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Maximising net returns to fertiliser use by financially constrained smallholder farmers in uganda

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Abstract

Financial constraints usually limit fertiliser use by smallholder farmers and it is important that they maximise net returns on their investment. Fifteen crop-nutrient response functions, including six crops, were derived from results of 84 trials conducted in Uganda. The benefit:cost ratio (BC) for typical fertiliser 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.). Next most profitable was P applied to groundnut (*Arachis hypogaea* L.) and soybean (*Glycine max* L.), followed by N applied to maize (*Zea mays* L.)and grain sorghum (*Sorghum bicolor* L.), with lower or no BC for the remaining nine response functions. The Fertiliser Optimisation Tool was developed for Uganda to maximise net returns to fertiliser use for finance-limited crop management in consideration of the area of each crop to be planted, fertiliser costs, expected grain value, and money available for investment. The tool optimises across the 15 response functions to provide the crop-nutrient-rate combinations expected to maximise net returns. The tool does not account for soil test information, expected yield, and previous crop as these did not account for significant variation in yield. In an example with 1 ha each of the above six crops and US$135 available for fertiliser use, the optimised BC was 17.4 compared 4.5 and 6.2 for N applied to maize and rice at rates to maximise net returns ha^{-1}. The solution commonly determines low or zero rates for nutrients applied to some crop but the greatly improved returns on investment create the potential for gradually increasing future investments in fertiliser. This approach to fertiliser use of maximising net returns on investment has potential to gradually enable much increased fertiliser use because of the relatively high returns on investment compared to traditional fertiliser use recommendations.

Key words: Bean, grain sorghum, groundnut, peanut, rice, soybean, fertiliser, Uganda

Abbreviations: BC, benefit to cost ratio, or net returns to fertiliser use; C:P, the ratio of fertiliser use cost to the price or value of grain after considering harvest and post-harvest costs of handling the grain; EOR and EOxR, economically optimal rate where x = N, P, or K.

Introduction

The yield 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 (Greenland *et al.*, 1994; Sanchez *et al.*, 1996; Muchena *et al.*, 2005). Fertiliser use by financially constrained farmers has not increased substantially. Cost of fertiliser use per kg applied is often two to six times higher in sub-Saharan Africa than in the USA 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 fertiliser expenses lead to unfavorable fertiliser use costs to grain price (C:P) and low BC ratios. Financially constrained farmers need large returns on their relatively small investment to justify the expense of fertiliser use. A guideline used in evaluating the potential for adoption of practices by financially constrained farmers is the need for a 100% net return on investment or BC > 1 (CIMMYT, 1988; Wortmann and Ssali, 2001).Excessively high nutrient costs and severely constrained budgetsrequire that such farmers strive to maximise their net returns on their small investment in fertiliser subject to the availability of financial resources.

Quadratic plus plateau response functions relating crop yield response to applied fertiliser N, P, and K estimate the increase in yield with nutrient application. 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 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 determination of nutrient application rates are considered (Fig. 1). i) The response functions can be used to determine the nutrient application rate to achieve a targeted percentage, for example 95%, of maximum yield ha^{-1}. ii) If C:P is considered, the application rate required to maximise net returns ha^{-1} resulting from application of a fertiliser nutrient, a common goal with financially unconstrained fertiliser use, can be determined. This rate is often called the economically optimal rate(EOR, Dobermann *et al.*, 2011) or the rate of maximum profit ha^{-1} where the additional fertiliser costs equals the value of the increased yield, beyond which profit diminishes with additional application even though yield continues to increase until the yield plateau is reached.iii) If C:P and a financial constraint of the farmer are considered, the nutrient application rate that maximises returns on the financially constrained investment in fertiliser use can be determined.Distinguishing between these three approaches to determination ofnutrient application rates is important for maximising profitability for financially constrained farmers.

