Fertilizer Use Optimization in Sub-Saharan Africa

Charles S. Wortmann and Keith Sones, editors

Published by CABI

Fertilizer Use Optimization in Sub-Saharan Africa is a 2017 CAB International publication.

An example citation is: *Kaizzi, K.C., M.B. Mohammed and M. Nouri. 2017. Fertilizer Use Optimization: Principles and Approach. In: Fertilizer Use Optimization in Sub-Saharan Africa. Charles S. Wortmann and Keith Sones (eds). CAB International, Nairobi, Kenya, pp. 9–19.*

ISBN (paperback): 978 1 78639 204 6

ISBN (e-book): 978 1 78639 205 3

Contents

Foreword 7

1. Fertilizer Use Optimization: Principles and Approach 9

1.1 Introduction 9
1.2 What is optimization? 9
1.3 Fertilizer use optimization 10
1.4 Fertilizer optimization tools 11
1.5 Using the Excel FOT 12
1.6 Paper versions of FOTs 15
1.7 Conclusion 17
1.8 References 17

2. Spatial Analysis for Optimization of Fertilizer Use 20

2.1 Background 20
2.3 Spatial data 21
2.4 OFRA Inference Tool 21
2.5 References 23

3. Integrated Soil Fertility Management in Sub-Saharan Africa 25

3.1 Introduction 25
3.2 Integrated Soil Fertility Management 25
3.3 Common ISFM practices for sub-Saharan Africa 26
3.3.1 Land application of organic resources 26
3.3.2 Organic resources complemented with fertilizer application 27
3.3.3 Crop residue management and tillage 27
3.3.4 Intercropping with legumes 29
3.3.5 Green manure 31
3.3.6 Cereal-legume rotation 32
3.3.7 Adding perennials to the annual crop rotation 33
3.3.8 Parkland agriculture 33
3.3.9 Biochar 34
3.3.10 Good fertilizer use practices 34
3.3.11 Water availability 37
3.4 Conclusion 37
3.5 References 38

4. Optimizing Fertilizer Use within an Integrated Soil Fertility Management Framework in Burkina Faso 40

4.1 Introduction 40
4.2 Agricultural systems of the agro-ecological zones (AEZ) in Burkina Faso 41
4.3 Soil nutrient management, including fertilizer use, in Burkina Faso 43
4.4 Optimizing fertilizer use in Burkina Faso 43
4.5 Fertilizer use optimization tools (FOT) for AEZ of Burkina Faso 45
4.5.1 The Excel FOT 45
4.5.2 Paper versions of the FOT 48
4.5.3 The fertilizer substitution value of other practices 48
4.6 Targeted crops by AEZ 49
4.7 References 50

5. Optimizing Fertilizer Use within an Integrated Soil Fertility Management Framework in Ethiopia 52

5.1 Agricultural systems in Ethiopia 52
5.2 Soil fertility management 53
5.3 Diagnosis of nutrient deficiencies in Ethiopia 54
5.4 Optimizing fertilizer use in Ethiopia 55
5.5 Fertilizer use optimization tools 57
5.5.1 The Excel Solver FOT 57
5.5.2 The paper FOTs 57

5.5.3 The fertilizer rate adjustment tool....59
5.6 Targeted crops by AEZ....60
5.7 Conclusion....62
5.8 References....62

6. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Ghana....67

6.1 Soil nutrient management, including fertilizer use in Ghana....67
6.2 Fertilizer use and recommendations....69
6.3 Current fertilizer use....70
6.4 Fertilizer use integrated with other practices....70
6.5 Diagnosis of nutrient deficiencies in Ghana....71
6.6 Optimizing fertilizer use in Ghana....71
6.7 Fertilizer use optimization tools (FOT) for Ghana....73
6.8 Adjusting fertilizer rates for other practices and soil test information....77
6.9 Targeted crops and cropping systems by AEZ....78
6.10 References....81

7. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Kenya....82

7.1 Agricultural systems of Kenya....82
7.1.1 Introduction....82
7.1.2 Agro-ecological zones (AEZ)....82
7.2 Soil fertility management....85
7.3 Diagnosis of soil nutrient deficiencies....86
7.4 Optimizing fertilizer use in Kenya....86
7.5 Crops targeted for optimization by region....88
7.6 Fertilizer use optimization tools (FOT) for Kenya AEZ....93
7.7 Conclusions....98
7.8 Acknowledgements....98
7.9 References....99

8. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Mali....100

8.1 Agricultural systems of Mali....100
8.2 Current soil fertility management....102
8.3 Diagnosis of nutrient deficiencies in Mali....103
8.4 Optimizing fertilizer use in Mali....103
8.5 Fertilizer use optimization tools for Mali....105
8.6 Targeted crops and cropping systems by AEZ....109
8.7 Conclusion....111
8.8 Acknowledgements....111
8.9 References....112

9. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Malawi....113

9.1 Agricultural systems of Malawi....113
9.1.1 Agro-ecological zones (AEZ)....113
9.1.2 Current soil fertility management in Malawi....114
9.1.3 Fertilizer use and recommendations....115
9.2 Soil diagnosis and diagnostic trials in Malawi....116
9.3 Optimizing fertilizer use in Malawi....116
9.4 Targeted crops and cropping systems by AEZ....122
9.5 Acknowledgements....124
9.6 References....124

10. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Mozambique....125

10.1 Introduction....125
10.2 Agricultural systems of Mozambique....125
10.2.1 Agro-ecological zones (AEZ)....126

10.2.2 Soil fertility management in Mozambique ... 127
10.2.3 Diagnosis of nutrient deficiencies ... 127
10.3 Fertilizer use optimization in Mozambique ... 127
10.4 Fertilizer optimization tools for Mozambique ... 129
10.5 Fertilizer use in an integrated nutrient management framework ... 132
10.6 Crops addressed by region for optimized fertilizer use ... 133
10.7 Acknowledgements ... 135

11. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Niger ... 136

11.1 Agricultural systems of Niger ... 136
11.1.1 Agro-ecological zones (AEZ) ... 136
11.1.2 Current soil fertility management ... 137
11.2 Diagnosis of nutrient deficiencies in Niger ... 139
11.3 Optimizing fertilizer use in Niger ... 139
11.4 Targeted crops and cropping systems by AEZ ... 141
11.5 Fertilizer use optimization tools for Niger AEZ ... 143
11.6 Paper fertilizer optimization tools ... 143
11.7 Adjusting fertilizer rates in consideration of other practices and soil test information ... 146
11.8 Acknowledgements ... 146
11.9 References ... 146

12. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Nigeria ... 148

12.1 Introduction ... 148
12.2 Agricultural systems of Nigeria ... 149
12.3 Traditional practices affecting soil fertility ... 151
12.4 Fertilizer use and recommendations ... 151
12.5 Diagnostic results for the Northern Guinea Savanna AEZ ... 152
12.6 Optimizing fertilizer use in the savanna biome of Nigeria ... 153
12.7 Fertilizer optimization tools for Nigerian AEZ ... 154
12.7.1 The Excel Fertilizer Optimization Tool ... 154
12.7.2 Paper fertilizer optimization tools ... 157
12.7.3 Fertilizer use in an integrated soil fertility management context ... 159
12.8 Targeted crops by AEZ ... 159
12.9 Acknowledgements ... 162
12.10 References ... 162

13. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Rwanda ... 164

13.1 Agricultural systems of Rwanda ... 164
13.2 Soil fertility management in Rwanda ... 165
13.3 Diagnosis of nutrient deficiencies in Rwanda ... 166
13.4 Optimizing fertilizer use in Rwanda ... 167
13.5 Fertilizer use optimization tools for AEZ of Rwanda ... 169
13.6 Crop nutrient response functions by AEZ in Rwanda ... 173
13.7 Conclusion ... 175
13.8 Acknowledgements ... 175
13.9 References ... 175

14. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Tanzania ... 176

14.1 Importance of agriculture in Tanzania ... 176
14.2 Agro-ecological zones (AEZ) of Tanzania ... 176
14.3 Current soil fertility management ... 178
14.4 Diagnosis of nutrient deficiencies in Tanzania ... 180
14.5 Optimizing fertilizer use in Tanzania ... 180
14.6 Fertilizer use optimization tools (FOTs) for Tanzania ... 182
14.7 Adjusting fertilizer rates for other practices and soil test information ... 185
14.8 Targeted crops and cropping systems by AEZ ... 186

14.9 Conclusion ... 189
14.10 Acknowledgements ... 191
14.11 References ... 191

15. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility in Uganda ... 193

15.1 Agro-ecological zones (AEZ) of Uganda ... 193
15.2 Current soil fertility management ... 197
15.3 Diagnosis of nutrient deficiencies in Uganda ... 198
15.4 Optimizing fertilizer use in Uganda ... 199
15.5 Targeted crops by AEZ ... 204
15.6 Conclusion ... 205
15.7 Acknowledgements ... 209
15.8 References ... 209

16. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Zambia ... 210

16.1 Introduction ... 210
16.2 Agricultural systems of Zambia ... 210
16.3 Current soil fertility management ... 212
16.4 Fertilizer use optimization ... 212
16.5 Fertilizer optimization tools for Zambia ... 214
16.6 Fertilizer use in an integrated nutrient management framework ... 216
16.7 Crops addressed by region for optimized fertilizer use ... 216
16.8 Acknowledgements ... 219
16.9 References ... 219

17. Enabling Fertilizer Use Optimization in Sub-Saharan Africa ... 220

17.1 Introduction ... 220
17.2 Enabling fertilizer use optimization by farmers ... 220
17.3 Creating demand for fertilizer use optimization ... 222
17.4 Training farmer advisors on fertilizer use optimization ... 223
17.5 Lessons learned ... 223
17.6 Conclusion ... 224
17.7 Acknowledgements ... 224
17.8 References ... 224

List of Abbreviations ... 225

List of Crops and Other Plants with Scientific Names ... 227

Foreword

Low soil fertility costs Africa's farmers US$4 billion a year in reduced yields. This usually results in low incomes and poor livelihoods. Part of the problem is that fertilizer use in the continent is only about 12 kg/ha/yr.

Africa's smallholder farmers are mostly very poor and have little financial ability to invest in inputs such as fertilizer. However, they are generally responsive to perceived high profit opportunities with little risk. The key to increased fertilizer use is to improve the profitability of its use with little risk. Achieving this gives farmers the opportunity to reduce the severity of their financial constraints and to gradually improve their crop management.

Fertilizer recommendations are available for some crops in most African countries, but too often these are decades-old blanket recommendations that cover large regions or even whole countries, are not well supported by field research and are more oriented to achieving high yields rather than high farmer profits.

The AGRA-funded project 'Developing and fine-tuning fertilizer recommendations within an integrated soil fertility management framework', abbreviated as the Optimizing Fertilizer Recommendations in Africa (OFRA), was implemented to develop the basis for fertilizer use optimization, that is, more profitable fertilizer use.

Through OFRA, national research institutes of 13 sub-Saharan African countries partnered together, and with CABI and the University of Nebraska-Lincoln, to develop the field research-based information needed for fertilizer use optimization decisions. Results of past research and OFRA-supported research were compiled and systematically analysed. This was applied to determine crop nutrient response functions for the important food crops in each of 67 agro-ecological zones (AEZ) or recommendation domains across the 13 countries. When several response functions for an AEZ are considered, it becomes apparent that profit potential varies according to which nutrient is applied to which crop and the rate of application. Therefore, especially for financially constrained farmers, the crop-nutrient-rate choices are very important to maximizing profitability. The choice of fertilizer types may include blends but maximizing profit potential requires adequate availability of single- (such as urea and triple superphosphate) and multi-nutrient, compound fertilizers (such as diammonium phosphate and potassium chloride).

Country teams integrated the crop nutrient response functions into decision tools that use linear programming to determine recommendations specific to a farmer's context intended to maximize profit from fertilizer use (see Chapter 1 and country chapters 4-16). These decision tools are called OFRA Fertilizer Optimization Tools (FOT); computer versions are available and also paper versions for use when a computer is not available. The FOT considers the farmer's financial ability, choice of crops and land allocation, crop values and fertilizer costs to determine the crop-nutrient-rate choices expected to maximize farmer profit from fertilizer use.

Sharing of research results across countries was enhanced with the development of the GIS tool called the OFRA Inference Tool. This tool uses GIS layers for soil properties of Africa Soil Information Service (AfSIS) and climatic properties, elevation, latitude and crops of HarvestChoice in geo-transfer of research results within and across countries between areas of similar growing conditions (see Chapter 2).

Fertilizer use optimization is within the framework of integrated soil fertility management with recommended fertilizer rates adjusted according to soil property information and the use of complementary practices (see Chapter 3).

Much early progress in enabling fertilizer use optimization with farmers and their advisors has been made, but this still requires a tremendous effort with much stakeholder support. Many more government and non-government extension staff and input retailers need to be trained in advising farmers in fertilizer use optimization. Farmers need training in the use of the paper FOTs to make fertilizer use choices according to the 4Rs (right type, rate, time and method of nutrient application) of nutrient stewardship and with proper calibration of

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

application). Extension training resources have been developed and applied and many advisors have been trained. This is addressed in Chapter 17 with lessons learned for more effective progress in the future.

AGRA is delighted with the success of the OFRA partnership of 13 countries in 1) developing a strong database of crop nutrient responses while recognizing that more research is needed to address secondary and micro nutrients, intercropping and rotations, and otherwise fine-tuning existing information, 2) providing computer and paper FOTs for 67 recommendation domains, 3) effectively applying GIS in sharing research results across recommendation domains and countries, 4) capturing in the 17 chapters of this book a great deal of information applicable to fertilizer use optimization within integrated soil fertility management framework, and 5) training many extension staff and other stakeholders, realizing that much more of this is needed to achieve fertilizer use optimization throughout sub-Saharan Africa.

Rebbie Harawa,
Interim Head, Farmers' Solution Program,
Alliance for a Green Revolution in Africa

Bashir Jama Adan,
Divisional Manager, Islamic Development Bank (and previously Head, Soil Health Program, Alliance for a Green Revolution in Africa)

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.

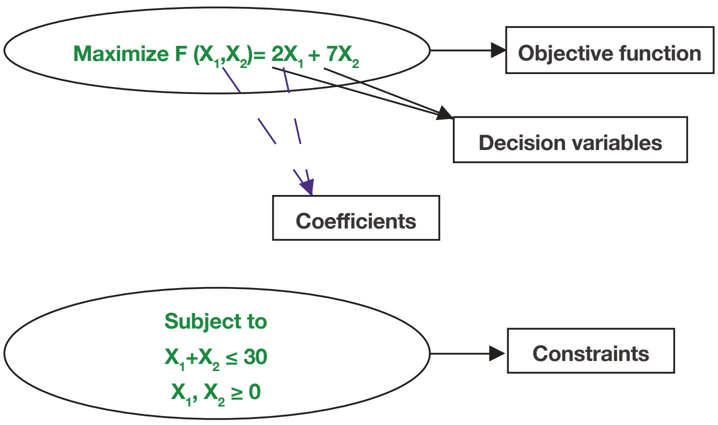


Figure 1.1: Schematic illustration of LP optimization.

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),

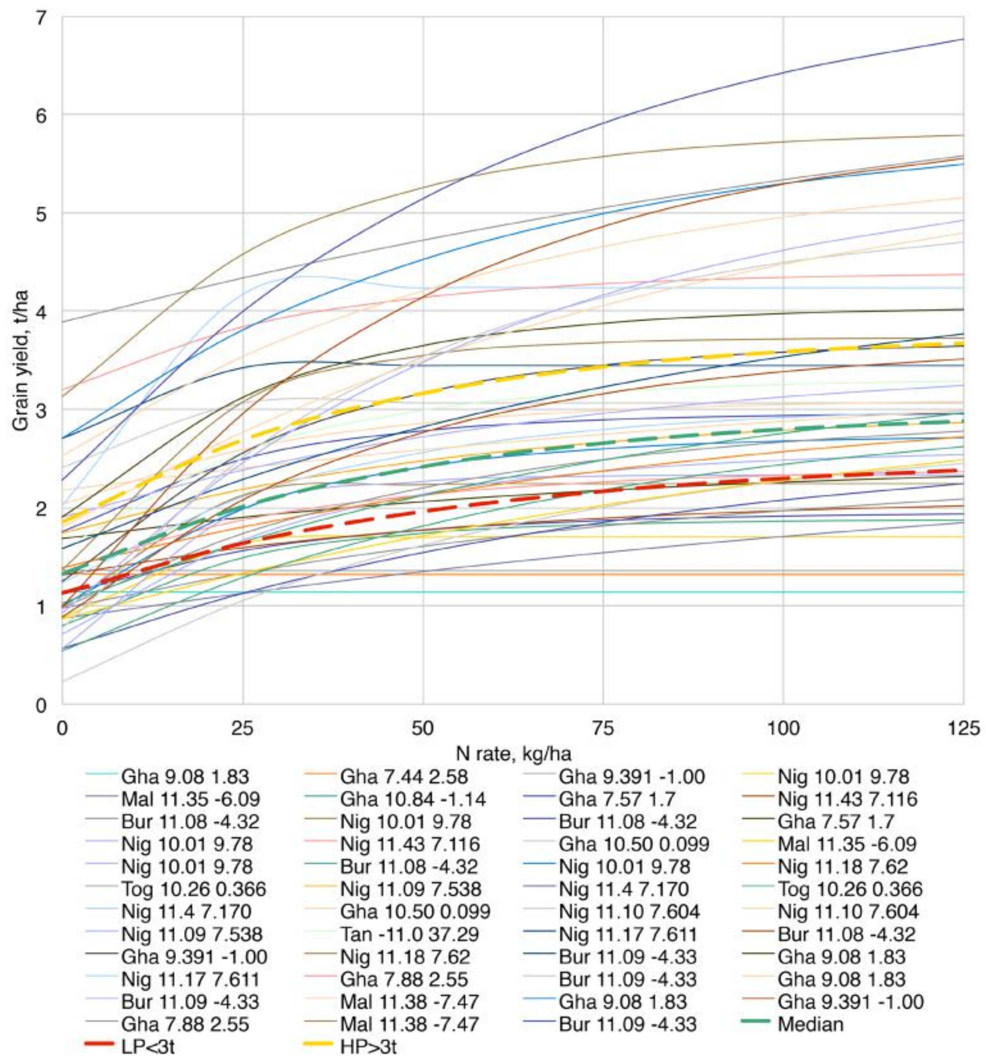


Figure 1.2: Maize nitrogen response functions available for determination of response functions for the Transitional/ Derived Savanna of Ghana and Nigeria.

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.

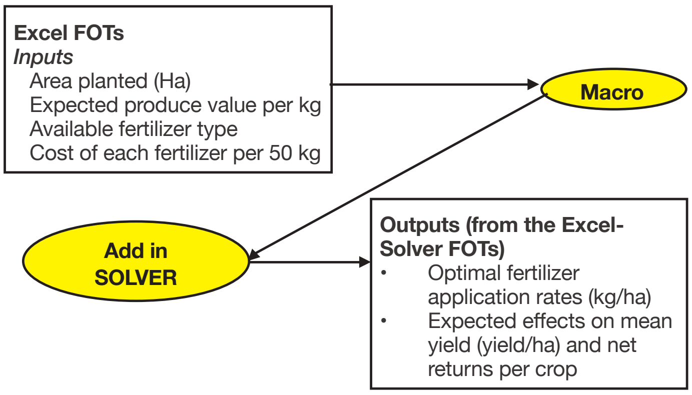


Figure 1.3: Fertilizer optimization process (Adapted from Jansen et al., 2013).

