, respectively. The expected fertilizer nutrient costs were US\$1.5, 2.5, and 1.0 kg^{-1} for N, P, and K, respectively.

Finally, with a mean allocation of US\$113 ha^{-1}, or 100% of the full budget allowance, the MVI was 3.75 and the net return to fertilizer use was increased by 2.4% compared with application at 75% of the full budget. The mean yield increase was 171% compared with no fertilizer applied and 7.1% compared with the application of 75% of the full budget allowance.

DISCUSSION

There is a great advantage to financially constrained farmers in applying fertilizer based on optimized choices of crop–nutrient–rate combinations (Table 2). Development of the Fertilizer Optimization Tool required good field research to develop robust crop–nutrient response functions. The data required to determine such functions is lacking for most crops in most countries of sub-Saharan Africa. The existing data generally have not been applied for the development of fertilizer use recommendations based on maximizing net returns to financially constrained fertilizer use. This implies a need for conducting fertilizer response research in many countries, improving the basis for adapting and extrapolating crop–nutrient responses across agroecological conditions, and interpreting the results for production where fertilizer use is financially constrained.

Fertilizer use decisions need to be within an integrated soil fertility management framework that accounts for factors that might reduce or increase nutrient application rates for a given field (Wortmann and Ssali, 2001). Nutrients from manure application can substitute for fertilizer nutrients. A green manure crop produced during the previous season may greatly diminish the response to applied nutrients, with better net returns from the application of nutrients to another field. Intercrops compared with sole crop nutrient needs should be considered. These and other factors are not built into the Fertilizer Optimization Tool, and tool construction and use would be much more complex by including them. Instead, guidelines have been drafted and are being refined for use by crop production advisors in Uganda on adjustment of the nutrient application rates determined by the tool in consideration of other soil fertility management practices, partly based on Wortmann and Ssali (2001).

The tool does not consider soil test and yield values because these did not account for significant variations in yield response to applied nutrients (Kaizzi et al., 2012a, 2012b, 2012c). This may change when and where higher yield levels are achieved in the future by better management of other abiotic and biotic constraints to yield. Also, soil testing services currently available to finance-constrained smallholder farmers typically are not adequately prompt or of sufficient quality to be of much value in deciding on nutrient application. The guidelines for using the tool within an integrated soil fertility management framework are outside the scope of this study but could include rate adjustments for soil test values although it is rare for finance-constrained farmers in Uganda to have reliable soil test information for their fields. Based on research done elsewhere, the guidelines could, for example, advise against P application with Mehlich 3 >15 mg kg^{-1} or advise increased K application when extractable K is <120 mg kg^{-1}.

The Fertilizer Optimization Tool now runs with Excel Solver. Access to a computer is limited for many smallholder farmers. Training is provided to government and non-government extension, including private-sector crop advisors, expecting them to run the tool for farmers. Development of a cell phone application is planned that would enable people to provide the input data to a virtual server based version of the tool that would then reply with the output.

The capacity of the Fertilizer Optimization Tool could be extended to estimate land allocation to crops within farmer-imposed minimum and maximum constraints on the area allocated to each crop. This has the potential for further increasing net returns to fertilizer use. A prototype version of the tool with the capacity to estimate optimal land allocation to crops has been developed but has not yet been evaluated with Ugandan stakeholders.

The underlying concepts of this approach to fertilizer use optimization by financially constrained farmers described here are widely applicable. It requires that fundamental fertilizer use research be conducted in more countries and for other important crops to develop the crop nutrient response curves, especially at moderate to low levels of application. The tool can then be easily adapted for those countries, changing coefficients and crops as needed. The availability of single-nutrient fertilizers such as urea and triple superphosphate is important to optimization of fertilizer use. Many countries provide P and K only as components of compound fertilizers, but this requires farmers to buy and apply nutrients that do not result in the greatest net returns, thereby reducing the profitability of fertilizer use.

CONCLUSION

The research-based Fertilizer Optimization Tool for Uganda provides an opportunity to greatly improve the net returns and increase productivity per hectare to financially constrained fertilizer use. The expectation is that farmers will gain the capacity for fertilizer use as the improved net returns allow increased fertilizer use. Fertilizer use should be within an integrated nutrient management framework, considering nutrient availability from applied manure and other sources.

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