Farmers in Uganda commonly have diverse cropping systems with several crops likely to be responsive to applied

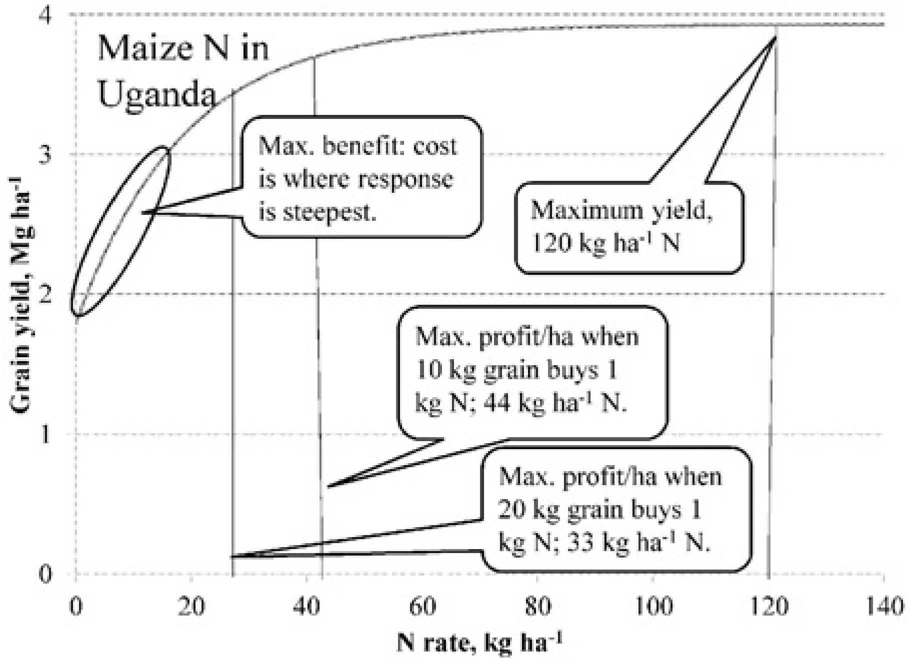

Figure 1. Fertiliser rates can be determined from quadratic plus plateau yield response functions with the aim of: i) achieving maximum, or some percent of maximum yield; ii) maximising net returns per hectare due to fertilizer use in consideration of fertilizer cost relative to grain value; or iii) maximising net returns on a finance-constrained investment in fertiliser.

nutrients (Wortmann and Eledu, 1999). The crop-nutrient combination, in addition to rate of application, needs to be considered in maximising net returns to financially constrained fertiliser use. Maximising net returns to financially constrained fertiliser investment requires prioritising crop-nutrient combinations according to BC until the monetary investment is exhausted. Dependent on the availability of financial resources, some crops may not receive fertiliser and others with only low application rates.

Methodology

Nitrogen, P and K response trials were conducted for maize, sorghum, upland rice; P and K response trials for groundnut and soybean in the main maize production areas of Uganda from 2009 to 2010 (Table 1). The sites were Kawanda and Tororo, Ngetta, Bulindi, and Kapchorwa located in the Lake Victoria Crescent, Northern Moist Farmlands, Western Mid-Altitude Farmlands,and Mt. Elgon Farmlands Agroecological Zones, respectively (Wortmann and Eledu, 1999). The soils varied with site and included Nitisols, Petric Plinthsols, and Acric Ferralsols. The soils at all site-seasons had rooting depths greater than 1.0 m. Trials at research stations had three replicates; for on-farm trials, each farmer was regarded as a replicate. Surface soil samples for the 0- to 20-cm depth consisting of 10 cores per site-season were collected with hand probes before planting and fertiliser

Table 1. The coefficients for crop-nutrient asymptotic response functions of grain yield determined for Uganda†

Crop	Site seasons	Nitrogen			Phosphorous		
		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	240	0.958	3.79	0.556	0.947
Dry bean	12	1.79	0.99	0.892	1.81	0.286	0.926
		Phosphorous			Potassium¶		
		a	b	c	a	b	c
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

† Sources: Kaizzi et al., 2012 a,b,c. The upland rice results were submitted to Nutrient Cycling for publication.
‡ The coefficients of the asymptotic functions for yield (Y, Mg ha-1) with $Y = a - bc^n$, where a was the yield at the response plateau or maximum yield, (Mg ha^{-1}), *b* was the gain in yield (Mg ha^{-1}) due to nutrient application, and c^x represented the shape of the quadratic response where *c* was a curvature coefficient and *n* the nutrient application rate (kg ha^{-1})
¶ Potassium effects were not significant for cereal crops and bean

application to determine soil pH, soil organic matter (SOM) (Walkley and Black, 1934), and available P and exchangeable K measured in a single Mehlich-3 extract and buffered at pH 2.5 (Mehlich, 1984)). Soil texture was determined by the hydrometer method (Bouyoucos, 1936). The details are presented in Kaizzi *et al.*, 2012a, b, c.