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

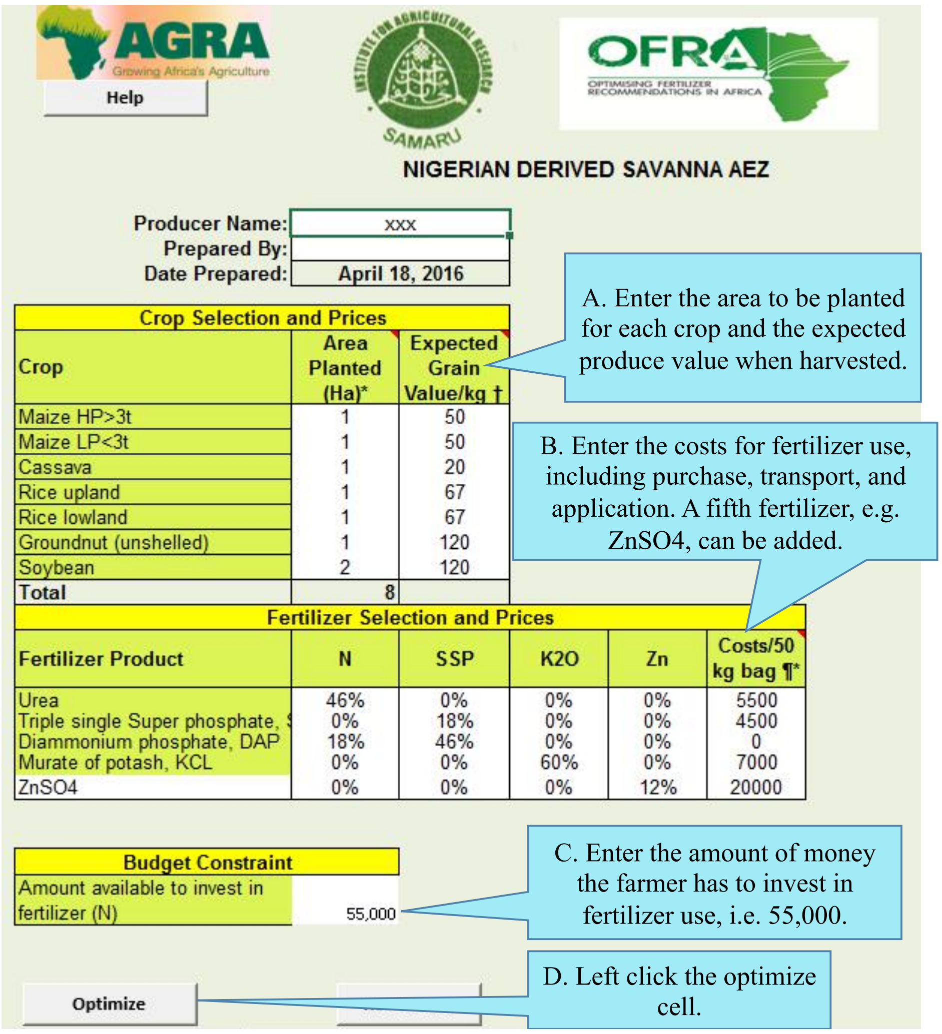
Use of the Excel FOT requires that the Solver add-in is engaged. If Solver is activated, it will appear under the Data tab, far to the right on the Quick Access Toolbar. The following steps to activating Solver are also available in the 'Help and Instructions' worksheet of FOTs and, in more detail, in 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

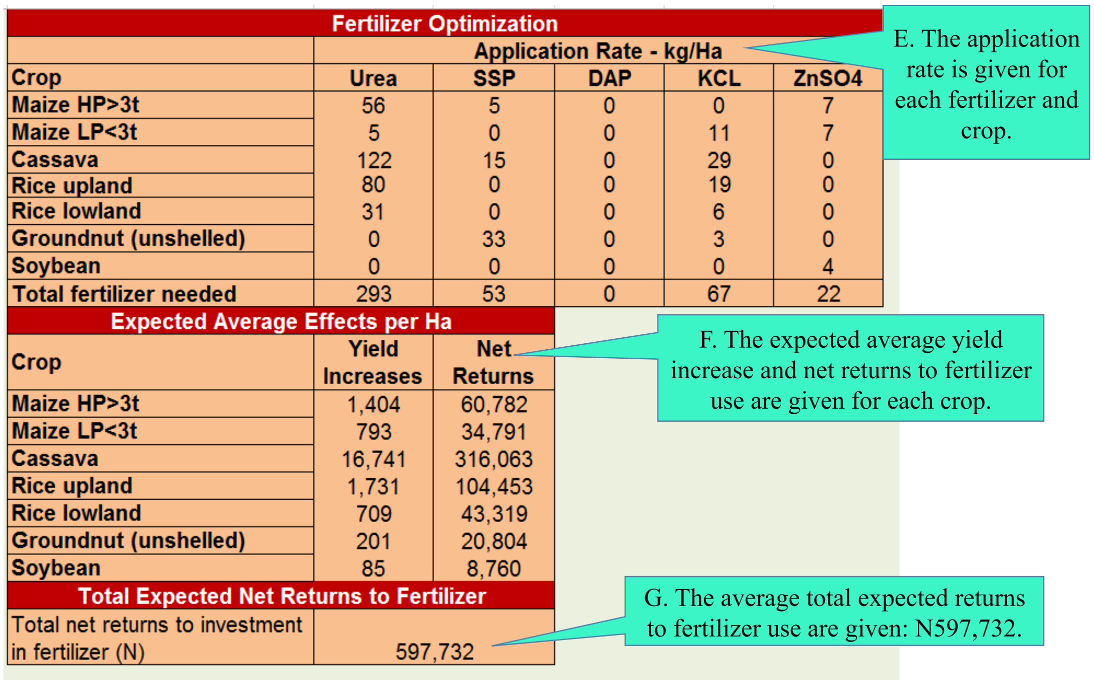


Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Maize HP>3t	1	50
Maize LP<3t	1	50
Cassava	1	20
Rice upland	1	67
Rice lowland	1	67
Groundnut (unshelled)	1	120
Soybean	2	120
Total	8	

Fertilizer Selection and Prices					
Fertilizer Product	N	SSP	K2O	Zn	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	5500
Triple single Super phosphate, S	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

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

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	[redacted]	Enter grain values for maize and bean sole crop.
Rice	1	50	
Wheat HP >3t	1	30	
Wheat LP <3t	1	30	
Total	**7**		

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

2. Spatial Analysis for Optimization of Fertilizer Use

Charles S Wortmann[1] cwortmann2@unl.edu, Maribeth Milner[1] and Gebreyesus Brhane Tesfahunegn[2]

[1]Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE 68583

[2]College of Agriculture, Aksum University-Shire Campus, P.O. Box 314, Shire, Ethiopia

2.1 Background

Sub-Saharan Africa (SSA) has a land area of 24 million km^2 and experiences widely varying crop growing conditions (Figure 2.1; HarvestChoice 2010). For most of Africa the mean monthly temperature (relative to sea-level) exceeds 18°C (64.4°F) year round (i.e. tropical) although parts of the continent experience temperatures as cool as 5°C (41°F) for one or more months (i.e. subtropical). Cool temperatures at high elevations impact crop growth (i.e. cool highlands) as well as timely precipitation.

Growing period (in days) is that time interval when mean temperature is 5°C or more and total water exceeds half the local potential evapotranspiration (PET). The arid to humid moisture class range represents less than 70 to over 270 day growing periods, respectively.

More climatic distinctions are evident at larger (or fine) scales as seen in Nigeria's agro-ecological zone (AEZ) map (Figure 2.2). The Sahelian, Sudanian and Guinean savanna to forest transition (White 1983) occurs with increasing rainfall and distance from the Sahara Desert. Deforested areas are referred to as derived savanna. The mid- and high-altitude classes correspond to the cool-humid class in Figure 2.1.

2.2 Inference space concept

The best crop production practices in one area can potentially inform decisions made in similar and possibly distant areas. One can estimate the inference space where research results are potentially relevant from critical crop-limiting thresholds. Likewise, queries of research sites' critical threshold values can identify relevant information for a location where research has not been conducted. The accuracy of a site's inference space model depends upon the understanding of a crop's response to the range of local environmental conditions and the availability and accuracy of regional data sets used to characterize limitations (Aiken et al., 2001).

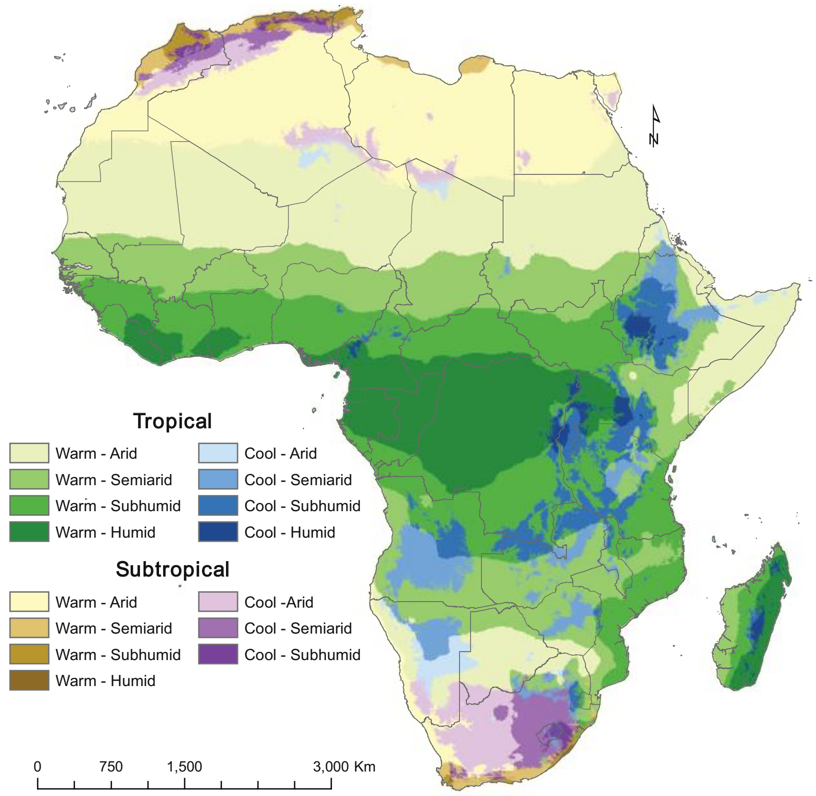


Figure 2.1. Africa climate zones from agro-ecological zones of sub-Saharan Africa (HarvestChoice 2010).

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

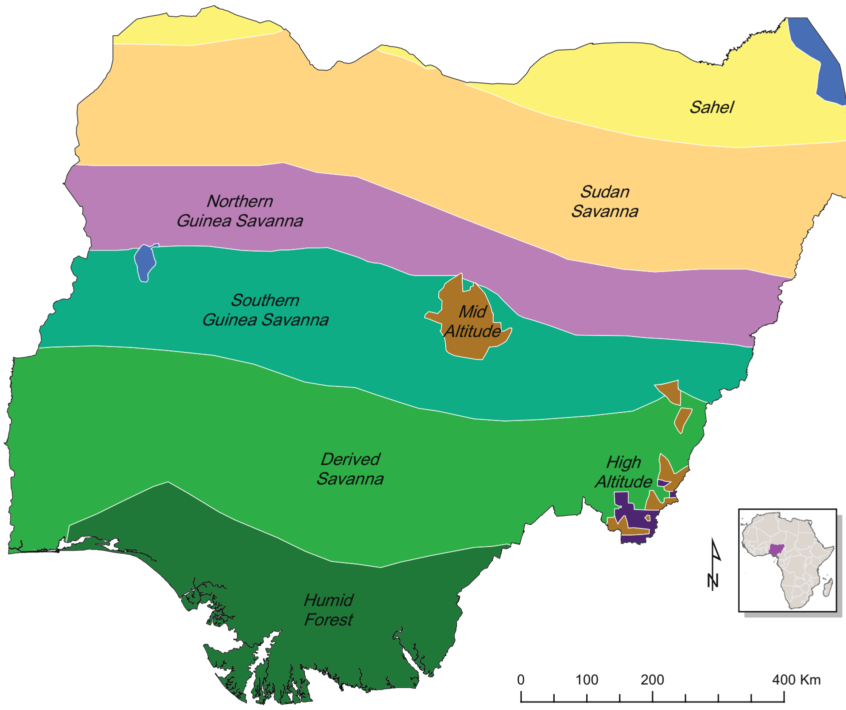


Figure 2.2. Nigerian climate zones.

2.3 Spatial data

Several agriculturally relevant SSA spatial data are available. Though the resolution is coarse, the data describes regional trends that influence potential crop production (Van Wart et al., 2013) and guide local crop suitability decisions. The Africa Soil Information Service (AfSIS) modelled soil properties at six soil depths. Several climate indices have been published (WorldClim, CGIAR CSI). The 2000 Shuttle Radar Topography Mission's elevation data are available worldwide for locations between 60°N and 56°S latitudes. Elevation derivatives are also available (HydroSHEDS) and the MAPSPAM project provides crop production estimates.

Spatial raster, vector and object data are processed with Geographic Information System (GIS) software programs. GIS packages often include complex spatial analysis and modelling tools in addition to basic mapping and data processing functionality. Several free (DIVA-GIS, GeoDa, GRASS, gvSIG Desktop and Mobile, SAGA, SPRING, QGIS, Whitebox Geospatial Analysis Toolbox) and proprietary (TerrSet (formerly IDRISI), ArcGIS, ERDAS IMAGINE) programs are available.

The Optimising Fertilizer Recommendations in Africa (OFRA) project strives to improve greatly the profitability of fertilizer use, especially for financially constrained fertilizer use as is the case for most smallholder farmers (Chapter 1). The OFRA approach uses results of past and recent research to determine crop nutrient response functions relevant for each site's agro-ecological zone (or inference space) so that economic analysis can be applied. Use of spatial data is important to finding and compiling information from research conducted under crop growing conditions similar to the conditions of the targeted recommendation domain.

2.4 OFRA Inference Tool

The OFRA Inference Tool (Wortmann and Milner 2015) is an ArcGIS 10.3 ArcPy script tool that identifies SSA research results and crop production estimates associated with growing conditions similar to those found at a user-defined point of interest (http://agronomy.unl.edu/OFRA).

The tool queries seven raster layers selected for agronomic importance. The amount of annual rainfall relative to potential evapotranspiration relates to water availability for crop production and is captured in CGIAR CSI's 30-arc second Global Aridity Index (Zomer et al., 2007, 2008). The manner in which temperature varies throughout a year impacts crop selection and is represented by WorldClim's 30-arc second Temperature Seasonality (bio4) layer (Hijmans et al., 2005). Mean temperature and the annual accumulation of growing degree days is dependent upon elevation, which is represented by Hydroshed's 3-arc second digital elevation model (DEM) (Lehner et al., 2008) resampled to 7.5 arc-seconds. Distance from the equator expressed as the absolute value of degrees latitude (as degrees x 1000; 7.5 arc-second) relates to rainfall distribution which changes from bimodal at the equator to increasingly unimodal with distance from the equator. Latitude also affects day length which impacts photoperiod sensitive crops. AfSIS 5-15 cm depth soil pH (as pHx10) (30-arc second; Hengl et al., 2014), sand content and soil organic carbon (SOC) content (7.5-arc second; Hengl et al., 2015) are included in the inference space analysis. Sand content is negatively related to clay content. Sand, pH and SOC are determinants of cation exchange capacity. Sand and SOC content are also important determinants of a soil's available water holding capacity. The average growing degree days (base 0) raster is highly correlated with elevation so it is not used to identify similarity but it is provided for reference. The raster was calculated from WorldClim.org's 30 arc-second mean monthly temperature data (Hijmans et al., 2005). All data are in geographic coordinates referenced to the WGS 1984 datum (GCS_WGS_1984).

The inference tool identifies the above seven raster values at the point of interest and uses a set of pre-defined queries to select crop nutrient response data from locations that have similar raster values. The query threshold values are editable from the script tool interface, but the query structure is not. The seven queries and editable default threshold values are:

Aridity Index (ai; range = 0 to 49,240):

If the selected ai value is <6000, then similarity equals the selected ai value + 1000. If ai is >6000, similarity equals ai values >5000.

Temperature Seasonality (ts; range = 62 to 8,933):

Temperature Seasonality similarity equals the selected ts value + 1000.

SOC (g/kg; 5-15 cm; range = 0 to 249):

If the selected SOC value is <35, then similarity equals the selected SOC value + 10. If soc is >35, similarity equals SOC values >25.

pH × 10 (range = 32 to 91)

If the selected pH × 10 value is <54, then similarity equals the selected pH × 10 value + 4. If pH × 10 is >54, similarity equals pH × 10 values >50.

Sand (%; range = 0 to 100):

If the selected sand value is >75, then similarity equals the selected sand value + 20. If sand is <75, similarity equals sand values <80.

Elevation (m; range = -178 to 5,844):

If the selected elevation value is <700, then similarity equals the selected elevation value + 1000. If elevation is >700, similarity equals elevation values >250.

Distance from Equator (DE; degrees × 1000; range = 0 to 11,691):

Distance from Equator similarity equals the selected DE value + 3000.

The tool queries two shapefiles, a point file of more than 5,300 georeferenced crop nutrient response functions and a polygon file of the 5-arc minute crop production raster cells with associated bean, cassava, cowpea, groundnut, maize, millet (pearl and small (finger)), Irish potato, rice, sorghum, soybean and wheat production (metric tons (mt)) values (HarvestChoice 2015a-l; You et al., 2014). The point file includes raster values at a representative point for each research plot (from which crop response is calculated) while the polygon file includes the median raster values associated with each 5-arc minute cell.

The OFRA Inference Tool outputs information for the point of interest's inference space: an Excel file containing a subset of crop response functions; two .pdf crop production maps (Figure 2.3); and a .dbf file containing crop production summaries (total production as metric tons and as the percentage of Africa's total crop production). The .dbf file also contains the point of interest's geographic coordinates and raster values as well as the queries used in the analysis.

The OFRA Inference Tool folder available at (http://agronomy.unl.edu/OFRA) includes

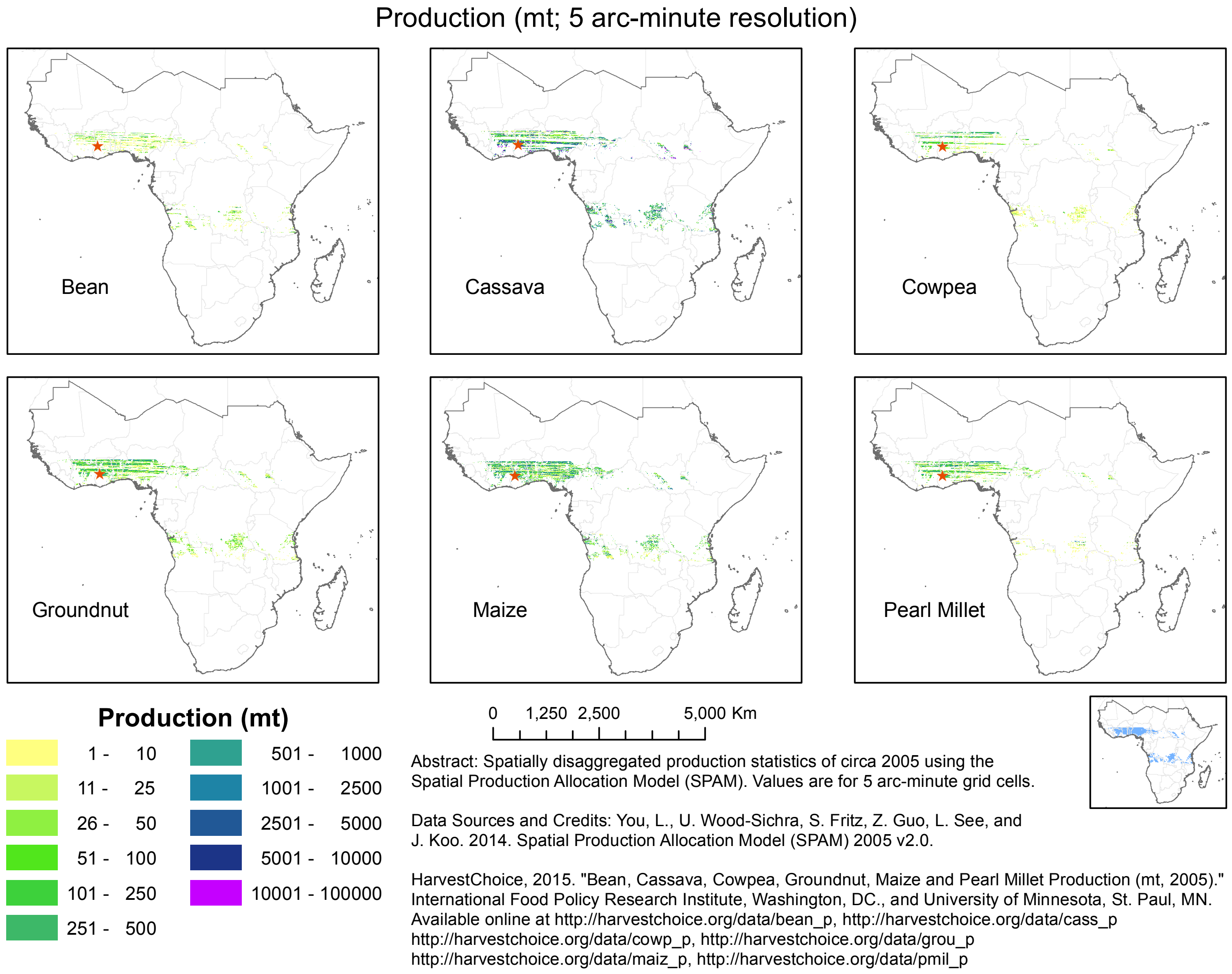


Figure 2.3. Bean, cassava, cowpea, groundnut, maize and pearl millet HarvestChoice production data associated with Wenchi, Ghana.

the ArcGIS script tool (OFRA Project.tbx), documentation, the GIS layers and data. The OFRA Inference Tool Documentation PowerPoint presentation provides instructions for use of the tool.

2.5 References

Aiken RM, Thomas V, and Waltman W (2001) Agricultural Farm Analysis and Comparison Tool (AgriFACTs). Regional Institute Online Publishing. Retrieved from http://www.regional.org.au/au/gia/05/126aiken.htm

HarvestChoice (2010) Agro-ecological Zones of sub-Saharan Africa. International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/node/8853.

HarvestChoice (2015a) Bean Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/bean_p

HarvestChoice (2015b) Cassava Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/cass_p

HarvestChoice (2015c) Cowpea Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/cowp_p

HarvestChoice (2015d) Groundnut Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/grou_p

HarvestChoice (2015e) Maize Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/maiz_p

HarvestChoice (2015f) Pearl Millet (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/pmil_p

HarvestChoice (2015g) Small Millet (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/smil_p

HarvestChoice (2015h) Potato Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/pota_p

HarvestChoice (2015i) Rice Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/rice_p

HarvestChoice (2015j) Sorghum Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/sorg_p

HarvestChoice (2015k) Soybean Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/soyb_p

HarvestChoice (2015l) Wheat Production (mt, 2005). International Food Policy Research Institute, Washington DC, and University of Minnesota, St. Pail MN. Retrieved from http://harvestchoice.org/data/whea_p

Hengl T, de Jesus JM, MacMillan RA, Batjes NH, Heuvelink GBM, Ribeiro E, Samuel-Rosa A, Kempen B, Leenaars JGB, Walsh MG, and Gonzalez MR (2014) SoilGrids1km—Global soil information based on automated mapping. Plos One 9(8) doi:10.1371/journal.pone.0105992

Hengl T, Heuvelink GMB, Kempen B, Leenaars JGB, Walsh MG, Shepherd KD, Sila A, MacMillan RA, de Jesus JM, and Tamene L (2015) Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. Plos One, doi:10.1371/journal.pone.0125814

Hijmans RJ, Cameron SE, Parra JL, Jones PG and Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Internat J Climat 25:1965-1978

Lehner B, Verdin K and Jarvis A (2008) New global hydrography derived from spaceborne elevation data. Eos, Transactions, AGU 89:93-94. Available from http://onlinelibrary.wiley.com/doi/10.1029/2008EO100001/abstract

Van Wart J, Grassini P and Cassman KG (2013) Impact of derived global weather data on simulated crop yields. Global Change Biol. 19:3822-3834

White F (1983) The vegetation of Africa, a descriptive memoir to accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa (3 Plates, Northwestern Africa, Northeastern Africa, and Southern Africa, 1:5,000,000). UNESCO, Paris

You L, Wood-Sichra U, Fritz S, Guo Z, See L, and Koo J (2014) Spatial Production Allocation Model (SPAM) 2005 v2.0. Available from http://mapspam.info/

Zomer RJ, Bossio DA, Trabucco A, Yuanjie L, Gupta DC and Singh VP (2007) Trees and Water: Smallholder Agroforestry on Irrigated Lands in Northern India. Colombo, Sri Lanka: International Water Management Institute. pp 45. IWMI Research Report 122 http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB122/RR122.pdf

Zomer RJ, Trabucco A, Bossio DA, van Straaten O, Verchot LV (2008) Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agric Ecosyst Envir 126:67-80

3. Integrated Soil Fertility Management in Sub-Saharan Africa

Patson Nalivata[1] patienalivata@yahoo.com, Catherine Kibunja[2], James Mutegi[3], Francis Tetteh[4], Bitrus Tarfa[5], Mohammed K. Dicko[6], Korodjouma Ouattara[7], Rusanganwa A. Cyamweshi[8], Maman K. Nouri[9], Wondimu Bayu[10] and Charles S. Wortmann[11]

[1]*Lilongwe University of Agriculture and Natural Resources, Bunda Campus, P.O. Box 219, Lilongwe, Malawi*
[2]*KALRO-Kabete, P.O. Box 14733- 00800, Nairobi, Kenya*
[3]*IPNI-Sub-Saharan Africa Program, P.O. Box 30772-00100, Nairobi, Kenya*
[4]*CSIR-Soil Research Institute, Academy Post Office, Kwadaso-Kumasi. Ghana*
[5]*Department of Soil Science, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Zaria Nigeria*
[6]*Institut d'Economie Rurale, B.P. 258, Rue Mohamed V, Bamako, Mali*
[7]*Institut de l'Environnement et de Recherches Agricoles (INERA), O4 BP 8645 Ouagadougou 04, Burkina Faso*
[8]*Rwanda Agriculture Board, P.O. Box 5016, Kigali, Rwanda*
[9]*Institut National de Recherche Agronomique du Niger (INRAN), BP 240, Maradi, Niger*
[10]*CABI, Canary Bird 673, Limuru Road Muthaiga, PO Box 633-00621, Nairobi, Kenya*
[11]*279 Plant Science, University of Nebraska-Lincoln, Lincoln, NE 68583-0915, USA*

3.1 Introduction

Soil fertility decline on smallholder farms contributes to low per capita food production in sub-Saharan Africa (SSA). Nutrient depletion for agricultural land in 37 African countries was estimated to average 660, 75 and 450 kg/ha of N, P and K between the years 1960 and 2000 (Smaling et al., 1997). These figures represent the balance between nutrient inputs as fertilizer, manure, atmospheric deposition, biological N2 fixation (BNF) and sedimentation, and nutrient outputs as harvested products, crop residue removal, leaching, gaseous losses, surface runoff and erosion. The gap between actual and rainfed potential yield has been estimated to be more than 4 t/ha for cereals and 2 t/ha for pulse crops (Haggblade and Hazell 2010; Haggblade and Plerhoples 2010). Actual mean yield for rainfed maize and irrigated rice is 10 to 30% and 30 to 50%, depending on country, of estimated potential yield (Global Yield Gap Atlas 2016). The yield gaps are attributed to a range of biotic and abiotic constraints, poor agronomic practices and low use of agricultural inputs including fertilizer.