Fertiliser 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, b, c). Responses were determined using asymptotic quadratic-plateau functions taking the form of an exponential rise to a maximum or plateau yield. The asymptotic function was $Y = a - bc^n$, where *Y* was yield (t ha^{-1}), *a* was the maximum or plateau yield (Mg ha^{-1}), *b* was the gain in yield (Mg ha^{-1}) due to nutrient application, and c^n represented the shape of the quadratic response, where *c* was a curvature coefficient and *n* the nutrient application rate (Mg ha^{-1}).

Results

The grain yield response function for N and P were significant for maize, grain sorghum, upland rice, and dry bean, and P and K response functions were significant for soybean and groundnut (Table 1). Although rate x site-season interactions occurred, variation in response was not related to variation in grain yield, rainfall amount, soil test results, or previous crop (Kaizzi *et al*., 2012a, b, c).

Predicted netbenefits associated with incremental fertiliser units applied differed for crop-nutrient combinations (Fig. 2). For each additional US$ ha^{-1} invested, the resulting returns for that dollar investment was 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 combinations that are expected to maximise net returns, or BC, for a finance-constrained investment in fertiliser use.

Selection of the crop-nutrient-rate combinations that are expected to maximise BC is complex for the farm with diverse crops with fertiliser needs in excess of investment capacity. The objective of this research was to develop a user friendly decision tool for optimisation of choice of crop-nutrient-rate combinations for maximisation of BC on finance-constrained fertiliser investment.

Features of the fertiliser optimisation tool

The Fertiliser Optimisation Tool developed for financially constrained fertiliser use in Uganda maximises net returns to fertiliser N, P, and K investments. The Fertiliser Optimisation Tool optimises solutions using the Solver add-on (Frontline Systems Inc., Incline Village, NV, USA) 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 stageof the Fertiliser Optimisation Tool considers the farmer input data or farmer specified constraints, pre-determined model constraints, and the model's optimisation mode (Fig. 3). The farmer imposed constraints include:i) the expected land area to be planted and 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) fertilisers available including urea, triple super phosphate (TSP), diammonium phosphate (DAP), murate of potash (KCl), or another available product with its N-P_2O_5-K_2O content specified; iii)the cost of using each fertiliser including purchase, delivery, and application costs; and iv)the farmer's budget constraint, or the amount of money available for fertiliser use (Fig 4a). The model is constrained to avoid exceeding the range of inference for the underlying equations with maximum and minimum fertiliser 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 C:P values below the range of inference of the equations. Minimum nutrient application ratesof zero kg ha^{-1}for all crop-nutrient response functions prevents a non-negativity constraint of the objective function. Finally, in accordance with research methodology to determine the relevant crop-nutrient response functions, 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 response to an applied nutrient such as expected yield or rainfall amount, soil test results, or previous crop as these did not affect the crop-nutrient responses (Kaizzi *et al.*,

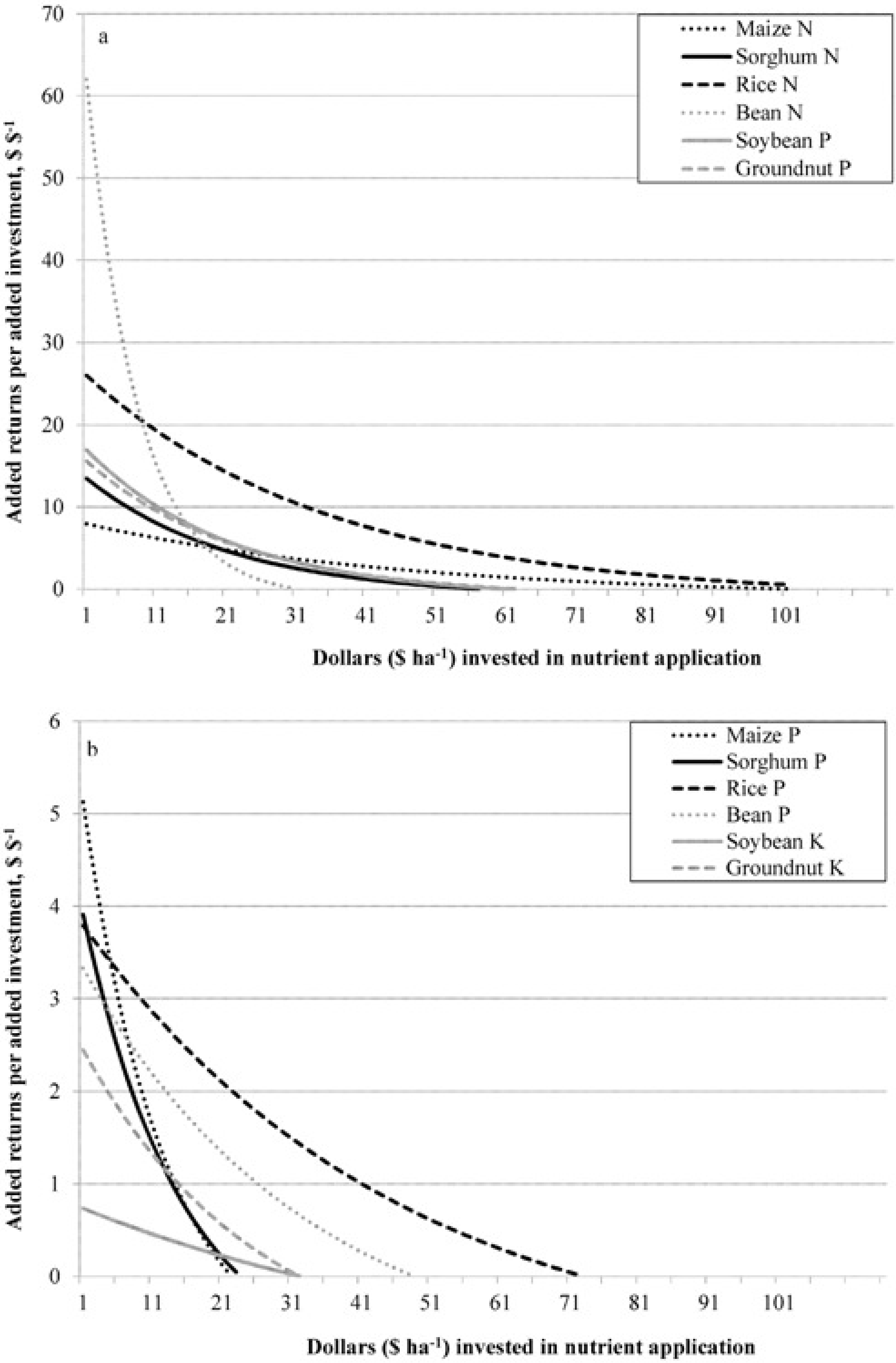

Figure 2. Added net returns of each added unit invested in fertiliser for six crop-nutrient combinations each with relatively high (a) and low (b) net returns.

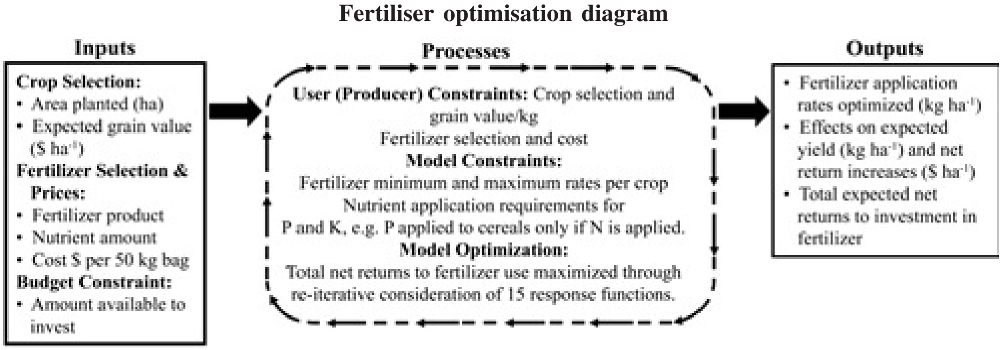

Figure 3. Operational flow model of the fertiliser optimisation tool developed for Uganda.