Improved soil fertility management is key to increased smallholder agricultural productivity where fertilizer application to cropland averages about 15 kg/ha/yr. Fertilizer use needs to be specific to crops and agro-ecological zones (AEZ) and with the application of the right nutrients at the right rates, times and placements (the 4Rs of nutrient stewardship) to ensure nutrient use efficiency, environmental sustainability and profitable yield increases.

Fertilizer use must be coupled with optimized use of organic resources for nutrient supply and maintenance or improvement of soil aggregation, soil microbial activity, soil water infiltration and retention, resistance to erosion and nutrient transformation. However, the availability of organic resources is not sufficient to meet the nutrient needs of substantially increased productivity. For example, a 5 t/ha maize grain harvest, depending on the harvest index, requires the uptake of approximately 100, 24, and 85 kg/ha of N, P, and K (Table 3.1).

3.2 Integrated Soil Fertility Management

Vanlauwe et al. (2010) defined Integrated Soil Fertility Management (ISFM) as a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs and improved germplasm adapted to local conditions, aimed at high agronomic use efficiency of the applied nutrients and improving crop productivity. It implies efficient use of fertilizer and organic resources coupled with such good agronomic practices as planting improved varieties with appropriate spacing and timing and good control of weeds, insect pests and diseases. Vigorous crop growth is associated with an extensive and vigorous root system capable of efficient uptake of soil nutrients and water. The full benefits of ISFM may be achieved in a stepwise fashion as farmers learn to best adapt and integrate potential components and gain access to financial resources for higher levels of management (Figure 3.1). Potential organic soil fertility practices vary by AEZ and may include

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

Table 3.1: Amount of N, P and K removed in plant parts

	Nutrient uptake kg/t					
	Grain/produce			Plant residue		
	N	**P**	**K**	**N**	**P**	**K**
Maize	13	2.4	2.7	5.4	1.8	11
Sorghum	15	2.6	3.1	3.5	0.7	3.7
Wheat	9	1.7	1.8	5.1	1.8	8.3
Soybean	55	5.5	13	5.2	1.8	16
Rice	12	2.8	5.0	6.4	0.7	13
Bean	46	5.4	27	7.8	1.0	7.7
Groundnut	43	3.5	6	15	1.3	13
Irish potato	16	2.5	21	11	1.0	20

agroforestry such as fallows with fast-growing leguminous trees, leguminous annual cover or green manure crops for BNF, biomass transfer from plants growing outside the production area, manure and compost application, managing crop residue for soil maintenance and improvement, non-legume with legume rotations and intercropping, and rotation with well managed grass or grass-legume leys. While ISFM as a term and its definition are relatively recent creations, the underlying principles have been long recognized in soil fertility research, teaching and management. Many studies have addressed components of ISFM and their integration (Bationo et al., 2007). It is not the intent of this chapter to review all or any of these. Rather the chapter gives an interpretation of a synthesis of results with reference to a few key synthesis publications done for SSA. While good agronomic practices are key to ISFM and nutrient use efficiency generally, only practices with implications for soil nutrient supply and soil productivity will be addressed.

3.3 Common ISFM practices for sub-Saharan Africa

3.3.1 Land application of organic resources

The value of land application of organic resources is widely recognized by African smallholders and the resources are widely used. Inadequate supply often constrains greater use. Organic resources can supply soil nutrients but nutrient contents range widely. Manure nutrient concentrations range from 0.5 to 2.5% N, 0.4 to 3.9% P_2O_5, 1.2 to 8.4% K_2O and 0.3 to 5.4% CaO (Table 3.2). Green leaves of legumes range from 2.9 to 4.4% N, 0.13 to 0.30% P and <1 to 2.8% K (Table 3.3). Crop residues, including residues of legume pulse and oil seed crops, typically have <1% N and K and <0.1% P content. Nutrient contents should not be interpreted as fertilizer nutrient substitution values, with the exception of K which is readily released from dead organic materials. High carbon to nitrogen ratio (C:N) and high contents of lignin and polyphenols delay decomposition and organic nutrient mineralization of lower quality resources. Large quantities of most organic materials may be needed to equal the nutrient uptake associated with much increased crop yield. Transport of such huge amounts of low quality biomass and its capacity to immobilize soil mineral N due to high C:N limits the feasibility of using some organic resources. Available organic resources often have alternative uses such as livestock feed, fuel and construction material which further limits availability for land application.

The soil amendment effect of applied organic resources may exceed and certainly complement the nutrient supply effect. The amendment effect can be especially great on soils with low available water holding and nutrient supply capacity such as sandy soils of low soil organic matter (Chivenge et al., 2011). The amendment effect may also be great in cases of weak soil aggregation if susceptibility to

Table 3.2: Typical nutrient concentrations (%) for animal manures (Kaola, 2001)

Manure	Water	N	P_2O_5	K_2O	CaO
Farmyard manure	38 – 54	0.5 – 2.0	0.4 –1.5	1.2 – 8.4	0.3 – 2.7
Cattle dung	34 – 40	1.7 – 2.0	0.5 – 3.7	1.3 – 2.5	0.9 – 1.1
Sheep and goat droppings	40 – 52	1.5 – 1.8	0.9 – 1.0	1.4 – 1.7	0.9 – 1.0
Pig manure	35 – 50	1.5 – 2.4	0.9 – 1.0	1.4 – 3.8	1.3 – 1.5
Poultry manure	10 – 13	2.3 – 2.5	2.3 – 3.9	1.0 – 3.7	0.6 – 4.0
Compost manure	49 – 52	0.5 – 1.7	0.3 – 0.5	5.0 – 7.4	4.6 – 5.4

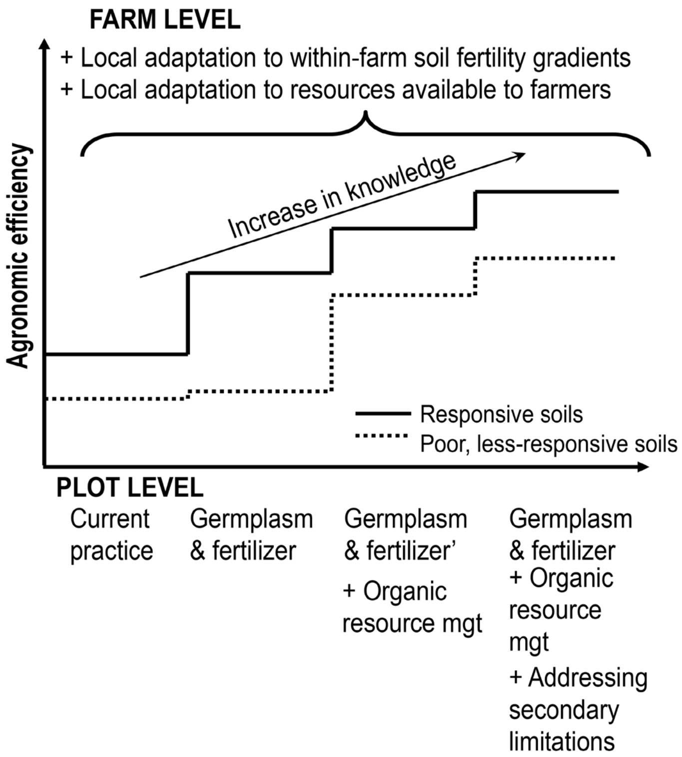


Figure 3.1: Conceptual relationship between agronomic efficiency (AE) of fertilizers and organic resource and the implementation of various components of ISFM culminating in complete ISFM towards the right side of the graph. Soils that are responsive to NPK based fertilizer and those that are poor and less responsive are distinguished. Source: Vanlauwe et al., 2010.

erosion and crusting is reduced. With such soils, there may be little response to fertilizer nutrients applied alone, but a much greater response to fertilizer when an organic resource is also applied (Figure 3.1).

3.3.2 Organic resources complemented with fertilizer application

Chivenge et al., (2011) compiled and analysed the results of 52 research studies conducted in SSA to evaluate the effects on maize yield of combined application of organic resources and fertilizer N compared with using either alone.

The synergist effects varied with properties of soil and the organic resource. The effect of the applied organic resources alone increased with rate and the capacity to supply N. High quality organic resources applied in sufficient quantities could fully meet maize N requirements, including sandy soil. Organic resources with <2.5% N concentration were considered low quality as were some high N plant materials with high lignin and polyphenol concentration. Application of organic materials alone resulted in more yield increase in situations of <5 t/ha maize yield compared with fertilizer N alone. The percent yield increase was greater with the combination of fertilizer N and low compared with high quality organic resource but this was not necessarily true for the quantity of yield increase. The benefit of the combination was greater with <600 compared with >1000 mm/yr rainfall. With loam soils and >600 mm/yr rainfall and therefore of relatively high productivity, there was little yield benefit with the combination compared to fertilizer N alone. The residual effect of the organic resources on the subsequent crop was, however, greater for loam compared with sandy soils.

The effect of 25 years of continuous cropping was determined in Central Kenya where the initial soil organic C was 2%. Soil organic C declined with all soil management practices. The soil organic C decline was 37% for a combination of fertilizer N and P and 10 t/yr of farmyard manure applied plus retention of crop residues in the field, but 54% with another treatment (Kibunja et al., 2012).

3.3.3 Crop residue management and tillage

The value of crop residues in soil management has been long recognized, especially in densely populated areas. Allan (1965) described several examples such as use as mulch for banana and

Table 3.3: Elemental nutrient concentration of above ground biomass of various plant materials (Zingore et al., 2014; Kaizzi and Wortmann 2001)

Organic Source	Species	Plant part	%N	%P	%K
Tree or shrub	*Calliandra calothyrsus*	Leaves	3.3	0.17	0.8
	Leucaena leocephala	Leaves	3.9	0.19	2.1
	Tephrosia vogelii	Leaves	2.9	0.18	1.1
	Fleminga macrophylla	Leaves	2.7	0.16	0.7
	Lantana camara	Prunings	2.7	0.16	2.7
Herbaceous legume	*Crotalaria grahamiana*	Leaves	3.0	0.13	0.8
	Crotaralia juncea	Leaves	3.8	0.16	1.3
	Mucuna pruriens	Leaves	4.4	0.30	1.6
Herbaceous, other	*Senna hirusta*	Plants	3.0	0.18	4.6
	Aspilia kotschyi	Plants	1.3	0.11	4.0
Grain legume	Pigeonpea	Leaves	3.3	0.19	1.3
	Groundnut	Leaves	3.0	0.17	2.4
	Soybean	Leaves	3.6	0.15	2.4
	Beans	Leaves	2.9	0.30	2.8
	Cowpea	Leaves	2.9	0.10	2.1
Cereals	Maize	Leaves/husks	0.9	0.07	0.7
	Rice	Leaves/husks	1.0	0.07	0.7

coffee in Eastern Africa, the Matengo pit system of southwestern Tanzania, the Mambwe mound system of northeastern Zambia and the Dagomba system of the Guinea Savanna in Ghana. With the exception of mulching, each of these systems aims to fully use crop residue as a nutrient source with an enhanced rate of decomposition and nutrient cycling.

While there are competing uses for the crop residues, much burning of residues continues. Crop residues are low quality organic resources in regards to nutrient supply as indicated by low N concentrations (Table 3.3). Incorporation compared with removing soybean crop residue was found in the Guinea Savanna of Nigeria to have a fertilizer N value of about 15 kg/ha for maize that received no fertilizer N (Figure 3.2). However, crop residues left in the field and not consumed by termites and ruminants contributes to soil organic matter which regulates numerous soil properties and processes. It has been most common to incorporate plant residues before planting the next crop but there is potential advantage in avoiding tillage and leaving the crop residues on the soil surface.

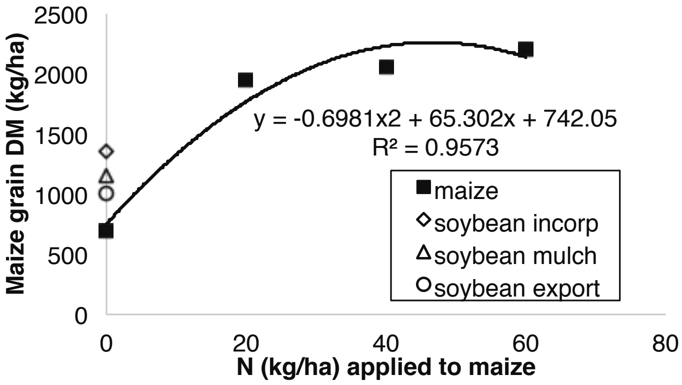


Figure 3.2: Effect of management of soybean residues on soybean rotation effect (Singh et al., 2001).

Conservation agriculture (CA) integrates reduced or no tillage, ground cover by plants and plant residues, and crop rotation. Pittelkow et al. (2015) did a globally comprehensive analysis of 610 studies with 5463 comparisons of CA with some other management system. In considering the tillage component alone, mean yields were 11.9% less with no pre-plant tillage compared with the conventional tillage practice but the reduction was less in drier compared with humid production situations. However, under semi-arid rainfed conditions, there was a 7.3% mean yield increase when all three components of CA were applied with residue retention and crop rotation contributing equally to overcome the negative effect of no tillage. The benefit of residue retention plus rotation with tillage compared with no tillage was not reported. The results did not show that CA became more effective over time.

These results are largely supported by an earlier and smaller analysis of numerous studies conducted for SSA and South Asia where annual crop yields were typically less with no-tillage compared with conventional tillage and the negative effect was lessened if combined with crop rotation and crop residue retention (Brouder and Gomez-Macpherson 2014). In each study, good targeting of CA is emphasized. For example, mean sorghum yield over 7 yr at two locations in Uganda was 11% more with direct planting without tillage compared with conventional inversion tillage (Nansamba et al. 2016). In a review for sorghum production systems, mostly of the Sudan Savanna, Mason et al. (2015) found yields with no-till to be 12% less on average compared with shallow tillage. Yields were increased with crop residue left on the soil surface compared with residue removal. Sorghum yield in rotation with cowpea was consistently higher compared with sorghum monoculture. The Nansamba and Mason works demonstrate that one or more components of CA are often beneficial to yield on their own and additively without much evidence of synergy.

In a review of over 100 published studies with a focus on SSA and South Asia, Palm et al. (2014) found that both crop residue retention and reduced tillage resulted in the improvement of several soil properties in the surface 10-cm soil depth but there was a lack of evidence for synergistic effects and generally there was little or no effect below 10-cm depth. Overall for the surface 10-cm soil depth, with both no-till compared to conventional tillage and crop residual retention compared with removal, there were increases in total and particulate soil organic matter, soil microbial biomass and diversity, earthworms, aggregate stability and plant available water. No-till and residue retention compared with the management alternatives resulted in reduced runoff, erosion and evaporation. Soil porosity was generally reduced with no-till and increased with residual retention.

3.3.4 Intercropping with legumes

Legume integration into cropping systems is an important component of ISFM. Legume production in intercrop association with maize, sorghum, pearl millet, banana, cassava and other non-legumes is widely practised and more common in SSA than legume rotation with these crops. Intercropping benefits include increased land productivity and reduced risk compared with sole crop production. Much bean production in SSA is by intercropping with maize, but also with sorghum, banana, cassava and other crops. In the Sahel, pearl millet/cowpea, pearl millet/groundnut and sorghum/groundnut are the most common intercropping systems. In higher rainfall AEZ of West Africa, maize intercropped with cowpea, groundnut or soybean is common. Pigeonpea is commonly produced by intercropping with maize.

When crops are complementary in terms of growth pattern, aboveground canopy, rooting system and/or periods of high water and nutrient demand, intercropping enables more efficient use of photosynthetically active radiation, water and nutrients. Intercropping may provide better soil cover compared to sole crop for weed suppression and reduced soil erosion and crusting. The legume intercrop may suppress Striga infestation of the cereal crop but probably less effectively than with rotation. The intercrop complementarity is often achieved through differences in maturity times with legumes often making much of their growth and nutrient and water uptake before the associated crop forms a full canopy and maturing earlier than the non-legume. In such cases, fallen legume leaves may decompose enough to release nutrients to the associated crop. In other cases, such as with long season pigeonpea or relay intercropping of cowpea, the legume makes much of its growth after the maize or other associated crop matures.

The intercropped legumes can fix atmospheric N but are also likely to compete with the non-legume for available soil N. Given the amount and timing of soil N availability, soil N depletion by the non-legume may stimulate BNF. Most fertilizer N should therefore be applied in-season when the non-legume has a high rate of N uptake. Significant BNF may occur, such as with long duration pigeonpea or with relay intercropping legumes into the cereal where the legume makes much of its growth after the cereal crop matures and has depleted soil mineral N. In cases of cereal-legume intercrop that is fertilized to meet the N need of the cereal, BNF may be very little as the legume will be competitive for uptake of the applied N while legume suppression by the vigorously growing cereal will also suppress BNF. It is not likely that significant transfer of N from the living legume to the cereal occurs although the later maturing non-legume may access N mineralized from decomposing leaves and nodules following senescence. More BNF as well as transfer of N from the legume to the grass is likely with a perennial grass-legume ley compared with annual cereal-legume intercropping.

The associated crops do compete for all essential soil nutrients and water but differences in timing of their high uptake rates reduces this competition. Most legume pulse and oil seed crops have tap roots. When the legume has extensive root development, it may tap deep immobile nutrients and leached nutrients such as nitrate-N, use these for growth and return some to the soil through decomposition of crop residue. Long season and perennially growing pigeonpea can be especially effective in taking up deep soil nutrients and cycling some to the topsoil through decay of roots and above ground crop residues. With a good legume grain harvest, however, N removed in the harvest commonly exceeds the atmospheric N that is fixed.

It is common that yield of both associated crops is less with intercropping compared with sole crop but the total of the intercrop yields relative to their sole crop yields commonly exceeds sole crop yield. This is assessed by land equivalent ratio (LER); if LER is greater than one, productivity has been improved by intercropping. Intercropping can be managed to favour one associated crop relative to the other. Planting the legume after the associated cereal has emerged will enhance the relative competitiveness of the cereal compared with planting both on the same day. A basal application of little or no N and withholding most N application until six weeks or longer after planting is expected to increase the relative competitiveness of the legume compared with applying 50% or more of the fertilizer N at or before planting.

Intercrop planting pattern varies including planting all crops in the same row, alternative rows or pairs of rows, and alternating strips of more than two rows which may include rotation of crops across these strips. The planting pattern variation also has temporal aspects with both or all crops planted on the same day or on different days. Planting pattern is expected to affect the relative competitiveness of the component crops.

An innovative intercropping system, named MBILI (Kiswahili for two, and an acronym for 'Managing Beneficial Interactions in Legume Intercrops') consists of two maize rows alternated with two rows of bean, groundnut and/or another legume which allows more light penetration for the under-storey legume component and reduces legume access to N applied for the maize component. In the Sahel, alternating four rows each of cowpea and pearl millet combined with crop rotation has resulted in similar pearl millet yield and increased cowpea yield compared with the respective sole crops.

Relay intercropping of maize and cowpea is common in the Guinea Savanna of Nigeria. One planting pattern is to plant on the same day two rows of medium maturity maize alternated with four rows of a 65 days maturity cowpea variety. After cowpea harvest, the entire field is weeded and a medium maturity cowpea variety is planted in the rows of harvested legumes and also inter-planted between the maize rows. After the harvest of the maize, the entire field becomes a cowpea sole crop that matures during the dry season (Photo 1).

Photo 1: Cowpea was relay intercrop planted into maize and continues to grow following maize harvest.

'Doubled-up legume' intercropping refers to intercropping of two legumes and is practised in Malawi. Species complementarity is improved with differing growing habits and maturity periods such as with tall growing and late maturing pigeonpea intercropped with groundnuts or soybean. Doubled-up legume intercropping has been observed to result in more BNF compared with the sole crops. The earlier maturing legume makes much of its growth before the tall legume intercepts much radiation. The tall late maturity legume uses water of late rains and residual soil water following maturity of the associated crop. Soybean and cowpea have been observed to lack complementarity in doubled-up legume intercropping.

The implications of intercropping for nutrient application rates have generally not been well determined. An exception is for maize-bean intercropping in Kenya where the optimal rate of N and P is higher with intercropping compared with soil crop maize (see Chapter 6).

3.3.5 Green manure

Legumes can add much to the N balance of a farm operation through BNF. Giller and Wilson (2001) estimated the BNF capacity of various legumes at 105 to 206 kg/ha N for pulses, 110 to 280 kg/ha for green manure crops and 162 to 1063 kg/ha over several years for tree legumes Some species-specific annual BNF rates are presented in Table 3.4.

A green manure crop is a legume that is grown for BNF to supply N to following crops and organic matter for soil property improvement. It is often terminated before maturity although may be allowed to grow to maturity when maximized production of a relatively higher C:N biomass is desired such as for ground cover or increasing soil organic C. It is commonly incorporated into the soil but may be left on the soil surface as a mulch. Green manure crops are cover crops but not all cover crops are green manure crops in that cover crops often are not legumes and may be grown for other purposes than N supply, such as protection against erosion or for weed suppression. Green manure and other cover crops are by definition not harvested although a farmer may decide in the end to instead harvest it as a forage or grain crop.

Much research on green manure and cover crops has been done in SSA and the results were well synthesized by Eilitta et al. (2004). Common green manure species include mucuna *Mucuna pruriens*, several crotalaria species, *Canavalia ensiformis, Dolichos lablab* and cowpea. The green manure may be a sole crop, especially during the minor rainy season where bimodal rainfall occurs. It may also be relay intercropped with another species, such as planting of the green manure crop at second weeding of the main crop with the green manure crop continuing to grow after harvest.

There is ample evidence of increased yield of the following non-legume crop, even in some cases with fertilizer N applied. Depending on the C:N of the biomass of the green manure crop and the time since termination of the crop before planting the next non-legume crop, some fertilizer N might be applied to support the early growth of the non-legume crop while organic N in the green manure biomass becomes crop available. For example, application of up to 30 kg/ha of fertilizer N is recommended in Tanzania for rice production following the incorporation of mucuna green manure biomass.

Table 3.4: Potential biological N fixation rates of various leguminous species (Giller and Wilson, 2001)

Species	Potential BNF rate (N/ha/yr)	References
Acacia mangium	50-100	Atangana et al., 2014
Casuarina equisetifolia	360	Atangana et al., 2014
Gliricidia sepium	86-309	Liyanage et al., 1994
Tephrosia vogelii	100	Werner 2005, FAO 2010
Pigeonpea	90	Werner 2005, FAO 2010
Crotalaria grahamiana	142	Werner 2005
Crotalaria juncea	130	Becker 1995, FAO 2010
Mucunapruriens	130	Werner 2005, FAO 2010

Despite much study of green manure in SSA with promising results, there is little green manure production practised. Farmers have not been able to justify to themselves the value of producing a crop that they will not harvest.

3.3.6 Cereal-legume rotation

Studies across SSA and elsewhere have found rotation benefits of increased yield both for the cereal following the legume and the legume following the cereal in rotation compared to cereal or legume continuous production. These rotation benefits commonly are 5 to 15% yield increases, although cases of much lower and others of much greater benefit have been reported, as by Mason et al. (2015). The percent but less so the magnitude of yield increases due to rotation are often greater with low compared with adequate soil fertility situations. Some of the rotation benefit to the following cereal crop may be due to increased N availability but the benefit can occur even when adequate fertilizer N is applied. Breaking disease and insect cycles likely contributes much to rotation benefits. Soil microbial communities are affected by the previous crop and the type and quantity of crop residues produced as well as the type and quantity of organic materials applied (Kamaa et al., 2011); these shifts may contribute to the rotation effect such as more effective colonization of roots by vesicular arbuscular mycorrhiza that contribute to improved nutrient and water uptake.

Legumes in rotation can add much to the N balance of a farm operation through BNF (Table 3.4). However, harvest of forage and grain legumes typically removes more than the equivalent of the N derived from BNF. Legumes prefer to use available soil N as BNF requires plant energy. Soil mineral N is often observed to be more depleted following a pulse compared with a cereal harvest. Even so, fertilizer N need for the cereal following a legume in rotation is commonly less, even with the increased yield due to the rotation effect, compared with continuous cereal production. This N benefit is likely due to factors other than a direct contribution from the legume crop to the cereal crop that may include: relatively quick decomposition of the legume leaf residue compared with cereal crop residue; less crop residue of lower C:N ratio for the legume compared with the cereal crop and therefore less immobilization of soil and fertilizer N following the legume crop; and generally healthier and more vigorous root systems for more effective nutrient uptake for cereals following legumes compared with following a cereal.

Soil organic matter during the legume compared with the cereal phase of the rotation typically shows some decline as photosynthesis and biomass production is typically less during the legume phase while plant and soil respiration are similar for both phases. This decline is at least partly if not fully compensated for by increased productivity of the rotation compared with cereal monoculture. However, rotation of a cereal with an annual leguminous pulse or oil seed crop, with its numerous benefits, should not be seen as a means to increasing soil organic matter.

Fertilizer P use may differ for cereal-legume rotations compared with continuous production of a single crop with evidence that the cereal is less responsive to applied P following a legume compared with a cereal. Application of fertilizer P often results in increased BNF by legumes. Some therefore advise that rather than applying fertilizer P every year, all fertilizer P be applied to the legume and to produce the cereal on the residual P. However, other evidence contradicts this in that the legume such as soybean is less sensitive to low soil test P than maize, resulting in a preference to apply all fertilizer P to maize and producing soybean on the residual P. In cases of high P fixation by the soil and where fertilizer use is constrained by inadequate finance, application of some fertilizer P each year may be most profitable and preferred. The OFRA approach to optimizing fertilizer use is to maximize profit. With poor farmers, this profit needs to be gained within a short time and they cannot afford to wait for more than a year for production to benefit from the residual effect of a fertilizer application. Therefore fertilizer use decisions need to be based on the expected net returns with the next crop. As seen from the country chapters of this book, net returns for P application to legumes compared to non-legumes are overall relatively good.

3.3.7 Adding perennials to the annual crop rotation

Based on research begun in the 1930s, Uganda has a rarely used recommended rotation of three to four years in annual crop rotated with three years of well managed perennial ley. The ley could be established from natural revegetation or planting, such as with Napier grass. The effectiveness of ley in the rotation in maintaining soil productivity was greater than planting of green manure crops. The forage could be grazed or harvested for animal feeding. The benefit appeared to be due to the increase in active soil organic matter, improved soil physical properties and improved soil P availability. The greatest benefit may be on sandy soils of low organic matter that are not very responsive to fertilizer use. An added advantage on erodible land is the protection from erosion throughout the rotation by having good vegetative ground cover for the ley, the improved resistance to erosion because of improved soil aggregation and the enhanced productivity and ground cover of the annual crops. Perennial ley in rotation is similar to fallow but the ley needs to be well managed to be effective.

Fallowed lands are commonly abused by unregulated overgrazing, giving the plants little opportunity to develop good root systems and achieve high productivity. The rotation can be profitable not only because of the increased annual crop yields but also through use of the forage produced for profit-oriented intensive ruminant production. The system cannot work well where farmers have no control of grazing as even severe overgrazing during the dry season is likely to delay perennial recovery and reduce productivity and soil improvement.

Another means of adding perennials to annual crops is with short duration treelots. The treelots may be solely as a form of improved fallow and a green manure crop. More often the trees will have a harvested product such as high protein forage for dairy or producing wood products. Leguminous trees add N to the system and cycle deep nutrients but such trees are likely to be less effective in increasing soil organic matter and improving soil aggregation compared with perennial grass.

3.3.8 Parkland agriculture

Parkland agriculture is a term used in the Sahel and Sudan Savannas and refers to annual crop production under and around generally large, erect trees (Depommier 1996). It is practised elsewhere in some semi-arid parts of eastern and southern Africa, often on sandy soils of low productivity and with low soil organic matter, but the term parkland agriculture is commonly used only in west Africa.

The trees add organic material to the soil and improve soil water holding capacity and nutrient availability. The most recognized parkland tree is *Faidherbia (Acacia) albida* (Photo 2). It is unique for its reverse phenology in that it sheds its leaves during the rainy season reducing direct competition for water, light and nutrients. In the hot and dry season it produces leaves which can be used as fodder. The dry season shade leads to ruminant livestock gathering under the trees where more excretion of faeces and urine occurs compared with open areas. Faidherbia is a legume adding N to the farming system. Compared with open fields, the N and P availability under trees have been determined to be 200 and 30% more, respectively, and crop performance is noticeably better with measured yield increases of greater than 100%.

Other trees such as the shea-tree (*Vittelaria paradoxa*) are also effective, although less so compared with Faidherbia, in improving annual crop productivity while providing its own economically valuable yield. *Parkia biglobosa* is

Photo 2: Pearl millet production is commonly greater under Faidherbia trees. These trees do not have leaves during the rainy season and are leafy during the dry season (reverse phenology).

another important parkland species. Farmers recognize the value of parkland agriculture but establishment of trees is difficult due to unrestricted overgrazing during the dry season.

3.3.9 Biochar

Biochar is charcoal or pyrogenic carbon that is applied in small pieces to amend soil (Guo et al., 2016). The major advantage of adding biochar compared with the original organic material is that the biochar C is much more persistent in the soil compared to the C applied in organic resources. The half-life in soil of C applied in organic materials is typically less than a year as decomposition occurs through soil microbial activity with C released to the atmosphere through microbial respiration. In comparison, the half-life of biochar C in the soil may be longer than 100 years.

Biochar application increases cation exchange capacity, water holding capacity, soil aggregation and soil porosity. The amendment effect is expected to be greatest with soils of low nutrient supply and low water holding capacity. Such soils amended with biochar can have much improved response to applied nutrients. The benefit of biochar is expected to be less with soils that are relatively good for these properties and more where there is greater opportunity for improvement of these soil properties. The biochar is not a good C and energy source for soil microbes but can enhance microbial habitat. The magnitude of effects varies with the rate of application. Biochar in most cases will be a very limited resource as are organic resources for soil management, but what is potentially available could often be used to great benefit.

There is some traditional 'biochar' practice with smallholders of SSA although it has not been recognized as such. In Madagascar, there is a tradition of 'burning' low productivity Ferralsols and Andosols, the latter with very high P fixation capacity. At the end of a fallow period, they do not pile and do combustion burning of the bush and grass plant material. Instead, furrows of approximately 20 cm depth are dug, the dried plant material arranged in the furrows, and then covered using the excavated soil. The furrow ends are left open and the material ignited. Once ignited, pyrolysis slowly progresses down the covered furrow for a week or more with little oxygen supply, charring the covered plant materials. Subsequent production over these burn furrows is much greater than for unburnt soil. The combined benefit of heating the soil, ash deposition and biochar has not been well differentiated but it is expected that the biochar effect will be long term. It is likely that even with slash and burn systems, significant amounts of existing soil C is pyrogenic C due to incomplete combustion of some of the vegetative material.

The feasibility of biochar depends on the availability of plant materials and of the potential of improving a soil such as a sandy soil of low nutrient supply and water holding capacity. Crop residues that are not consumed by termites or someone else's livestock can be valuable to the farmer for diverse reasons if left in the field, including for reduced evaporation and erosion, and improvement of surface soil aggregation. However, often the residues are consumed with little in-field value. There is also much combustion burning of plant materials by smallholders, e.g. following fallow, rice straw and hulls, strong stalks of tall traditional sorghums and even maize stover. Very often the burning of plant materials is associated with low productivity soils that could benefit from increased stable soil C supplied as biochar.

Numerous simple and inexpensive kiln options are available that are appropriate for smallholder use including some consisting of little more than a 200-litre drum (http://www.appropedia.org/Simple_Biochar_Kilns). A small kiln that can be easily moved to accumulations of plant materials in the field greatly reduces the labour of transporting the plant material, especially if the biochar is used *in situ*. The biochar will be most effective if crushed into small bits. Biochar has low density and should be incorporated into the soil to prevent removal by runoff.

3.3.10 Good fertilizer use practices

Good fertilizer use practices have been encapsulated in the term '4Rs of nutrient stewardship' including the right fertilizer source (or type) applied at the right rate, at the right time and in the right place (Johnson and Bruulsema 2014). In the case of poor smallholders, potential profit from fertilizer use needs to be of primary concern. Profit also needs to be a concern of well financed crop production but needs to be balanced with concerns about effects on soil, ground and surface waters, and the atmosphere.

The right fertilizer. The right fertilizer source or type means matching the fertilizer to the crop's need for applied nutrients. Therefore, the fertilizer needs to supply one or more nutrients which are inadequately available in the soil to meet crop needs. Fertilizer formulations differ in cost per nutrient supplied with added complexity and processing adding to cost. The effect of the fertilizer type on the soil needs to be considered. For example, some fertilizers have a greater soil acidifying effect than others which is a consideration for soils with or nearing problematic low soil pH. However, economics needs to be considered. While nitrate, unlike urea and ammonium, in fertilizer does not contribute to soil acidity, nitrate production requires more fossil fuel consumption and production costs. The more economical approach may be to use a less expensive source of N with an acidification effect and to manage soil acidification with lime application as compared to using a more costly N source of less acidifying effect.

The right rate. The rate of fertilizer nutrient application is overall the most important of the 4Rs for profitability and environmental consequences. Fertilizer N rates are especially of concern in good nutrient stewardship as much N is applied but it is a nutrient that is at risk of loss due to leaching, volatilization, denitrification, runoff and nitrous oxide emission. Excessive N application contributes unnecessarily to soil acidification, and the acidification effect is greater for N lost to leaching compared with that recovered by the crop. The rate of application should not normally exceed the economically optimal rate (EOR), that is, the rate expected to maximize net returns to fertilizer use per hectare. Often the rate should be less than EOR. Smallholders who are financially constrained in fertilizer use are expected to get better returns on their constrained fertilizer use by applying at a rate where the yield increase per kg/ha of applied nutrient is relatively great compared to the increase near EOR. An environmental concern, such as risk of nitrate leaching to groundwater, may result in a regulation for applying N at some rate less than EOR. In reality, EOR varies greatly by field and year and is not well predicted. Essential to approximating EOR are representative crop nutrient responses functions such as have been determined by OFRA for food crops in 67 AEZ (see Chapter 1). Estimation of EOR can be improved by considering soil test information, rotation effects, organic resource application and other practices as addressed in this chapter and in Chapters 4-16. Some low productivity soils require amendment such as with lime or organic resources to have good crop response to fertilizer (Figures 3.3 and 3.4). Biotic constraints, such as severe Striga infestation, may reduce the potential of crop response to applied fertilizer. Due to low predictability of N EOR in a given season, in-season N application with adjustment of rates according to canopy colour has gained practice globally.

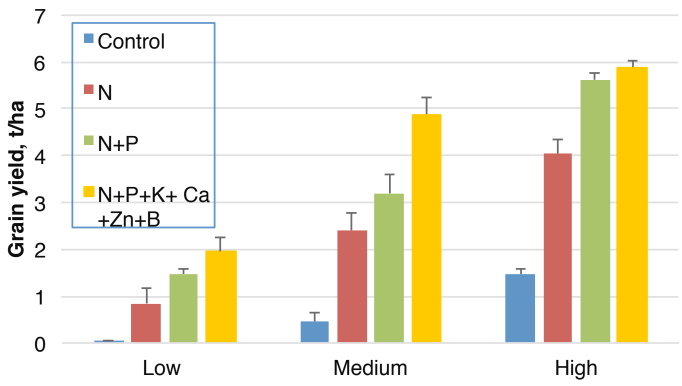


Figure 3.3: Maize response to applied nutrients for low, intermediate and high productivity soils in southern Malawi (Zingore et al., 2011).

Fertilizer micro-dosing is point application of fertilizer nutrients at low rates at planting, post

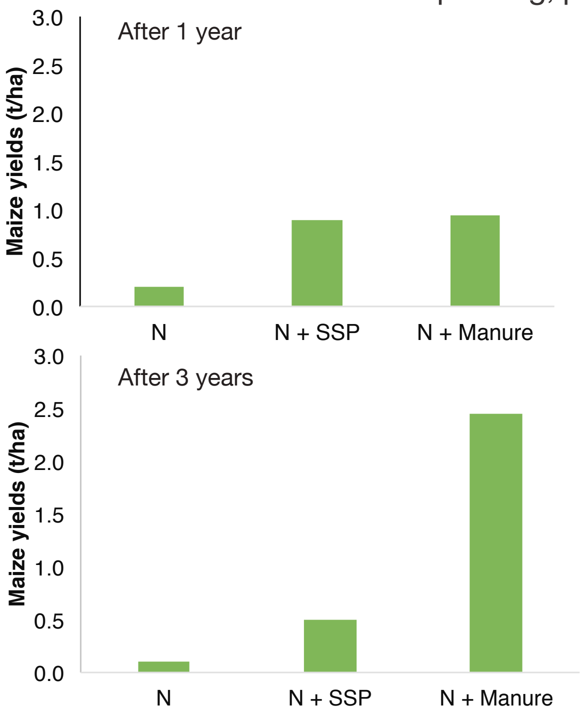


Figure 3.4: Effect of manure on crop response to fertilizer in non-responsive sites (Zingore et al., 2007).

Table 3.5: Average maize grain in relation to micro-dosing and banding application methods in Hawasa, Ziway and Melkassa regions in Ethiopia (Sime and Aune 2014)

Method	Fertilizer rate DAP+Urea kg ha	Hawassa	Location Ziway	Melkassa
Control	0	6334b[1]	4054b	3649b
Microdosing	27+27	7539a	5864a	5320a
	53+53	7222a	6042a	5542a
	80+80	7086a	5743a	5221a
Banding	100+100	7636a	5815a	5226a

[1]Means sharing the same letter are not significantly different from each other

emergence or several weeks after emergence, as appropriate, for low productivity soils in low rainfall areas such as the Sahel. Sorghum and pearl millet yield increases of 44 to 120% due to micro-dosing have been reported which were comparable to yield increases with the higher recommended rates (Bagayoko et al., 2011; Tabo et al., 2011). Micro-dosing was evaluated with maize in Ethiopia with a mean grain yield with no fertilizer applied of 4.7 t/ha; yield increases were similar with all rates of N and P application which ranged from 17 and 5 kg/ha of N and P to 64 and 20 kg/ha of N and P, respectively (Table 3.5) (Sime and Aune 2014).

The right time. The time of fertilizer application is important. It is very common to apply P, some N and maybe K and/or other nutrients before or at planting as often there is a pop-up effect to stimulate early growth and root development. Delay in basal fertilizer application can result in yield loss as found by Sakala (1998) in Zambia. In cases of risk of poor crop establishment, however, this basal application may be more wisely done shortly after crop emergence and maybe with a rate adjustment according to establishment success. In-season application of some N is a common practice globally and in SSA, and is especially beneficial on sandy soils and where much rainfall occurs during the season (Zingore et al., 2014). An important advantage of in-season N application, in addition to reduced risk of N loss to leaching, is that the farmer can judge the condition of the crop and may decide in cases of poor crop condition, due to biotic or abiotic problems or to management, to apply no or a reduced rate of N. This adaptive management is expected to increase in importance as the frequency of extreme weather events increases. In-season N application should

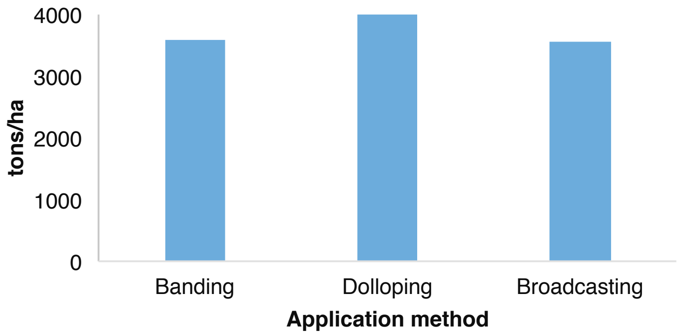


Figure 3.5: Effect of fertilizer application method on maize yield in Malawi. (Adapted from a presentation by Benson T.D.) http://www.slideshare.net/IFPRIMaSSP/maximizing-returns-to-fertilizer-use-on-maize-in-malawi-lessons-from-onfarm-agronomic-research-by-todd-benson-ifpri.

correspond to near the beginning of very rapid N uptake by the crop, such as at the 8-leaf stage of maize.

The right place. Placement of fertilizer is important. Placing the fertilizer at a point under or very near the seed or plant creates the risk of fertilizer salt damage. Legumes with tap roots are especially vulnerable to high salt fertilizers, such as KCl placed under the seed, even if well covered with soil. Point or band placement of basal fertilizer, at least 5 cm from the seed or plant, is often more efficient than broadcast application for maize and other crops with widely spaced planting when fertilizer application rates are low but there are exceptions (Figure 3.5).