2012a, b, c).The tool does not consider nutrients other than N, P, and K, and only the above mentioned six crops, as adequate crop-nutrient response functions are not yet available although these could be added once available.

The re-iterative process performed by Fertiliser Optimisation Tool using Microsoft Office Excel Solver version 7 or later to iteratively search for a solution that optimises a specified mathematical function, often referred to as an objective function, subject to specified constraints. The objective function in this case was to maximise net returns to fertiliser use as the difference of added crop revenue and added fertiliser costs, subject to farmer input imposed constraints and internal constraints of the tool.The 15 crop-nutrient response functions (Table 1) were combined with fertiliser use costs and expected crop values to estimate expected net income given investment limitations until the financial resource is exhausted. It selected the crop-nutrient-rate combinations that deliver the highest net return on investment. The selection of the crop-nutrient-rate combinations relate to a circular reference where each combination must satisfy all constraints imposed by the user and tool. The tool achieved the objective function of maximising total expected net returns to fertiliser use by determining the optimal combination of crop-nutrient-rates subject to the budget and response function constraints. The costs for the total amount of fertiliser recommended cannot exceed the financial resources available for investment.

Once the optimal crop-nutrient-rate combinations was determined, the results were displayed (Fig. 4b) including the optimised crop-fertiliser application rates for the 15 possible crop-nutrient combinations, expected effects on yield and net returns to fertiliser use, and total expected net returns to investment in fertiliser use. Each set of constraints imposed by the user delivers a unique, but optimised solution based upon attributes pertinent to the farmer's production and economic environment.

Application examples

The Fertiliser Optimisation Tool allows for consideration of area planted and expected value of selected crops, the costs of fertiliser use, and the total budget available for investment in fertiliser use. These parameters vary with each specific smallholder's circumstances and preferences, and the resulting optimised solution is a unique result. The effects the

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

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

Figure 4. User input (a) and output (b) interface of the fertiliser optimisation tool developed for Uganda.

Fertiliser Optimisation Tool has on allocation of limited investments in fertiliser use, net returns to fertiliser use, and BC was illustrated with a set of scenarios with varying monetary resources for fertiliser use, keeping all other input data constant.

The set of optimisation scenarios evaluated have a land area of one hectare planted for each of the six crops considered by the tool. Based on the observations, expected commodity values and fertiliser costs reflected those of 2011 in Uganda. Expected grain values include 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 fertiliser 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$135, 270, 405, and 540 $farm^{-1}$were devised to reflect 25, 50, 75, and 100%, respectively, of the total investment necessary to maximise net returns to fertiliser use, or the full budget allowance, for the six ha of crop land.

Results of the scenario optimisations illustrate that the marginal value of investment, or BC, incrementallydeclined as the percentage of the full budget allowance increased, but the net returns $farm^{-1}$ increased (Table 2). When constrained at 25% of the full budget allowance, 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 BC of 17.4 and net return to fertiliser use of $2,345 $farm^{-1}$. Application rates were low and no nutrient was applied for nine of the crop-nutrient combinations, but the mean yield increase was 107% compared with no fertiliser applied.

Application rates increased with a doubling of the budget to $270 ha^{-1} or 50% of the full budget allowance with an allocation to P applied to maize and rice, and K applied to groundnut.The BC equaled 11.5 and net return to fertiliser use was $3,103 $farm^{-1}$. The mean yield increase was 147% compared with no fertiliser applied.

With a budget constraint of 75% of the full budget allowance, or $405 $farm^{-1}$, rates were further increased and some P and K are applied to grain sorghum and soybean, respectively. The BC was 8.46 and the net return to fertiliser use was $3,425 $farm^{-1}$. The mean yield increase was 175% compared with no fertiliser applied.