Deep placement of urea super granules (USG) may add to N use efficiency in lowland rice production. The USG are oval compacted pellets, commonly of 1.8 or 2.7 g, produced using briquetting machines. One USG is placed at 5-7 cm depth in puddled transplanted rice fields at one week after transplanting between four rice plant stands spaced at 20 × 20 cm. No additional fertilizer N is applied. Benefits to the use of USG

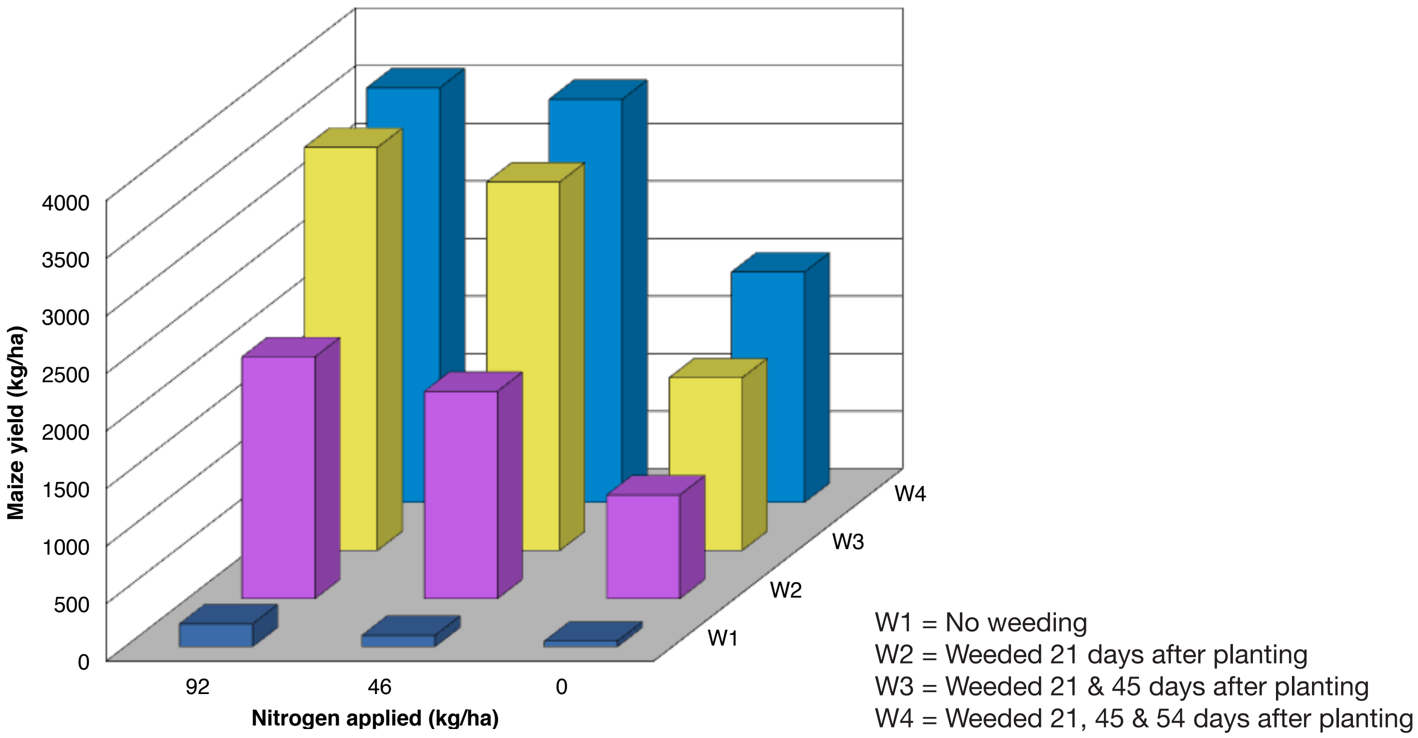


Figure 3.6: Effect of different weeding levels on maize yield.

deep placement include reduced N rate, fewer N applications, increased yield, less weeding and better applied N recovery with less denitrification and runoff loss of N.

3.3.11 Water availability

Water is the direct source of the essential nutrient hydrogen and is necessary for plant uptake of nutrients as well as for plant metabolism and growth generally. Soil water deficits may be prevented with timely irrigation. Mason et al. (2015) reviewed 21 papers addressing tillage and water conservation in the Sahel and found generally higher yields by planting pearl millet into tilled compared with untilled soil because of improved water infiltration with tillage, a large positive effect of water conservation with tied-ridges and zai, and that there was often a positive interaction of combining nutrient application with water conservation.

Zougmoré et al. (2004) found that water harvesting and conservation alone did not improve crop productivity in Burkina Faso but was effective when organic material and fertilizer were added. They found that combining compost with stone bunds or grass strips resulted in 180% more sorghum grain yield, while the same soil conservation measures used jointly with fertilizer N only increased yield about 70%. Sorghum yield was more with zai half-moon micro-catchments combined with compost or animal manure application compared with fertilizer application.

Weed control is important to water and nutrient availability. Inadequate control may reduce maize yields by more than 50% and two weeding cycles of maize are often needed (Kabambe and Kumwenda 1995) (Figure 3.6).

3.4 Conclusion

Improved soil nutrient availability is essential for much increased crop productivity in SSA. Smallholder farmers are typically very poor and need to get high net returns on their use of money such as for fertilizer use. Therefore, cost effectiveness of improved soil nutrient supply is very important. This chapter has explored alternatives of nutrient supply and management for high nutrient use efficiency.

Potential synergies of combining different alternatives sometimes exist, especially for situations of low soil productivity and little response to fertilizer application, but more often effects are mostly additive. Increases and improved use of organic resources, increased integration of legumes in rotations, crop rotation, increasing soil organic matter and improvement in associated soil properties such as through rotation of perennial with annual crops and use of biochar, better use of fertilizer and reducing soil water deficits, are addressed.

Most practices have trade-offs. No single practice may be universally appropriate. Practices need to be well targeted for greatest effectiveness.

3.5 References

Allan W (1965) The African Husbandman. Greenwood Press, Westport CT. p 505

Atangana A, Khasa D, Chang S and Degrande A (2014) Tropical Agroforestry. ISBN: 978-94-007-7722-4

Bagayoko M, Maman N, Palé S, Sirifi S, Taonda SJB, Traore S and Mason SC (2011) Microdose and N and P fertilizer application rates for pearl millet in West Africa. African J Agricul Res 6: 1141-1150

Bationo A, Waswa B, Kihara J and Kimetu J (Eds) (2007) Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer, Dordrecht, the Netherlands. p1091

Becker M (1995) Green manure technology: Potential, usage, and limitations. Plant and Soil 174:1-2

Brouder S and Gomez-Macpherson H (2014) The impact of conservation agriculture on smallholder agricultural yields: a scoping review of the evidence. Agric Ecosyst Environ 187:11–32

Chivenge P, Vanlauwe B and Six J (2011) Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. Plant Sci 342:1-30

Depommier D (1996) Structure, dynamique et fonctionnement des parcs à Faidherbia albida (Del.) A. Chev. Caractérisation et incidence des facteurs biophysiques et anthropiques sur l'aménagement et le devenir des parcs de Dossi et de Watinoma, Burkina Faso. Thèse de doctorat, Paris VI, Université Pierre et Marie Curie, France

Eilitta M, Mureithi J and Derpsch R (2004) Green Manure/Cover Crop Systems of Smallholder Farmers (Eilitta M, Mureithi J and Derpsch R, Eds). Kluwer Academic Publishers. p 335

FAO (2010) Green manure/cover crops and crop rotation in Conservation Agriculture on small farms. Integrated Crop Management

Giller K and Wilson KJ (2001) Nitrogen Fixation in Tropical Cropping Systems (2nd edition). CAB International, Wallingford, UK. p 441

Global Yield Gap Atlas (2016) http://www.yieldgap.org/gygamaps/app/index.html

Guo M, He Z and Uchimiya SM (2016) Agricultural and Environmental Applications of Biochar: Advances and Barriers. SSSA Special Publication 63. SSSA, Madison, WI USA

Haggblade S and Hazell P (Eds) (2010) Successes in African Agriculture: Lessons for the Future. Johns Hopkins University Press, Baltimore

Haggblade S and Plerhoples C (2010) Productive impact of conservation farming on smallholder cotton farmers in Zambia. Working paper No. 47. Food Security Research Project, Lusaka, Zambia

Johnston AM and Bruulsema TW (2014) 4R nutrient stewardship for improved nutrient use efficiency. Procedia Engineering 83:365-370

Kabambe VH and Kumwenda JDT (1995) Weed management and nitrogen rate effects on maize yield in Malawi. In Jewell D, Waddington S, Ransom J and Pixley K (Eds) Maize Research for Stress Environments. CIMMYT, Harare, Zimbabwe

Kaizzi CK and Wortmann CS (2001) Plant materials for soil fertility management in sub-humid tropical areas. Agron J 93:929-935

Kamaa M, Mburu H, Blanchart E, Chibole L, Chotte JL, Kibunja C and Lesueur D (2011) Effects of organic and inorganic fertilization on soil bacterial and fungal microbial diversity in the Kabete long-term trial, Kenya. Biol Fertil Soils 47:315-321. doi:10.1007/ s00374-011-0539-3

Kaola S (2001) Integrated soil fertility management for central Kenya highlands.ISFM extension module. AFNET

Kibunja CN, Mwaura FB, Mugendi DN, Gicheru PT, Wamuongo JW and Bationo A (2012) Strategies for maintenance and improvement of soil productivity under continuous maize and beans cropping system in the sub-humid highlands of Kenya: Case study of the long-term trial at Kabete pp 59 – 84. In Bationo A, Waswa B, Kihara J, Adolwa I, Vanlauwe B and Saidou K (Eds). Lessons Learnt from Long-term Soil

Management Experiments in Africa. Springer. doi:10.1007/978-94-007-2938-4

Liyanage MS, Danso SKA and Jayasundara HPS (1994) Biological nitrogen fixation in four *Gliricidia septum* genotypes. Plant Soil 161:267-274

Mason SC, Maman N and Palé S (2015) Pearl millet production practices in semi-arid West Africa: a review. Expl Agric 1-21 doi:10.1017/S0014479714000441

Nansamba A, Kayuki CK, Twaha AB, Ebanyat P and Wortmann C (2016) Grain sorghum response to reduced tillage, rotation, and soil fertility management in Uganda. Agron J (in press)

Palm C, Blanco-Canqui H, DeClerck F, Gaterea L and Grace P (2014) Conservation agriculture and ecosystem services: An overview. Agric Ecosyst Environ 187:87-105

Pittelkow CM, Liang X, Linquist BA, van Groenigen KJ, Lee J, Lundy ME, van Gestel N, Six J, Venterea RT and van Kessel C (2015) Productivity limits and potentials of the principles of conservation agriculture. Nature 517:365-370

Sakala WD (1998) Nitrogen dynamics in maize/pigeonpea intercropping in Malawi. 1998 PhD Thesis. Wye College, University of London

Sime G and Aune JB (2014) Maize response to fertilizer dosing at three sites in the Central Rift Valley of Ethiopia. Agron 4:436-451

Singh A, Carsky RJ, Lucas EO and Dashiell K (2001) Maize grain yield response to previous soyabean crop and residue management in the Guinea Savanna of Nigeria. In Impact, Challenges and Prospects of Maize Research and Development in West and Central Africa. Badu-Apraku B, Fakorede MAB, Ouedraogo M and Carsky RJ (Eds) Proceedings of a Regional Maize Workshop 4-7 May, 1999, Cotonou, Benin. IITA, Ibadan, Nigeria pp 214-224

Smaling EMA, Nandwa, SM and Janssen, BH (1997) Soil fertility is at stake. In Replenishing Soil Fertility in Africa. Buresh RJ, Sanchez PA and Calhoun F (Eds). SSSA Special Publication Number 1, American Society of Agronomy, Madison, Wisconsin, USA

Tabo R, Bationo A, Amadou B, Marchal D, Lompo F, Gandah M, Hassane O, Diallo MK, Ndjeunga J, Fatondji D, Gerard B, Sogodogo D, Taonda JBS, Sako K, Boubacar S, Abdou A and Kaola S (2011) Fertilizer Microdosing and “Warrantage” or Inventory Credit System to Improve Food Security and Farmers’ Income in West Africa. In Innovations as Key to the Green Revolution in Africa. Bationo A et al. (Eds) Springer Science+Business Media BV pp 113-121

Vanlauwe B, Bationo A, Chianu J, Giller KE, Merckx R, Mokwunye U, Ohiokpehai O, Pypers P, Tabo R, Shepherd K, Smaling E, Woomer PL and Sanginga N (2010) Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outlook on Agric 39:17-24

Werner D (2005) Production and biological nitrogen fixation of legumes in tropical agriculture. Forest Ecol Environ 4:1-13

Zingore S (2011) Maize productivity and response to fertilizer use as affected by soil fertility variability, manure application and cropping system. Better Crops 95:4-6

Zingore S, Murwira H, Delve R and Giller K (2007) Soil type, management history and current resource allocation: three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Res 101:296–305

Zingore S, Njoroge S, Chikowo R, Kihara J, Nziguheba G and Nyamangara J (2014) 4R Plant Nutrient Management in African Agriculture: An Extension Handbook for Fertilizer Management in Smallholder Farming Systems. International Plant Nutrition Institute (IPNI). ISBN: 978-0-9960199-0-3

Zougmoré R, Ouattara K, Mando A and Ouattara B (2004) Rôle des nutriments dans le succès des techniques de conservation des eaux et des sols (cordons pierreux, bandes enherbées, zaï et demi-lunes) au Burkina Faso. Note de Recherche, Sécheresse 15:41-48

4. Optimizing Fertilizer Use within an Integrated Soil Fertility Management Framework in Burkina Faso

Korodjouma Ouattara[1] korodjouma_ouattara@hotmail.com, Idriss Serme[1], Alimata Arzouma Bandaogo[1], Souleymane Ouedraogo[1], Adama Sohoro[1], Zakaria Gnankambary[2], Sansan Youl[3], Pascal Yaka[4], Tahibou Pare[2]

[1]*Institut de l'Environnement et de Recherches Agricoles (INERA), O4 BP 8645 Ouagadougou 04*
[2]*Bureau National des Sols (BUNASOLS), 03 BP 7005 Ouagadougou*
[3]*International Fertilizer Development Center Burkina Faso (IFDC), 11 BP 82 Ouaga 11 Ouagadougou, Burkina Faso*
[4]*Centre Agroméorologique du Burkina Faso, 01 BP 4413 Ouagadougou 01, Burkina Faso*

4.1 Introduction

Nutrient application is important to increase crop productivity in Burkina Faso. While fertilizer use has increased by 50% during recent decades, the mean total of N, P_2O and K_2O applied was just 15.3 kg/ha/yr in 2013 (World Bank 2013). Only 8 to 35 % of farmers use fertilizer, depending on the region, in spite of government supported subsidies.

Increased crop production has depended on increased cropland area rather than on intensification. Soil nutrients are removed in harvests without replenishment through fertilizer application resulting in soil nutrient depletion and decreased soil productivity and crop yield (Bationo et al., 1998; Ouattara et al., 2006 and 2011; Mason et al., 2014 and 2015). More fertilizer is used where farmers have support from government and non-government extension services. Fertilizer use for food crop production is often constrained because farmers are inadequately informed and have little financial capacity for fertilizer use. Also, the fertilizer supply system is inefficient with untimely delivery.

Farmers wish to profit from fertilizer use. They are more likely to apply fertilizer to cash compared with food crops. If finance is adequate, farmers may apply fertilizer to maximize net returns per hectare resulting from fertilizer use. However, for those living in ongoing financial peril with little opportunity for improvement and much vulnerability, investment in fertilizer use competes with other pressing needs. Therefore, fertilizer use must give high returns with little risk. To reduce risk in fertilizer use, the recommendation should take into consideration the farmers' cropping system and financial conditions. Aspects of farmer profitability and risk were not adequately accounted for when developing fertilizer recommendations in Burkina Faso.

Fertilizer recommendations have been developed since 1974, first for commercial peanut and cotton production. The extension service applied the cotton recommendations to cereals. However, during the 1980s, with the support of a World Bank project known as Fertilizer for Food Crops, research was conducted to develop fertilizer recommendations for maize, sorghum and pearl millet in three main agro-ecological zones (AEZ) to account for annual rainfall differences. These recommendations are still general and do not account for variation in soil type, labour capacity and climate risk. Worse, most farmers are not informed of the recommendations.

The Optimizing Fertilizer Recommendation in Africa (OFRA) project worked to improve the basis for more profitable fertilizer use decisions without increased financial risks for the major crop producing AEZ. Based on multi-location experiments for two main soil types in each agro-ecological zone and for the main crops in Burkina Faso, OFRA has improved the information basis for fertilizer use optimization. Fertilizer use optimization in this chapter refers to maximizing profit from fertilizer use, including profit per hectare for farmers with adequate finance and profit on small investments in fertilizer use by the financially constrained.

This chapter describes the general agricultural context of Burkina Faso, the characteristics of the AEZ, the soil types, and the main cropping. It addresses fertilizer use optimization in Burkina Faso and factors that affect profitability of fertilizer. Computer-run and paper-based decision tools are introduced for optimizing fertilizer use giving choices expected to maximize profit to fertilizer use. Also, a tool for adjusting fertilizer rates according to practices such as manure use and according to soil test information is provided. A comparison is made of current fertilizer rate recommendations with the rates that are expected to maximize net returns per hectare due to fertilizer use, called in this chapter the economically optimal rates (EOR) of nutrient application.

4.2 Agricultural systems of the agro-ecological zones (AEZ) in Burkina Faso

The AEZ of Burkina Faso include the Sahel, the North Sudan Savanna and the South Sudan Savanna (Figure 4.1).

The Sahel is semi-arid. Mean annual rainfall in Dori, which is in this zone, is 485 mm, of which 47% falls in July, August and September (Table 4.1). Monthly mean maximum and minimum temperatures range from 32 to 42°C and from 16 to 29°C, respectively. The generally high sand content of upland soils combined with low and erratic rainfall makes the occurrence of drought a major constraint to crop production; the best adapted crops are pearl millet, cowpea and sesame. The main soils are: (i) tropical ferruginous

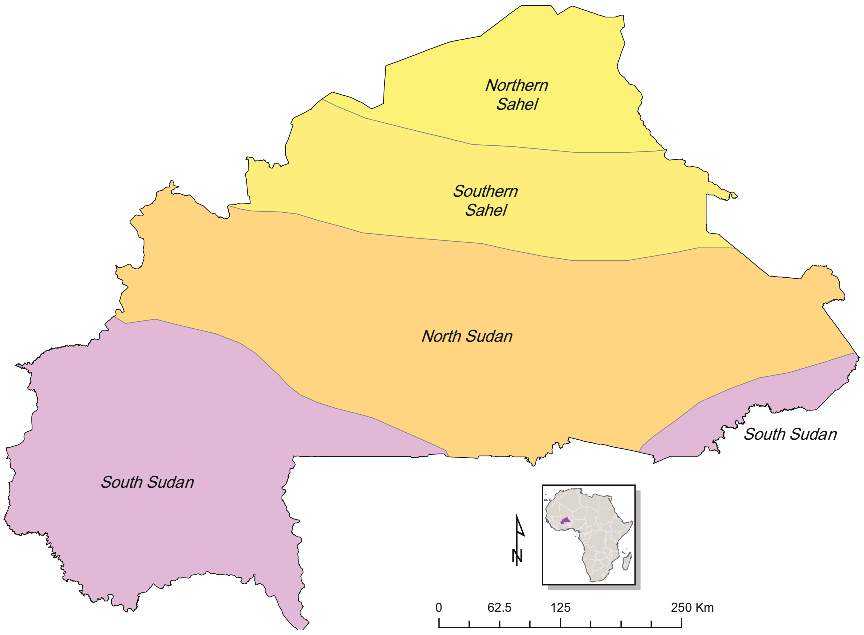


Figure 4.1: Map of the agro-ecological zones of Burkina Faso derived from the map of natural vegetation and land cover of Fontès and Guinko (1995).

Table 4.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Burkina Faso

	J	F	M	A	M	J	J	A	S	O	N	D
South Sudan Savanna, Farakoba												
Rainfall	6.8	0.0	26.1	41.5	59.7	175.0	201.5	304.4	327.7	61.2	17.3	0.3
Tmax	33.0	35.6	37.2	37.6	36.1	33.0	31.5	30.2	30.7	33.4	34.6	32.1
Tmin	19.3	22.1	24.3	25.7	25.2	23.2	22.5	22.0	21.5	22.6	22.1	18.8
North Sudan Savanna, Boni												
Rainfall	0.0	3.3	0.0	0.5	38.5	65.9	204.5	234.6	238.8	43.7	11.8	0.0
Tmax	33.0	35.6	37.2	37.6	36.1	33.0	31.5	30.2	30.7	33.4	34.6	32.1
Tmin	19.3	22.1	24.3	25.7	25.2	23.2	22.5	22.0	21.5	22.6	22.1	18.8
Sahel, Dori												
Rainfall	4.3	0.0	13.6	0.0	6.1	54.8	124.4	160.8	106.6	15.1	0.0	0.0
Tmax	32.6	34.4	38.9	41.6	42.0	39.2	36.0	33.4	35.1	39.0	37.8	32.1
Tmin	16.5	18.9	22.2	25.3	29.3	27.0	25.5	24.3	24.8	25.4	20.6	16.0

Sources: General Direction of National Agro-meteorology, Burkina Faso.

types, poorly to fully leached overlying sandy, clayey-sand and sandy-clay material; (ii) degraded holomorphic soils comprising solonetz overlying sandy-clay material; and (iii) tropical eutrophic brown soils overlying high clay parent material and poorly evolved erosional soil overlying gravelly material (CILSS and OMM, 2001). Crop and livestock production are both important and transhumance is practised. The livestock produce manure which is important to soil fertility management but also denude cropland of plant residue and expose the soil to erosion. The vegetation is characterized by Saharan and Sahelian species which are uncommon in higher rainfall areas including the woody species *Acacia ehrenbergiana, Acacia nilotica* variety *tomentosa, Acacia raddiana, Grewia tenax, Leptadenia pyrotechnica, Maerua crassifolia* and *Salvadora persica*. The thin riparian zones are dominated by *Anogeissus leiocarpus, Mitragyna inermis, Acacia ataxacantha* and *Acacia seyal*. The southern Sahel is a transition to the Sudan savanna and the composition of woody species changes with an increase in *Acacia laeta, Acacia nilotica variety adansonii, Acacia senegal, Boscia salicifolia, Commiphora africana, Dalbergia melanoxylon, Pterocarpus lucens* and *Grewia flavescens*. Sudan savanna species common in the southern Sahel are *Acacia macrostachya, Combretum glutinosum, Combretum nigricans* var. *elliotii* and form the composition of the bushes associated with *Pterocarpus lucens* and *Dalbergia melanoxylon* (Fontès and Guinka, 1995).

Mean annual rainfall in Boni, which is in the Northern Sudan Savanna, is 840 mm and 56% falls in July, August and September (Table 4.1). The rainfall season is wetter and begins earlier compared with the Sahel. Monthly mean maximum and minimum temperatures range from 30 to 38°C and from 19 to 26°C, respectively. The soils include tropical ferruginous soils, poorly evolved erosional soils and hydromorphic mineral to pseudogley soils overlying material of varied texture. The crops produced are sorghum, maize, groundnut, cotton and pearl millet, and also rice close to some seasonal streams. The Sudan Savanna becomes wetter moving south and the physiognomy is a succession of herbaceous, shrubby and bushy species, tending to a clear forest in the extreme south-west. The savanna landscape can be park-like with many big trees including *Faidherbia albida* (known for its reverse phenology bearing leaves during the dry season but shedding leaves with the start of the rains), *Adansonia digitata, Butyrospermum paradoxum* subsp. *parkii, Lannea microcarpa* and *Tamarindus indica*. In the shrubby stratum, combretaceae are well represented. The most regular species are: A*cacia dudgeoni, Acacia gourmaensis, Acacia seyal, Bombax costatum, Combretum micranthum, Combretum glutinosum, Combretum nigricans, Grewia bicolore, Guiera senegalensis* and *Sterculia setigera.*

The South Sudan Savanna is the more humid zone. Farakoba, which is in this zone, has an annual mean rainfall of 1220 mm (Table 4.1). The wettest period is July to September when 68% of the rainfall occurs. Monthly mean maximum and minimum temperatures range from 30 to 37°C and from 19 to 26°C, respectively. The main soil types are tropical ferruginous soils poorly to fully leached, hydromorphic mineral to pseudogley soils and ferralitic soils; partly desaturated overlying variable textured material (CILSS and OMM 2001). The cropping systems are cereal- and cotton-based. The crops produced are maize, sorghum, cotton, groundnut, pearl millet and irrigated and rainfed rice.

The 'General Population and Housing Census' (GPHC) in 2006 estimated Burkina Faso's population at 13.7 million, was 52% female and had a mean population density of 40 inhabitants per sq km. The mean rate of population increase between 1996 and 2006 was 2.5% per year. The population was unevenly distributed. The Center Region, in the North Sudan Savanna, accounted for 11% of the population. The Boucle du Mouhoun Region (10.5%) and the Hauts-Bassins Region (10.3%) in the South Sudan Savanna were the next two most populous regions. Conversely, the Cascades, Southwest, and Center South regions accommodated 3.8%, 4.6%, and 4.7% of the population, respectively. More than 80% of the population lived in rural areas. The population of Center Region was 77.5% urban, followed by Hauts-Bassins Region with 34.7% of its population living in towns. In the Sahel and East Regions, only 6.5% and 6.3% of the population, respectively, lived in urban areas. The largest sociolinguistic groups were the Mossi (about 48% of the total population) and Fulani (10%). Other ethnic groups were the Lobi, Bobo, Mande, Senoufo, Gourounsi, Gourmantche and Kel Tamasheq (Tuareg).

4.3 Soil nutrient management, including fertilizer use, in Burkina Faso

Traditional fallowing practices had various important ecological and sociological functions including restoration of soil fertility and biodiversity, hunting and supplies of medicinal plants. However, fallowing is less common than in the past due to demographic pressure and more intensive land use (Ouattara et al., 2006).

In Burkina Faso, estimates indicate that nutrient mining from 6.6 million hectares of cultivated land amounted to a total loss of 95,000 tonnes of N, 28,000 tonnes of P_2O_5 and 79,000 tonnes of K_2O, equivalent to US$ 159 million of NPK fertilizer (Bationo et al., 1998; MAHRH 1999). Arable lands are increasingly degraded in terms of soil productivity, biodiversity and ground water recharge due to shortening fallow periods, over-grazing and animal traffic. Other traditional soil fertility management practices include land application of organic resources such as manure and household wastes. The contracting of herdsmen to keep livestock overnight in the field during the dry season for excretion of urine and faeces has a strong tradition.

Fertilizer recommendations developed in the 1970s and 1980s differ by rainfall regime but do not consider other aspects of the farmer's situation. The application of organic fertilizer (OM) is recommended at 5 t/ha every two years for integration with fertilizer use. Evidence for adjusting fertilizer for soil test results is weak. OFRA activities have improved the information basis for fertilizer use decisions.

The soils in Sub-Saharan Africa are known for their low nutrient contents. Fertilizer use has resulted in crop yield increases. In on-station and on-farm trials conducted in 2014-15 in the three AEZ of Burkina Faso, nitrogen (N) application compared to the control gave mean grain yield increases of 27% for rice, 40% for sorghum, 53% for pearl millet and 181% for maize. For legume crops, P application resulted in mean yield increases of 43% for cowpea and 17% for groundnut. The diagnostic treatment containing N-P-K-S-Zn-Mg-B responded differently relative to the comparable N+P+K treatment by crop and AEZ. The percent yield increase was greater than the standard error of the mean for cowpea, maize, sorghum and rice, but the effect on pearl millet was inconsistent and groundnut was negatively affected (Figure 4.2a). The mean yield changes by AEZ, with and without manure applied, were less than the standard error except for a significant yield increase with the diagnostic treatment with no manure applied in the Sahel (Figure 4.2b). More information is needed to verify these observations and to determine which of the four nutrients of the diagnostic package accounts for these effects.

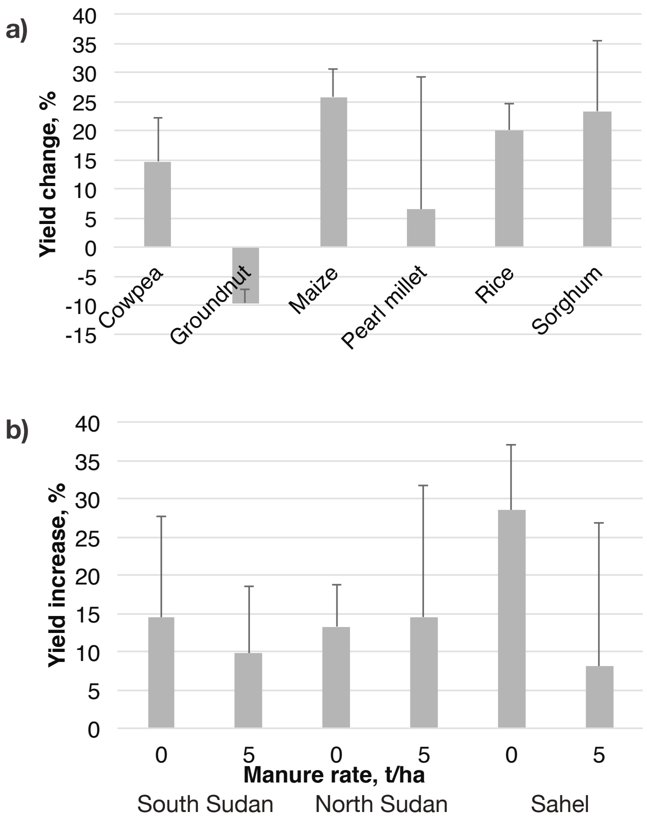


Figure 4.2: Percent yield change due to a diagnostic treatment (N+P+K+Mg+S+Zn+B) compared with N+P+K for a) several cereal and legume crops and b) by agro-ecological zone with and without 5 t/ha compost applied in Burkina Faso.

4.4 Optimizing fertilizer use in Burkina Faso

Field research under the OFRA project was conducted in 2014 and 2015 to improve the information base for fertilizer use decisions for sorghum, maize, pearl millet, rice, cowpea and groundnut. The research was conducted on the major agricultural soil types of the three AEZ described above for determination of crop nutrient response functions for N, P and K.

Data were analyzed to determine curvilinear to plateau responses as represented by maize response to N in the South Sudan Savanna (Figure 4.3). The response curve is represented by the equation $Y = a - bc^r$ where Y = yield, a and b = maximum yield (yield at plateau) and maximum yield increase achievable, respectively, with application of this nutrient; c, together with exponent r (nutrient rate), determine the shape of the curve.

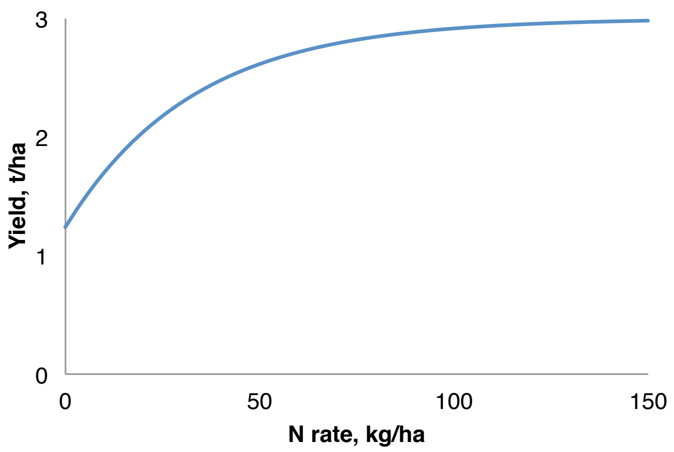


Figure 4.3: Maize response to N in the South-Sudan Savanna of Burkina Faso.

Maize yield was near the plateau with 90 kg/ha N applied but most of the yield gain was with 40 kg/ha N applied after which the rate of yield increase with more N diminished. Once the maize N response curve for yield has been determined for an AEZ, it is possible to determine net financial returns to N application at any rate, depending on fertilizer N cost and the value of maize grain, and to determine the N rate for maximizing profit per hectare from fertilizer application.

Most smallholders in Burkina Faso are financially constrained farmers who need to achieve high profit from fertilizer use. Some nutrients applied to some crops have much more profit potential than for other nutrients applied to the same or other crops (Figure 4.4). The amount of money invested in one nutrient applied to one crop is shown on the x-axis, that is, on the horizontal axis. The y-axis shows net returns to investment in one nutrient applied to one crop as the rate of nutrient application changes. Each curve represents the profit potential of one nutrient applied to one crop.

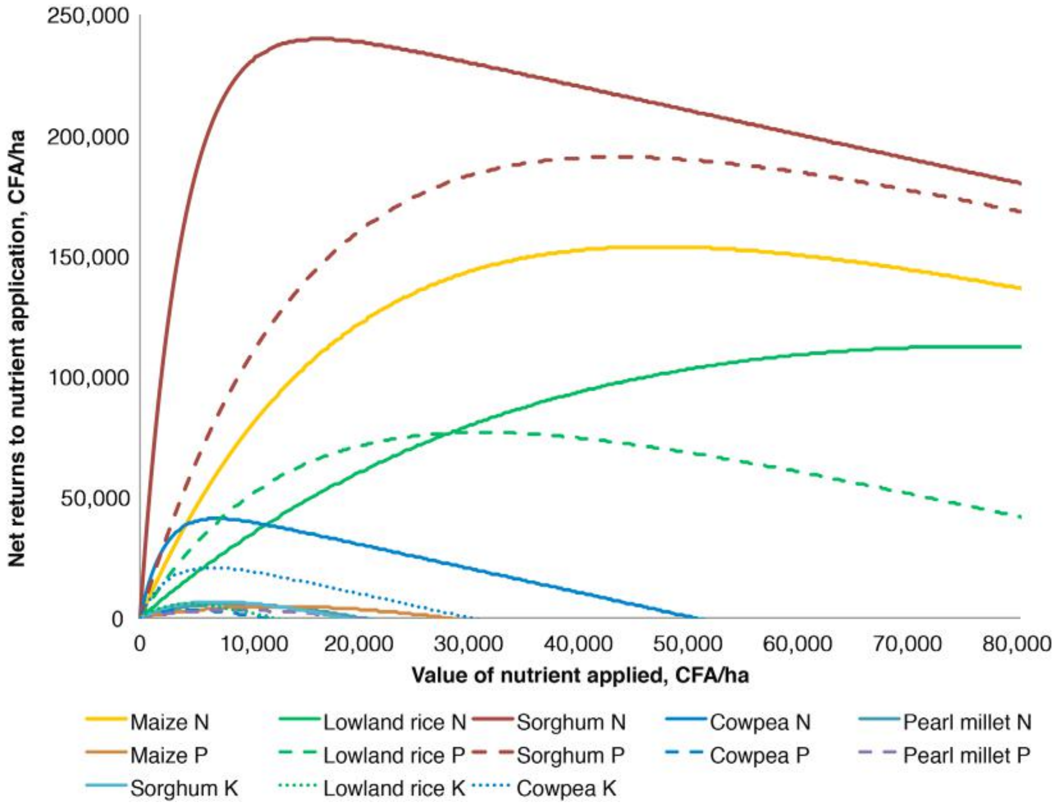


Figure 4.4: Net returns to investment in crop-nutrient for the South Sudan Savanna of Burkina Faso. The fertilizer use costs per 50-kg bag were FCFA 19000, 22500, 23000, 20750 and 23000 for urea, TSP, DAP, KCl and NPK, respectively. The crops values used were FCFA 125 per kg of maize and rice, and 150, 300, 400 and 500 per kg of sorghum, groundnut, pearl millet and cowpea respectively.

When the slope of the curve is steep, net returns to investment are very high. As the amount invested (the x-axis) increases the slope decreases but if still upward, profit is increasing. The curves reach a peak at the EOR, that is, the rate of maximum profit per hectare. When slopes decline with increased nutrient rate, profit is declining. The financially constrained farmer wants first to take advantage of the crop-nutrient combinations that will give the most net returns.

In the South Sudan Savanna, sorghum with N and P applied, and maize and lowland rice with N applied, have high profit potential with small investment (Figure 4.4). The highest rate of returns on investment is with a small amount of N applied to sorghum, up to about FCFA 5000/ha worth of N, but EOR is soon reached after which profit declines. The next steepest slope is with N applied to maize with a high rate of return up to FCFA 20,000/ha of N applied after which applying more N reduces profit. Nitrogen and P applied to rice has profit potential with the maximum return with FCFA 20,000/ha investment in P while the required investment to reach EOR for rice N is around FCFA 60,000/ha. Nitrogen and K applied to cowpea have moderate profit potential while other options with low lying curves have relatively little profit potential.

As for other AEZ of Burkina Faso, profit potential varies with crop-nutrient-rates. The financially constrained farmer needs to first take advantage of the high profit opportunities such as with N and P applied to sorghum and N applied to maize and lowland rice, if the farmer produces any of these crops. The rates of application should be less than EOR for P applied to sorghum and N applied to maize or rice as other fertilizer use options become competitive for profit potential, such as low rates of P applied to lowland rice or to maize.

The financially able farmer striving to maximize profit per hectare due to fertilizer use should not invest more than FCFA 30,000 per ha in an applied nutrient given the assumed fertilizer costs and grain values. The exception is with N applied to lowland rice in this AEZ; profit can increase by applying up to 60,000 FCFA per ha worth of N to lowland rice.

4.5 Fertilizer use optimization tools (FOT) for AEZ of Burkina Faso

Making decisions on choice of crop to fertilize and the amount of each nutrient to apply to maximize profit from fertilizer use is complex for the farmer producing several different crops. Not only the agronomy of the responses to applied nutrients by the different crops is important, but the farmer's choice of crops, expected crop values, fertilizer use costs and available money for fertilizer use need to be considered.

A computer program using linear optimization was developed for each AEZ to aid in the choice of fertilizer use options to maximize profit potential (https://agronomy.unl.edu/OFRA). The program is a Microsoft Excel Solver© (Frontline Systems Inc.) tool and is referred to as a Fertilizer Optimization Tool (FOT). The FOT uses complex mathematics in integrating the numerous crop nutrient responses functions with economic and agronomic information.

4.5.1 The Excel FOT

Use of the FOT requires the Excel add-in Solver and also for macros to be enabled. Step-by-step instructions are provided for this in the 'Help and Instructions' worksheet of the FOT. More detailed instructions are in Extension Materials and FOT Manual (https://agronomy.unl.edu/OFRA).

The FOT data input screen (Figure 4.5) allows for entry of how much land the farmer plans to plant for each crop of interest (under **Area planted, ha**) and the estimated commodity value on-farm at harvest time considering that some will be for home consumption (the most valuable) and that the surplus will be marketed (under **Expected grain value/kg**). The costs of using different available fertilizers are entered (under **Costs per 50 kg bag**). An additional fertilizer can be added below the four fertilizers where the fertilizer name and concentration of N-P_2O_5-K_2O-Zn can be entered (occupied by NPK 14-23-14-0 in the image at FCFA 20,000 for a 50 kg bag). Finally, the farmer's available money for fertilizer use is entered (under **Budget constraint**, 200,000 is entered). When data entry is complete, the below 'Optimize' cell is left-clicked to run the optimization.

AEZ South Sudan Savanna

Producer Name:	xxx
Prepared By:	Serme Idriss
Date Prepared:	July 6, 2016

Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Maize	1	125
Rice Upland	1	400
Sorghum	1	150
Rice Lowland	1	400
Cowpea	1	500
Groundnut	1	300
Pearl millet	1	400
Total	7	

Fertilizer Selection and Prices					
Fertilizer Product	N	P2O5	K2O	Zn	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	19000
Triple super phosphate, TSP	0%	0%	0%	0%	22500
Diammonium phosphate, DAP	18%	46%	0%	0%	23000
Murate of potash, KCL	0%	0%	60%	0%	20750
NPK	14%	23%	14%	0%	23000

Budget Constraint	
Amount available to invest in fertilizer	200000

Figure 4.5: The input screen image of the fertilizer optimization tool for the South Sudan Savanna of Burkina Faso.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	Urea	TSP	DAP	KCL	NPK
Maize	54	0	0	0	0
Rice Upland	116	0	94	28	0
Sorghum	9	0	66	0	0
Rice Lowland	36	0	0	8	0
Cowpea	15	0	3	11	0
Groundnut	0	0	34	6	0
Pearl millet	0	0	0	0	0
Total fertilizer needed	229	0	197	54	0

Expected Average Effects per Ha		
Crop	Yield Increases	Net Returns
Maize	930	95,910
Rice Upland	2,723	990,522
Sorghum	2,443	332,620
Rice Lowland	225	72,681
Cowpea	222	99,476
Groundnut	332	81,332
Pearl millet	1	344

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	1,672,886

Figure 4.6: The output screen image for the fertilizer optimization tool for the South Sudan Savanna of Burkina Faso.

The output results are displayed (Figure 4.6), including the amount of each fertilizer to apply to each crop in the upper table, the expected average yield increases and net returns per hectare for each crop in the middle table, and the total net returns to fertilizer use for the farm. Some recommended rates are too low to be feasible and it is suggest when the recommended rates are less than 20 kg/ha, the fertilizer or money be allocated elsewhere, such as the money for 9 kg/ha urea for sorghum be used to increase the DAP rate. Before such adjustments, the FOT has recommended that the available money for fertilizer use be for 229, 187 and 54 kg of urea, DAP and KCl, respectively.

In this South Sudan Savanna scenario of input data, the single nutrient fertilizers and diammonium phosphate (DAP) were found to have the greatest profit potential and the optimized solution does not include any application of the fertilizer NPK blend. This is expected as most crops do not have an economic response to all three nutrients and use of NPK often means paying for one or more nutrient that does not result in profit to the farmer. If fertilizer type availability is limited to urea and NPK, the expected average total net returns is 1,463,156 rather than 1,672,886 as shown in Figure 4.6 with several common fertilizers available, an expected profit loss to the farmer of about 210,000.

The yield increases are greater for upland rice, maize and sorghum compared with the other crops and the greatest profit per hectare from fertilizer use is with upland rice followed by sorghum; this implies that whole farm profits from fertilizer use may be increased by allocating more land to one or both of these crops.

Table 4.2: Example paper fertilizer optimization tool

BURKINA FASO SOUTH SUDAN SAVANNA FERTILIZER USE OPTIMIZER

The below assumes:
Calibration measurement is with a Lafti water bottle lip that holds 7.5 ml and about 5.25 g urea and 8.25 g DAP, TSP or KCl, or with a Gino tomato cup of 70 ml bottle to hold 50 g urea and 77 DAP, TSP or KCl.
Row spacing: maize and sorghum at 80 cm; soybean, cowpea, and groundnut at 40 cm; and rice 20 at cm.
Grain prices per kg: 126 maize; 142 sorghum; 119 rice; 310 groundnut; 290 cowpea; 143 soybean.
Costs for use of 50 kg of fertilize: 25,000 CFA urea and KCl; 26,000 CFA TSP and 42,000 CFA.
Broadcast width: 4 m; WAP = Week after planting.

Level 1 financial ability.	
Maize	band apply 54kg/ha urea (water bottle lid for 1.2 m) at 6 WAP
Sorghum	band apply 67 kg/ha of DAP (water bottle lid for 1.1 m) at 2 WAP.
Rice, lowland	broadcast apply 36 kg/ha of urea (water bottle lid for 7 m) at panicle initiation
Groundnut	band apply 36 kg/ha of TSP (water bottle lid for 2.9 m) at 2 WAP
Level 2 financial ability.	
Rice, lowland	broadcast 44 kg/ha urea (water bottle lid for 5.8 m) at 2 WAP and 44 kg/ha at panicle initiation (water bottle lid for 5.8 m)
Maize	band apply 53 kg/ha of urea (water bottle lid for 1.2 m) at 2 WAP and again at 6 WAP
Sorghum	band apply 100 kg/ha of DAP (water bottle lid for 0.8 m) at 2 WAP
Groundnut	band apply 32 kg/ha of DAP (water bottle lid for 2.4 m) and 39 kg/ha TSP (water bottle lid for 2.7 m) at 2 WAP
Level 3 financial ability (maximize profit per ha).	
Rice, lowland	broadcast 50 kg/ha urea (water bottle lid for 7.6 m) and 21kg/ha KCl (water bottle lid for 17.9 m) 2 WAP; broadcast 81 kg/ha urea at panicle initiation (water bottle lid for 4.7 m)
Maize	band apply 50 kg/ha of urea (water bottle lid for 1.3 m) at 2 WAP and 39 kg/ha of DAP (water bottle lid for 0.6 m) at 6 WAP; band apply 81 kg/ha urea at 6 WAP (water bottle lid for 0.8 m)
Sorghum	band apply 100 kg/ha of DAP (water bottle lid for 0.8 m) at 2 WAP
Groundnut	band apply 100 kg/ha of TSP (water bottle lid for 1.1 m) at 2 WAP

4.5.2 Paper versions of the FOT

Very often smallholder farmers and their advisors do not have access to a computer. Therefore, a paper version of the Excel FOT was developed for each AEZ (Table 4.2). The farmer's financial ability for fertilizer use is accounted for in three levels where the budget constraint is not more than one-third or two-thirds the amount required to apply fertilizer at EOR (the rate to maximize profit per ha) to all cropland for financial level 1 and 2, respectively. With level 3, the farmer can apply at EOR to at least some of the cropland.

The paper tool makes several assumptions as listed in Table 4.2. The recommendations are given for each financial level and address the 4 Rs of fertilizer use, that is, advice is given on the product, rate, time and method of application.

Guidelines are also provided for helping the farmer to calibrate his or her eye and feel for the rate of application. For example, under **"Level 3 financial ability (maximizes profit per ha)"**, the recommendation for maize is **Maize**: band apply 50 kg/ha of urea (water bottle lid for 1.3 m) at 2 WAP and 39 kg/ha of DAP (water bottle lid for 0.6 m) at 6 WAP; band apply 81 kg/ha urea at 6 WAP (water bottle lid for 0.8 m). Therefore, 50 kg/ha urea and 39 kg/ha DAP are applied to maize in a band at least 5 cm from the plants and covered with soil at two weeks after planting. The farmer calibrates his or her perception of the rates by applying one Lafti brand water bottle lid of urea for 1.3 m and one Lafti lid of DAP for 0.6 m of band. A topdressing application of 81 kg/ha urea is made at six weeks after planting in a band and covering with soil. The calibration for this application is for one Lafti lid of urea to 0.8 m of band.