Finally, with an allocation of $540 $farm^{-1}$ or 100% of the full budget allowance, BC was 6.5 and net return to fertiliser use was increased by less than 1%. The mean yield increase was186% compared with no fertiliser applied and 6.7% compared with the 75% of the full budget allowance. In comparison, if fertiliser were applied to maximise net returns to fertiliser use per hectare, the BC would be 4.5 for maize and 6.2 for upland rice.

Discussion

There is a great advantage to finance-constrained farmers in applying fertiliser based on optimised choices of crop-nutrient-rate combinations (Table 2). Development of the Fertiliser Optimisation 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 Sub-Saharan Africa countries. Existing data generally, has not been applied for development of fertiliser use recommendations based on maximising net returns to financially constrained

Table 2. The effects of fertiliser use decisions in Uganda on fertiliser nutrient allocation to crops and on net returns per investment

	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}	Fertiliser cost \$ ha^{-1}	Net return \$ ha^{-1}	Benefit: cost \$ \$$^{-1}$	Yield increase kg ha^{-1}
\$135 ha^{-1} invested, 25% of the amount needed to maximise net \$ ha^{-1} \$135ha^{-1}							
Maize†	8	0	0	11	131	11.43	714
Grain sorghum	7	0	0	11	112	10.56	612
Rice	14	0	0	21	408	19.38	1,072
Dry bean	20	6	0	39	559	14.41	996
Soybean	0	14	0	24	331	13.68	889
Groundnut	0	14	3	<u>29</u>	<u>813</u>	<u>28.11</u>	1,683
Overall				135	2,354	17.43	
\$270 ha^{-1} invested, 50% of the amount needed to maximise net \$ ha^{-1}							
Maize	23	3	0	38	289	7.60	1,635
Grain sorghum	16	0	0	25	192	7.67	1,083
Rice	41	30	0	103	870	8.41	2,433
Dry bean	20	9	0	42	575	13.57	1,029
Soybean	0	16	0	27	344	12.62	928
Groundnut	0	17	3	<u>34</u>	<u>834</u>	<u>24.54</u>	1,736
Overall				270	3,103	11.49	
\$405 ha^{-1} invested, 75% of the amount needed to maximise net \$ ha^{-1}							
Maize	37	7	0	66	350	5.31	2,082
Grain sorghum	28	9	0	55	281	5.13	1,682
Rice	60	27	0	127	928	7.29	2,637
Dry bean	27	20	0	68	632	9.30	1,167
Soybean	0	22	3	43	374	8.71	1,042
Groundnut	0	24	4	<u>46</u>	<u>859</u>	<u>18.65</u>	1,811
Overall				405	3,425	8.46	
\$540 ha^{-1} invested, 100% of the amount needed to maximise net \$ ha^{-1}							
Maize	46	10	0	84	362	4.32	2,226
Grain sorghum	38	10	0	71	290	4.10	1,803
Rice	76	30	0	156	944	6.04	2,751
Dry bean	33	25	0	84	642	7.64	1,210
Soybean	0	28	29	88	396	4.51	1,211
Groundnut	0	30	4	<u>57</u>	<u>865</u>	<u>15.07</u>	1,845
Overall				540	3,499	6.48	

†In this evaluation, the land area planted for each crop was one hectare. The grain prices were 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 1.5, 2.5, and 1.0 \$ kg^{-1} for N, P, and K, respectively

fertiliser use. This implies a need for conducting basic fertiliser response research in many countries, improving the basis for adapting and extrapolating crop-nutrient across agro-ecological conditions, and interpreting the results for financially constrained situations.

Fertiliser 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 fertiliser nutrients. A green manure crop produced during the previous season may greatly diminish response to applied nutrients with better net returns from application of nutrients to another field. These and other factors are not built into the fertiliser optimisation tool and tool construction and use would be much more complex by including them. Instead, guidelines have been developed for use by crop production advisors in Uganda on adjustment of the nutrient application rates determined by the optimisation 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 as these did not account for significant variation in yield response to applied nutrients (Kaizzi *et al*., 2012 a,b,c). 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 and/or of sufficient quality to be of much value in deciding on nutrient application.