4.5.3 The fertilizer substitution value of other practices

Manure application and other practices can improve soil nutrient availability. After the farmer

Table 4.3: A fertilizer substitution guide for the effects of alternative crop and soil management practices.

INERA

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT

FERTILIZER SUBSTITUTION

OFRA OPTIMISING FERTILIZER RECOMMENDATIONS IN AFRICA

ISFM practice	Urea	TSP/DAP	KCl
	Fertilizer reduction, % or kg/ha		
Previous crop was a green manure crop	100%	70%	70%
Farmyard manure per 1 t of dry material	4 kg	3 kg	2 kg
Residual value of FYM applied for the previous crop, per 1 t	2 kg	1 kg	1 kg
Poultry manure, per 1 t dry material	20 kg	13 kg	15 kg
Residual value of poultry manure applied for the previous crop, per 1 t	10 kg	6 kg	7 kg
Cattle manure, per 1 t dry material	5 kg	2 kg	3 kg
Residual value of cattle manure applied for the previous crop, per 1 t	2 kg	1 kg	2 kg
Sheep manure, per 1 t dry material	10 kg	6 kg	3 kg
Residual value of sheep manure applied for the previous crop, per 1 t	4 kg	3 kg	1 kg
Compost, per 1 t	10 kg	2 kg	2 kg
Residual value of compost applied for the previous crop, per 1 t	6 kg	1 kg	1 kg
Rotation	0% reduction but more yield expected		
Cereal-legume intercropping	Increase TSP by 7 kg/ha, but no change in N and K compared with sole cereal fertilizer		

or advisor has the FOT recommendation, consideration of the effects of other practices that may have been applied to a land parcel is suggested using Table 4.3. For example, if 2 t/ha of farmyard manure dry weight is applied, fertilizer rate reductions can be 8 kg/ha of urea, 6 kg/ha of DAP or TSP, and 4 kg/ha of KCl. Such practices are generally not applied each year to all, if any, land parcels and therefore the recommendations for most cropland are not likely to need adjustment.

4.6 Targeted crops by AEZ

Crop nutrient response functions were developed for the crops listed under AEZ in Table 4.4 a-c using results of past and recent nutrient response research. In the Sahel, crop yield response to applied P was determined to be greater compared with applied N and K (Table 4.4a). The EOR for N and K were less than the recommended rates (REC) but EOR of P was greater than REC for sorghum and pearl millet but EOR of P for cowpea and groundnut was less than REC.

Crop responses were greater with applied N compared with P for the North Sudan Savanna (Table 4.4b). The large increase in sorghum yield with just 30 kg/ha N applied is especially noteworthy suggesting a great profit opportunity but also efficient use of the applied N. There was no evidence of response to applied K for the crops considered. The EOR and REC were similar for lowland rice N. In all other cases, EOR was less than the currently recommended application rates.

Crop responses for the South Sudan Savanna were greater for applied N compared with P, and least with applied K except for cowpea (Table 4.4c). There were large yield increases with P applied to sorghum and upland rice. Comparing EOR and REC, these were similar for maize N, cowpea N, pearl millet P and cowpea K. The EOR was more than REC for P applied to lowland rice and sorghum, both otherwise EOR was less than REC. Generally, the EOR determined from relatively recently conducted field research was less than REC. In four of the 25 crop nutrient response functions considered, the EOR was higher than REC, but the REC was on average 25% more than EOR. Therefore, the financially capable farmer loses profit opportunity by applying fertilizer at REC. The financially constrained farmer should normally be applying at rates less than EOR to gain the advantage of the greater profit potential associated with steep crop yield response to increasing nutrient rates.

Only in the South Sudan Savanna were there crops that had an economic response to each of N, P and K and these were sorghum, cowpea

Table 4.4a: The Sahel. Response functions (col. 3-5), expected yield increases (t/ha) for different increases in nutrient application rate (col 6-9), and OFRA economically optimal rate (EOR) to maximize profit per hectare (col. 10) compared to current or recent (REC) recommendations (col. 11) by agro-ecological zones in Mali. P_2O_5 = P x 2.29; K_2O = K x 1.2. Crop nutrient combinations not included have a lack of evidence for profitable response

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate			Elemental nutrient rate change, kg/ha				Elemental nutrient rate change, kg/ha	
Crop	**Nutrient**	**A**	**B**	**C**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha				t/ha			t/ha
Pearl millet	N	0.742	0.223	0.93	0.198	0.022	0.003	0.000	21	37
Sorghum	N	1.098	0.273	0.97	0.164	0.066	0.026	0.011	18	37
					0-5	**5-10**	**10-15**	**15-20**		
Pearl millet	P	1.717	0.768	0.940	0.204	0.150	0.110	0.081	23	10
Sorghum	P	0.975	0.548	0.908	0.210	0.129	0.080	0.049	18	10
Groundnut	K	1.093	0.104	0.800	0.070	0.023	0.008	0.002	7	12
Cowpea	K	0.477	0.063	0.650	0.056	0.006	0.001	0.000	4	12

† EOR was determined with the cost of using 50 kg urea and TSP at CFA 13,500 and 18,000, respectively. Commodity values (CFA/kg) used were: rice 125; maize 125; sorghum 170; cowpea 200; groundnut 300; and pearl millet 200.

Table 4.4b: The North Sudan Savanna of Burkina Faso

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate			Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**A**	**B**	**C**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha				**t/ha**			**t/ha**
Rice, lowland	N	2.483	0.429	0.974	0.234	0.106	0.048	0.022	73	74
Maize	N	2.290	1.619	0.960	1.143	0.336	0.099	0.029	56	67
Sorghum	N	4.068	1.534	0.860	1.517	0.016	0.000	0.000	22	37
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	8	15
Cowpea	P	1.095	0.075	0.700	0.062	0.010	0.002	0.000	0	10
Groundnut	P	1.320	0.141	0.855	0.077	0.035	0.016	0.007	7	10

Table 4.4c: The South Sudan Savanna of Burkina Faso

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate			Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**A**	**B**	**C**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha				**t/ha**			**t/ha**
Maize	N	3.000	1.760	0.970	1.054	0.423	0.170	0.068	69	67
Rice, lowland	N	4.655	1.908	0.988	0.580	0.404	0.281	0.196	61	74
Sorghum	N	4.067	1.530	0.860	1.513	0.016	0.000	0.000	25	37
Cowpea	N	1.860	0.168	0.770	0.168	0.000	0.000	0.000	13	14
Pearl millet	N	1.111	0.110	0.930	0.098	0.011	0.001	0.000	19	37
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	8	15
Rice, lowland	P	3.633	0.979	0.904	0.388	0.234	0.141	0.085	30	20
Sorghum	P	2.770	1.470	0.910	0.553	0.345	0.215	0.134	24	10
Cowpea	P	0.929	0.040	0.700	0.033	0.006	0.001	0.000	4	10
Pearl millet	P	1.520	0.129	0.900	0.053	0.031	0.018	0.011	12	10
Sorghum	K	2.016	0.114	0.900	0.047	0.028	0.016	0.010	7	11
Rice, lowland	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	10	23
Cowpea	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	12	12

and lowland rice. For all other crop/AEZ options, the response to at least one of these nutrients was not economical. Therefore, farmers need access to single nutrient fertilizers to maximize profit from fertilizer use. An NPK blended fertilizer may supply one or two nutrients that have an economical response, but paying for the unneeded nutrients reduces the farmers' financial ability to use more fertilizer nutrients that have high profit potential. Therefore, the farmer suffers financial loss not only by paying for unneeded nutrients but missing a profit opportunity of applying more fertilizer for crop-nutrients that have high profit potential.

4.7 References

Bationo A, Lompo F, and Kaola S (1998) Research on nutrient flows and balances in west Africa: state-of-the-art. Agric Ecosyst Environ 71:19-35

CILSS and OMM (2001) Les aptitudes agricoles et pastorales des sols dans les pays du CILSS

Fontès J and Guinko S (1995). Carte de végétation et de l'occupation du sol du Burkina Faso. Institut de la carte international de la végétation, Toulouse

MAHRH (Ministère de l'Agriculture de l'Hydraulique et des Ressources Halieutiques) (1999) Rapport du comité national de prévision de la sécurité alimentaire. Burkina Faso

Mason SC, Ouattara K, Taonda SJB, Palé S, Sohoro A and Kaboré D (2014) Soil and cropping system research in semi-arid West Africa as related to the potential for conservation agriculture. Internat J Agric Sustain http://dx.doi.org/10.1080/14735903.2014.945319

Mason SC, Maman N, and Palé S (2015) Pearl millet production practices in semi-arid west Africa: a review. Exp Agric 51:501-521

Ouattara B, Ouattara K, Serpantié G, Mando A, Sédogo MP and Bationo A (2006) Intensity cultivation induced effects on soil organic carbon dynamic in the western cotton area of Burkina Faso. Nutr Cycl Agroecosys 76:331-339

Ouattara K, Nyberg G, Ouattara B, Sédogo PM and Malmer A (2011) Performances of cotton-maize rotation system as affected by ploughing frequency and soil fertility management in Burkina Faso. In Bationo A, Waswa B, Okeyo JM, Maina F and Kihara JM (Eds) Innovations as Key to Green Revolution in Africa. Spring Science + Business Media B.V. p 817-831

5. Optimizing Fertilizer Use within an Integrated Soil Fertility Management Framework in Ethiopia

Negash Demissie negash34@gmail.com and Israel Bekele

Ethiopian Institute of Agricultural Research, P.O. Box 2003, Addis Ababa, Ethiopia

5.1 Agricultural systems in Ethiopia

Agriculture is important for human welfare and economic growth in Ethiopia. Gross domestic product (GDP) from agriculture in Ethiopia is 41.6% of the total GDP. Exports are dominated by agricultural products and more than 80% of the population in Ethiopia depends on agricultural production for their livelihood. Ethiopia's 12.7 million smallholder farmers account for approximately 95% of agricultural GDP (Central Statistics Agency 2013).

With a total area of about 1.13 million km^2 and about 0.51 million km^2 of arable land, and with actual yields less than 25% of water-limited potential yield, the country has a tremendous potential for rainfed agricultural development (Global Yield Gap Atlas 2016). Nitosols (23%), Cambisols (19%) and Vertisols (18%) are the major agricultural soil groups in Ethiopia (Dubale 2001).

About 11% of total cultivated land is used by more than 6 million smallholders to produce non-food products. Cereal production occupied about 86% of the cropland with major cereals such as teff, maize, sorghum and wheat accounting for an estimated 24%, 17%, 15% and 13%, respectively, of cropland use during the main cropping season in 2015.

Use of fertilizer, seed of improved varieties, pesticides and irrigation remains low and agricultural production is primarily managed by low input-output rainfed smallholder farmers. Lack of timely input supply adds to the problem. Land holdings are small and fragmented.

Only 30–40% of smallholders use fertilizer (Spielman et al. 2011). Average fertilizer may be about 40 kg/ha of cropland. Farmers used improved seed on only 4.7% of cropland in the 2007/08 crop year (Spielman et al. 2011). Local

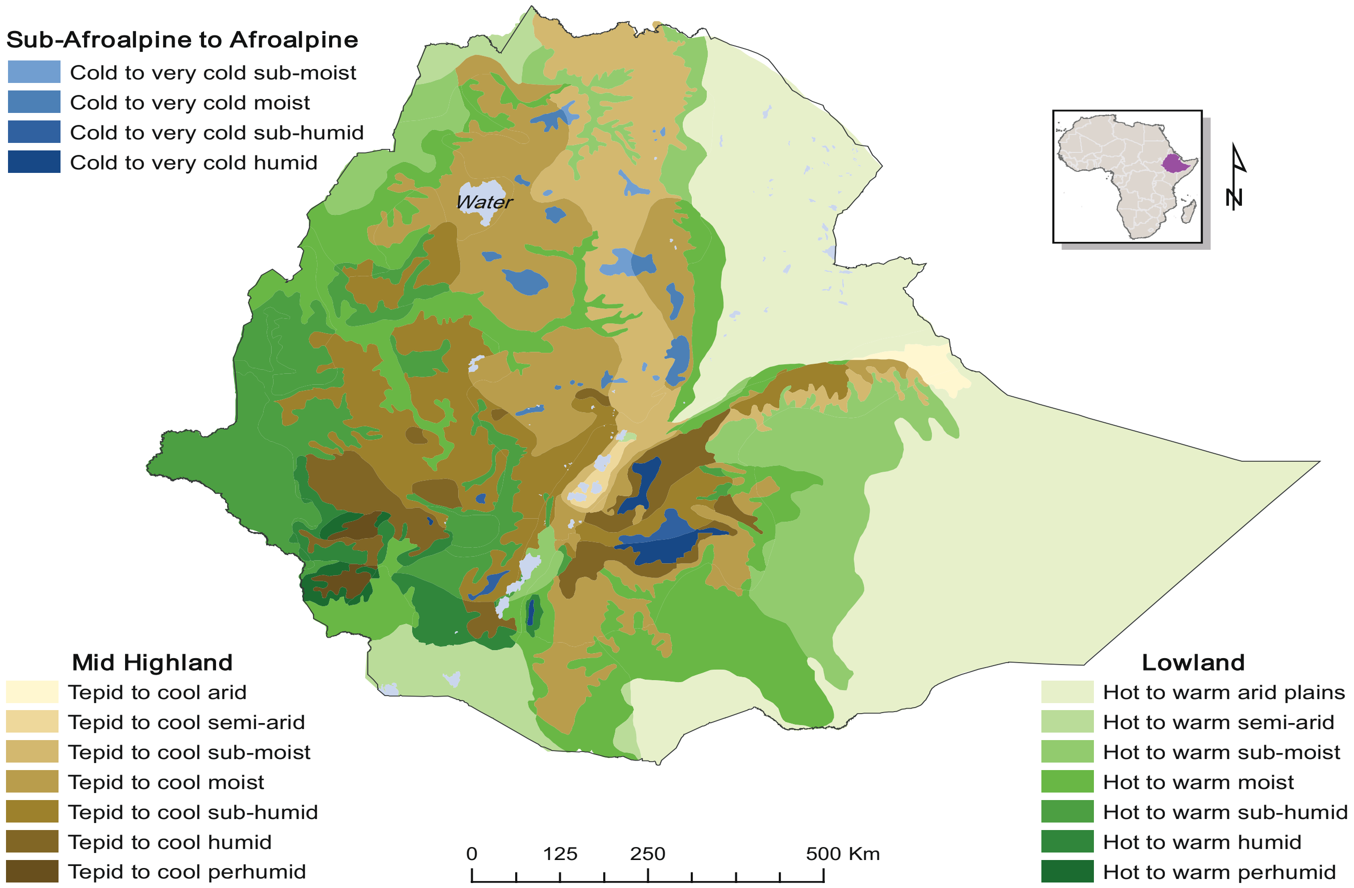


Figure 5.1: Agro-ecological zones of Ethiopia.

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

seed varieties and informal seed exchange systems account for most seed supply to smallholders.

Ethiopia has a great ecological diversity, ranging from tropical to temperate conditions. Altitude ranges from -126 masl (Danakil Depression) to 4620 masl in the Ras Dashen Mountains. Agro-ecological zones (AEZ) were determined with a crop suitability approach considering temperature, precipitation, soil characteristics and topography differences. The major crop growing areas are in sub-humid, humid, and moist semi-arid climatic zones (Figure 5.1). About 51% of the country is in arid, semi-arid and sub-moist zones (Fantaye 2016).

This chapter is focused on seven AEZ with the mid-highland AEZ sub-divided by altitude (Table 5.1) and lowland AEZ sub-divided by altitude or latitude. These AEZ cover most of the cropland of Ethiopia. The selected AEZ have an altitude ranging from 500 to > 3000 masl. Rainfall modality changes from near bimodal in the south to increasingly unimodal at higher latitudes. For example, 39 and 35% of annual rainfall occurs during March to May and September to November, respectively, at Konzo in southern Ethiopia. At Axum in northern Ethiopia, 83% of the rainfall occurs in July and August.

Table 5.1. Agro-ecological zones targeted for fertilizer use optimization in Ethiopia

Agro-ecological Zones	Altitude (masl)
Tepid to cold moist mid highland	1700 – 2200
Tepid to cold moist mid highland	>2000
Tepid to cold humid mid highland	1700 – 2200
Tepid to cold humid mid highland	>2000
Tepid to cold sub moist mid highland	1700 – 2200
Tepid to cold sub moist mid highland	>2000
Tepid to cold sub humid mid highland	1700 – 2200
Tepid to cold sub humid mid highland	>2000
Cold to very cold sub-afro Alpine	>2500
Hot to warm lowland, north of 9° latitude	
Hot to warm lowland, south of 9° latitude	
Hot to warm sub-moist and dry lowlands	<1000
Hot to warm sub-moist and drier lowlands	>1000

5.2 Soil fertility management

Ethiopia's diverse surface landforms and AEZ are associated with much diversity of indigenous knowledge and practices. Farmers in Ethiopia can characterize their local soil types and recognize differences in land used and crop suitability. Farmers distinguish soil fertility in terms of capacity of soils for long-term productivity, permeability, water holding capacity, drainage, tillage, manure requirement, cultivability, as well as crop productivity.

Farmers are aware and concerned of soil erosion and indigenous soil erosion control practices include traditional ditches locally called 'feses', waterways 'boi', stone terraces 'yedengay erken', cutoff drains 'tekebkeb', vegetative barriers 'geta' and contour ploughing 'shurube' and 'shaga'.

Many are aware that fertilizer use alone is not a solution to soil productivity problems. Traditionally, Ethiopian farmers used manure, crop rotation, mixed cropping, relay cropping and fallows for soil fertility maintenance.

Unfortunately, not all traditional practices are favourable to sustainable soil productivity. Erosion is a major cause of land degradation. The practice of transhumance is common with movement of livestock to semi-arid and arid grazing areas during the growing season but their return to crop production areas after harvest. Farmers have no control on cattle grazing of crop residues, thus leaving soil denuded with little organic material return and pulverized to dust by livestock traffic. As a result, soil physical properties are degraded and multiple tillage operations are conducted to overcome soil crusting as well as for weed control. The combined effect of destruction of soil aggregation, bare soil, soil crusting and tillage contribute to rainfall runoff and erosion.

Fertilizer use has increased from 250,000 t/yr in 1995 to 850,000 t/yr in 2014 according to unpublished estimates by the Ministry of Agriculture and Rural Development. Many smallholders have financial constraints to fertilizer use and are concerned about risk of lack of fertilizer response and/or difficulty in repaying loans. Between 30 and 40% of smallholders use some fertilizer, mostly for teff, wheat and maize production. Cereal production may account for 90% of fertilizer use with most of the remaining applied to pulse, oil seed crops and non-grain crops. Teff, wheat, maize, barley and sorghum production accounted for 40, 26, 17, 9 and 3% of fertilizer use. The main fertilizers used have been urea and diammonium phosphate (DAP).

Wheat and legumes often respond to applied sulphur (S) in the high potential Central Highlands where market-oriented crop production is associated with removal of crop residues, much tillage and little manure application leaving soil organic matter to be mostly very stable with little organic S mineralization.

Total cereal production has grown at 6% per year and production per capita at 3%, but yields per hectare have grown by just 0.5% per year. Fertilizer use has an additive effect and possibly a synergistic effect as well with other inputs (Dercon and Hill 2009). A poorly managed crop is not likely to be very responsive to applied nutrients. More than a threefold increase in fertilizer use in recent decades has not resulted in a significant increase in productivity.

Fertilizer is a costly input and its efficient use is important for profitability and minimizing nutrient loss to the environment and soil acidification due to excess N application. Key to efficient fertilizer use is to practise the 4Rs of nutrient stewardship, that is, to apply the right product, the right rate, at the right time and using the right method. The 4Rs are especially applicable to N which is subjected to loss through various pathways.

Most N application to non-legumes should be prior to or during the period of rapid crop growth when rate of N uptake is high, such as at 6- to 8-leaf stage of maize. For example, with maize, at least 50% of fertilizer N should be applied 4 to 7 weeks after planting; when the recommended rate of N is low, it is advisable to apply all of N at 4 weeks after planting. Aspects of the 4Rs are further addressed in section 5.3.

It is also important to have a healthy and well managed crop in order to achieve a good response to fertilizer. Therefore, good agricultural practices should be applied throughout including choice of variety, careful planting and good weed and pest control. Consideration of soil test information and the effects of other practices such as manure application is also important to fine-tune fertilizer use for greater profitability and efficient nutrient use. This topic is further addressed in section 5.5.3.

Recent recommendations and economically optimal rates (EOR) of nutrient application, determined from results of field research, are addressed in section 5.6.

5.3 Diagnosis of nutrient deficiencies in Ethiopia

Eighteen trials were conducted for determination of crop nutrient response functions that are essential for decisions aimed at maximizing profits from fertilizer use. The mean percent increases in grain yield of cereal crops for applied N, phosphorus (P) and potassium (K) were 55, 23 and 0%, respectively. Fertilizer optimization trials included treatments to determine the effect of the diagnostic nutrient

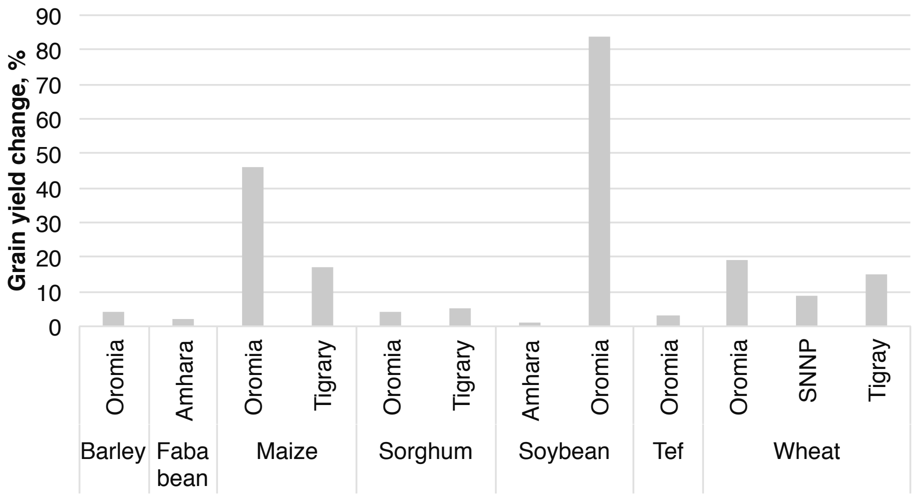


Figure 5.2: Percent yield increase due to a diagnostic treatment with N+P+K+Mg+S+Zn+B compared with N+P+K.

package of N+P+K+Mg+S+Zn+B compared with N+P+K on grain yield, where Mg is Magnesium, Zn is zinc and B is boron. A similar comparison was made for legumes with a low rate of applied N and/or with rhizobial inoculation.