The Fertiliser Optimisation Tool now runs with Excel Solver. Access to a computer is limited for many smallholder farmers. Training is provided to government and non-government, including private sector, extension and crop advisors expecting them to run the optimisation tool for farmers. We are preparing for development of a cell phone application enabling people to provide the input data to a virtual server based version of the tool which will reply with the output. The underlying concepts of this approach to fertiliser use optimisation by financially constrained farmers described in this paper is widely applicable. It requires that fundamental fertiliser use research be conducted in more countries and for other important crops to develop the crop nutrient response curves. The optimisation tool can then be easily adapted for those countries, changing coefficients and crops as needed. The availability of single nutrient fertilisers such as urea and TSP is important to optimisation of fertiliser use. Many countries provide P and K only as components of compound fertilisers, but this requires farmers to buy and apply nutrients that do not result in the greatest net returns thereby reducing profitability of fertiliser use.

Conclusion

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

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References

Bouyoucos, G.J. 1936. Directions for making mechanical analysis of soils by the hydrometer method. *Soil Science* 42:225-230.

CIMMYT, 1988. From agronomic data to farmer recommendations: an economics training manual. Mexico, D.F. pp. 34-35.

Dobermann, A., Wortmann, C.S., Ferguson, R.B., Hergert, G.W., Shapiro, C.A., Tarkalson, D.D. and Walters, D. 2010. Nitrogen Response and Economics for Irrigated Corn in Nebraska. *Agronomy Journal* 103:67-75.

Greenland, D.J., Bowen, G.D., Eswaran, H., Rhoades, R. and Valentin, C. 1994. Soil, water, and nutrient management research: a new agenda. International Board Soil Resource Management.

Heisey, P.W. and Mwangi, W. 1996. Fertiliser use and maize production in sub-Saharan Africa. Economics Working Paper. 96-01. CIMMYT, 1-25.

Kaizzi, K.C., Byalebeka, J., Semalulu, O., Alou, I., Zimwangguyizza, W., Nansamba, A., Musinguzi, P., Ebanyat, P., Hyuha,T. and Wortmann, C.S. 2012. Sorghum response to fertiliser and nitrogen use efficiency in Uganda. *Agronomy Journal* 104:83-90.

Kaizzi, K.C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza, W., Nansamba, A., Musinguzi, P., Ebanyat, P., Hyuha,T. and Wortmann, C.S. 2012. Maize response to fertiliser and nitrogen use efficiency in Uganda. *Agronomy Journal* 104:1-10.

Kaizzi, C.K., Wortmann, C., Byalebeka, J., Semalulu, O., Alou, I., Zimwanguyizza W., Nansamba, A., Musinguzi, P., Ebanyat, P. and Hyuha, T. 2012. Optimizing smallholder returns to fertiliser use: bean, soybean and groundnut. *Field Crops Research* 127: 109-119.

Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Comm. Soil Sci. Plant An.* 15:1409-1416.

Muchena, F.N., Onduru, D.D., Gachini, G.N. and de Jager, A. 2005. Turning the tides of soil degradation in africa: capturing the reality and exploring opportunities. *Land Use Policy* 22:23-31.

Sanchez, P.A. 2002. Soil fertility and hunger in Africa. *Science* 295:2019-2020.

Sanchez, P.A., Izac, M.N.A., Valencia, I. and Pieri, C. 1996. Soil fertility replenishment in africa: a concept note. In: Breth, S.A. (Ed.). Achieving greater impact from research investments in Africa. Sasakawa Africa Assoc., Mexico City. pp. 200-207.

Vlek, P.G. 1990. The role of fertilisers in sustaining agriculture in sub-Saharan Africa. *Fertiliser Research* 26:327-339.

Walkley, A. and Black, I.A. 1934. An examination of degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37:29-37.

Wortmann, C.S. and Eledu, C.A. 1999. Uganda's Agroecological Zones: A Guide for Planners and Policy Makers. CIAT, Kampala, Uganda.

Wortmann, C.S. and Ssali, H. 2001. Integrated nutrient managment for resource-poor farming systems: a case study of adaptive resarch and technology dissemination in Uganada. *Amer. J. Alternative Agric.* 16:161-167.