The diagnostic treatment increased grain yield compared to N+P+K treatment in all crop-region combinations but the yield increase was less than the standard error of the means for most cases except for maize in Tigray and for maize, soybean and wheat in Oromia (Figure 5.2). However, the yield increases due to the diagnostic treatment prevailed with on-station trials and the mean effect was not statistically different from zero for on-farm trials (Figure 5.3). This contrast was unexpected and may be due to years of heavy fertilizer N and P use with high yields and depletion of one or many of the diagnostic nutrients on-station compared with for the farmers' fields.

Fertilizer N and P are of high priority compared with other nutrients. Crop response results do not indicate any reason for immediate concern generally with K, Mg, S, Zn, and B deficiencies. However, increased yield levels can deplete those nutrients in soil and yield responses to these nutrients may eventually occur as witnessed in some fields at research centres.

Results do indicate the great importance of verifying or fine-tuning interpretation of soil test results with crop responses. Globally, including for high yield situations, soil test results generally have not been highly predictive of crop response to applied S and micro-nutrients, although prediction of response to Zn is relatively better. Prediction of crop response to fertilizer is expected to be even weaker when crops

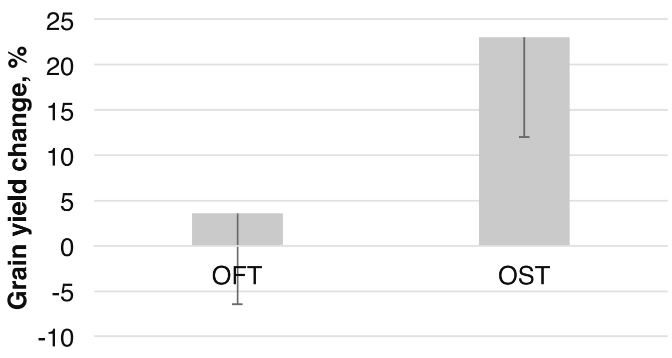


Figure 5.3: Percent yield increase due to a diagnostic treatment with N+P+K+Mg+S+Zn+B compared with N+P+K averaged over 20 on-farm (OFT) and on-station (OST) trials.

encounter any abiotic and biotic constraints in addition to nutrient deficiencies. For example, when soil water deficit is the most restricting constraint of yield in a given year, crop response to nutrients is likely to be small. Soil test results are used to determine if availability levels are enough to avoid future occasional yield losses, a useful strategy when finance for inputs is inadequate and risk of no net returns in the short term is a major concern. Where responses to the diagnostic package occurred, additional diagnostic information is needed to verify these responses and to determine which nutrient deficiencies were more important than others for crop response.

5.4 Optimizing fertilizer use in Ethiopia

Optimization of fertilizer use, in this chapter, refers to maximizing farmer profit resulting from fertilizer use, while not greatly adding to farmer risk. This implies maximizing profit per hectare for farmers with adequate finance and net returns on small investments in fertilizer use made by financially constrained farmers.

Estimation of profit from fertilizer use requires generating AEZ-specific robust nutrient response functions for important annual food crops from field research results. Crop response to an applied nutrient can be highly varied across site-years but when results of numerous trials are considered, the expected mean response is curvilinear to plateau. Such a response can be mathematically represented using asymptotic functions taking the form of an exponential rise to a maximum or plateau yield. The asymptotic function used for the Optimizing Fertilizer Recommendations in Africa (OFRA) research was $Y = a – bc^r$, where Y was yield (t/ha), coefficient a was the maximum or plateau yield (t/ha), coefficient b was the gain in yield (t/ha) due to nutrient application, and c^r represented the shape of the response curve, where c was a curvature coefficient and r the nutrient application rate (kg/ha).

Crop responses to applied N illustrate the curvilinear to plateau response in Figure 5.4. The curves differ in magnitude of response and shape of the curve. Maize and teff N curves are especially informative where there is a large yield increase per unit of applied N at low application rates. The curve becomes less steep as N rate

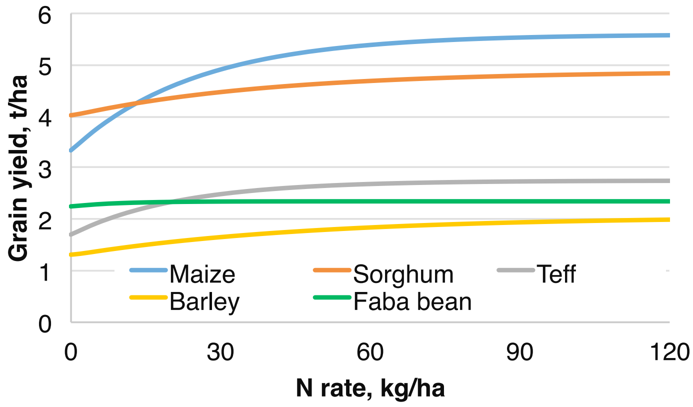


Figure 5.4: Curvilinear to plateau nature of crop response to applied N for the tepid to cold humid mid-highlands, 1700 - 2200 masl.

increases and rates > 80 kg/ha result in very little added yield. Response curves for sorghum and barley N are only slightly curvilinear without much slope suggesting relatively little N response compared with maize. The response of faba bean to applied N is curvilinear to plateau with the plateau reached at a low N rate, although magnitude of response is small. Response curves have economic implications. Farmers with adequate finance and risk security need to know the rate at which the value of yield gained justifies the cost of additional N in order to apply fertilizer at EOR. Financially constrained farmers need to apply fertilizer at less than EOR at a relatively steep part of the curve to maximize yield gain for a constrained investment.

Another economic consideration that is very important to financially constrained farmers is that the profit potential of applying a nutrient to a crop differs from the potential of applying the same nutrient to another crop and of other crop-nutrient combinations (Figure 5.5). In Figure 5.5, the x-axis gives the cost of a nutrient applied to a single crop (EtB/ha). The y-axis gives net returns to an investment in nutrient application. Each curve represents a different crop-nutrient combination.

The results show that the curve for N applied to teff is steep at low N rates and therefore has more profit potential per small investment than with other crop-nutrient options. At about EtB 750 worth of N applied to teff, P applied to teff at low rates has similar profit potential as indicated by a similar slope. Following teff, maize has a good profit potential to applied N. Lower in the chart are less profitable options. Some crop-nutrient options, such as K applied to crops other than maize, are not shown due to lack of profit potential. The financially constrained farmers need first to take advantage of the crop-nutrient-rate options with the highest profit potential if the crop is a part of cropping systems, and then go on to take advantage of some less profitable options in order to maximize profit from a constrained investment. Farmers with adequate finance

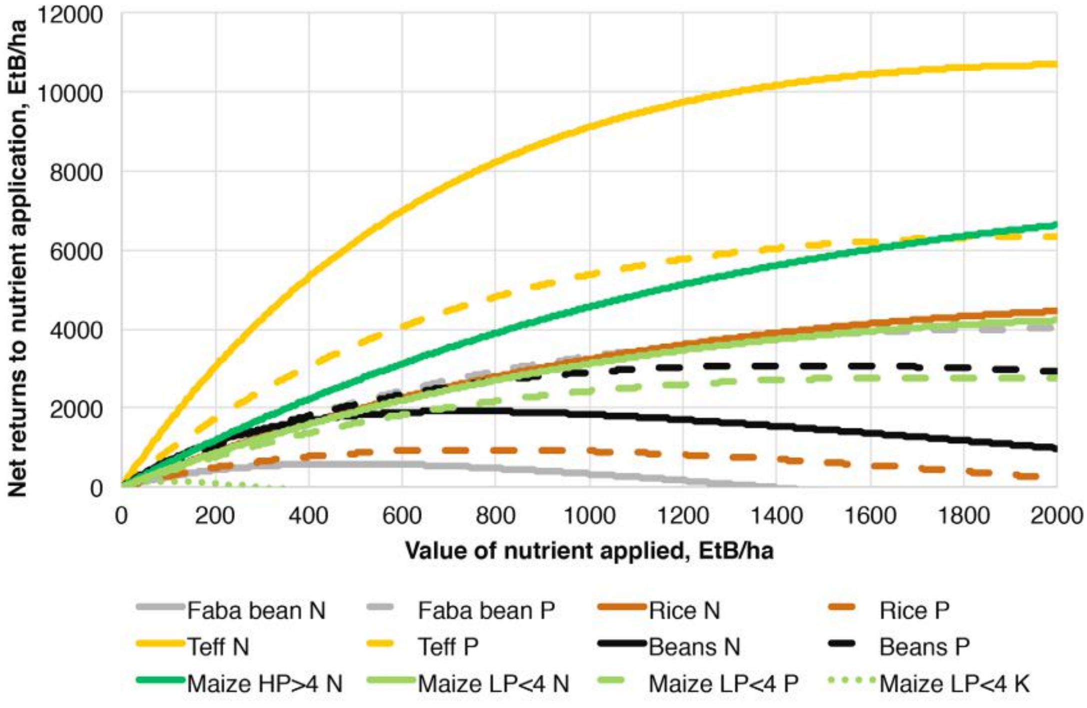


Figure 5.5: Net returns to investment in single nutrients applied to a crop for the tepid to cold moist mid-highlands, 1700-2200 masl.

need to maximize profit per hectare over all cropland and therefore need to apply fertilizer at a rate associated with the peak of the response curves. Note that the peak of net returns is not captured in the figure (Figure 5.5) for some curves, including for N applied to high potential maize, as the maximum investment on the x-axis is too low for the peaks to be reached.

5.5 Fertilizer use optimization tools

The decision on choices of crops, fertilizers to apply and the amount of each nutrient to apply requires consideration of several factors. Agronomy of nutrient responses for different crops that the farmer plants must be considered together with the farmer's land allocation to each crop, the expected commodity values, the costs of fertilizer use and the money available for fertilizer use. Soil test information and other practices that may affect the need for applied nutrients must be considered as well. With all these considerations, fertilizer optimization tools (FOTs) and a fertilizer rate adjustment tool were developed to help farmers decide on nutrient management for maximization of profit.

5.5.1 The Excel Solver FOT

Excel Solver © (Frontline Systems Inc., Incline Village, NV, USA) fertilizer optimization tools (FOTs) were developed for each of the 13 recommendation domains. The FOTs use complex mathematics of linear optimization but are easy to use.

The farmer needs to estimate how much land will be planted to each crop of interest, estimate the farm gate value per kg at harvest time considering that some is for home consumption (the most valuable) and the surplus will be marketed, and the costs of using different fertilizers (Figure 5.6). The amount of money which the farmer will invest in fertilizer use is also entered. In this example, the farmer allocates crops to four hectares and has EtB 6000 available for fertilizer use. Clicking on the 'Optimize' button then runs the optimization calculations.

The results are displayed as in Figure 5.7, including the amount of each fertilizer to apply to each crop, the expected average yield increases and net returns, and the total net returns to fertilizer use for the farm. Each of the selected crops has a recommendation for some fertilizer allocation. However, only 21 kg/ha of DAP is recommended for barley, which may be too little for feasible application and the farmer may want to allocate the fertilizer or the money elsewhere. A total of 241 kg/ha of DAP and 136 kg/ha of urea were recommended. No K application was recommended with this financial constraint. Net returns per hectare were highest for high potential maize, teff and faba bean, suggesting that the farmer may want to allocate more land to these crops, especially to faba bean, which achieves higher returns with relatively little fertilizer recommended. Expected average net return for this scenario is EtB 44,324 and a benefit to cost ratio of greater than 7. It is advisable that the farmer will use some of these net returns to gradually reduce financial constraint to fertilizer use and eventually apply fertilizer at EOR to all cropland.

5.5.2 The paper FOTs

Very often farmers and their advisors do not have access to a computer. Therefore, companion paper FOTs were developed for each recommendation domain (Table 5.2). The paper FOT is devised for three financial levels: 1) for a farmer who has no more money than one-third the amount required to apply fertilizer to all cropland at EOR; 2) for a farmer with more money but no more money than two-thirds the amount required to apply fertilizer to all cropland at EOR; and 3) for a farmer with enough money to apply fertilizer to at least some cropland at EOR.

The paper tool makes assumptions about the:

- calibration measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer
- crop row and plant spacing
- fertilizer use costs per 50-kg bag
- expected grain values at on-farm at harvest, considering value both for home consumption and for market.

The paper FOTs address the 4Rs of nutrient stewardship advising on the right product, rate, time and method of fertilizer application. It also advises on calibration, that is, the length of the band or distance, or the number of points, covered by one measuring unit for the recommended fertilizer rate.

AEZ Tepid to cold humid mid high l
Elevation 1700-2200m

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	**July 6, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Ha)***	**Expected Grain Value/kg †**
MaizeHP >5T	1	4
MaizeLP<5T	0.5	4
Sorghum	0.5	5.5
Teff	1	12
Barley	0.5	6
Faba bean	0.5	12
Total hectares	**4**	

Fertilizer Selection and Prices				
Fertilizer Product	**N**	**P2O5**	**K2O**	**Price/50 kg bag ¶***
Urea	46%	0%	0%	700
Triple super phosphate, TSP	0%	46%	0%	0
Diammonium phosphate, DAP	18%	46%	0%	850
Murate of potash, KCL	0%	0%	60%	800
xxx	%	%	%	0

Budget Constraint	
Amount available to invest in fertilizer	6000

Figure 5.6: Input screen of the fertilizer optimization tool of the tepid to cold mid-highlands, 1700 to 2000 masl.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**xxx**
MaizeHP >5T	48	0	68	0	0
MaizeLP<5T	51	0	61	0	0
Sorghum	0	0	64	0	0
Teff	63	0	62	0	0
Barley	0	0	21	0	0
Faba bean	0	0	76	0	0
Total fertilizer needed	**136**	**0**	**241**	**0**	**0**

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
MaizeHP >5T	4,274	15,275
MaizeLP<5T	2,491	8,209
Sorghum	1,574	7,578
Teff	1,264	13,229
Barley	216	934
Faba bean	1,350	14,919

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	44,324

Figure 5.7: The output results corresponding to the input data of Figure 5.6.

Table 5.2: Paper FOT for tepid to cold humid mid highland elevation 2000- 2700 masl

Assumptions:

Measurement is with a: 500ml Highland water bottle CAP that holds 6.7 ml, 4.7 g urea, and 7.4 g DAP, TSP, and KCl; 500ml Highland water (2-cm bottle) to hold 47 ml, 33 g urea and 52 g DAP, TSP, or KCl.

Row spacing: 75 cm for maize; 20 cm for wheat and barley; 40 cm for faba bean; and teff is broadcast.

Grain prices per kg (Et Birr): 4 maize; 6 Barley; 12 Faba bean; and 8 Wheat.

Cost 50 kg of fertilize costs (Et Birr): 700 urea; 750 TSP; 850 DAP and 1500 KCl.

Fertilizer rate > 25 kg/ha. Broadcast width 2m

Level 1 financial ability.	
Maize HP	point apply 51.1 kg/ha DAP (1.9 plants per CAP)
Maize LP	point apply 41 kg/ha urea after 3 weeks of planting (1.9 plants per CAP)
Wheat HP	56.8 kg DAP broadcast at planting (4.5 m per 2-cm bottle) and top-dress 34.3 kg/ha urea (4.5 m per 2-cm bottle)
Wheat LP	no input
Barley	no input
Faba bean	38.1 kg/ha DAP band apply at planting (4.8 m per CAP)
Level 2 financial ability.	
Maize HP	point apply 71 kg/ha DAP (1.3 plants per CAP) and 53 kg/ha urea topdress (1.1 plants per CAP)
Maize LP	point apply 81 kg/ha urea (0.7 plants per CAP) after 3 weeks of planting
Wheat HP	broadcast 81.7 kg/ha DAP at planting (3.2 m per 2-cm bottle) and top-dress 50 kg/ha urea (3.1 m per 2-cm bottle)
Wheat LP	broadcast 53 kg/ha DAP at planting 4 m per 2-cm bottle and topdress 51 kg/ha urea (3.1 m per 2-cm bottle)
Barley	broadcast 27.2 kg/ha DAP at planting (11.4 m per 2-cm bottle)
Faba bean	band apply 71.5 kg/ha DAP (2.6 m per CAP) at planting
Level 3 financial ability (maximize profit per acre).	
Maize HP	point apply 83 kg/ha DAP (1 plant per CAP) at planting and topdress 73 kg/ha urea (0.8 plants per CAP) after 3 weeks of planting
Maize LP	point apply 86 kg/ha DAP (1 plant per CAP) at planting and topdress 71 kg/ha urea (0.8 plants per CAP) after 3 weeks of planting
Wheat HP	broadcast 97.4 kg DAP (2.7 m per 2-cm bottle) at planting and top-dress 59.3kg/ha urea (2.6 m per 2-cm bottle)
Wheat LP	broadcast 83.5 kg/ha DAP 3 m per 2-cm bottle at planting and topdress 80.5 kg/ha urea (2 m per 2-cm bottle)
Barley	48.6 kg/ha DAP broadcast at planting (6 m per 2-cm bottle)
Faba bean	93.8 kg/ha DAP band apply at planting (2.0 m per CAP)

The paper FOT is easy to use and it is expected that many farmers will learn to use it on their own. For example, one level 1 financial ability recommendation is ‘Teff: broadcast 30 kg DAP (12.7 m per 2-cm bottle) at planting and topdress 42 kg/ha urea (7.3 m per 2-cm bottle)’. Therefore, 30 kg/ha DAP is to be applied at planting by broadcasting in 2-m wide passes. The farmer ‘calibrates’ his or her eye and feel using the 500 ml Highland brand water bottle cut to 2-cm height, which is enough for 12.7 m distance. Urea is topdress applied by broadcasting at 42 kg/ha; one 2-cm bottle is enough for 7.3 m with an application width of 2 m.

5.5.3 The fertilizer rate adjustment tool

Another aspect of optimizing fertilizer use is to consider soil test values and practices that reduce or increase the need for fertilizer such as timing, amount and quality of any recent manure application. If the previous crop was a legume, or there was a use of a green manure crop, one

Table 5.3: Adjustment of recommended fertilizer rates due to other practices or soil test information

ISFM practice	Urea	TSP/DAP	KCl/KSO_4
	Nutrient reduction, kg/ha or %		
Previous crop was a green manure crop	100%	100%	100%
Fresh vegetative material (e.g. pruning of lantana or tithonia) applied, per 1 t of fresh material	10 kg	4 kg	6 kg
Farmyard manure per 1 t of dry material	0 kg	4 kg	6 kg
Residual value of FYM applied for the previous crop, per 1 t	0 kg	2 kg	2 kg
Dairy or poultry manure, per 1 t dry material	10 kg	6 kg	10 kg
Residual value of dairy & poultry manure applied for the previous crop, per 1 t	4 kg	4 kg	2 kg
Compost per 1 t dry material applied	6 kg	6 kg	10 kg
Residual value of compost applied for the previous crop, per 1 t	6 kg	4 kg	2 kg
Rotation	0% reduction but more yield expected		
Cereal-bean intercropping	Increase DAP/TSP by 8 kg/ha, but no change in N and K compared with sole cereal fertilizer		
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 12 kg/ha, reduce urea by 20 kg/ha, and no change in K compared with sole cereal fertilizer		
If Mehlich III P >15 ppm	Apply no P		
If soil test K <100 ppm	Band apply 40 kg/ha K_2SO_4		

needs to consider nutrient credit from those practices and adjust nutrient application (Table 5.3). Soil test information may also provide helpful information to recommend optimal application rate.

Typically, these adjustment practices may not apply to all cropland of a farmer but only to one or a few, if any, parcels of land. There may be opportunities to reduce fertilizer application for some land parcels and to reallocate that fertilizer or money elsewhere (Table 5.3). For example, for each ton of farmyard manure applied, P_2O_5 and K_2O rates can be reduced by 2 and 3 kg/ha, respectively. With cereal-bean intercropping, however, fertilizer P rate should be increased. Soil test P is commonly low for smallholder fields and fertilizer P should be applied according to the FOT unless soil test P value is above 15 ppm by Mehlich III. Fertilizer K should be applied as recommended by the FOT unless the soil test K is less than 100 ppm when 40 kg/ha potassium sulphate should be applied, even if not recommended by the FOT.

5.6 Targeted crops by AEZ

Nutrient response functions of major crops were determined for the 13 recommendation domains (Table 5.4a-g) using results from past research and OFRA supported trials. The crops were maize, wheat, teff, sorghum, barley, rice, finger millet, Irish potato, bean, soybean and faba bean. Considering mostly unique characteristics of Ethiopian production conditions compared with agricultural areas elsewhere in Africa, few research results were considered from outside of Ethiopia.

Available results relevant to each AEZ were compiled and analyzed and used with other information, such as current recommendations (REC), in determining representative crop nutrient functions. In Table 5.4, crops targeted for an AEZ are listed in column 1 with AEZ differentiation by altitude or latitude (column 2). The nutrient and coefficients a, b, c of crop nutrient response functions are presented in columns 3-6. Expected average yield increases with increments of applied nutrient are in columns 7-10, followed by the EOR and recommended rate of nutrient application in columns 11-12.

All cereals, Irish potato and faba bean had economical responses to N in all AEZ where these were targeted (Table 5.4 a-g). Bean had

Table 5.4a: Tepid to cold moist mid-highland, differentiated by altitude. Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent recommendations (REC) in Ethiopia. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

	Altitude range (masl)	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC
				t/ha			t/ha			kg/ha	
Faba bean	<2200	N	2.300	0.117	0.890	0.113	0.003	0.000	0.000	14	18
Rice	<2200	N	3.363	1.112	0.975	0.592	0.277	0.130	0.061	98	69
Teff	<2200	N	2.735	1.235	0.948	0.986	0.199	0.040	0.008	61	69
Bean	<2200	N	2.100	0.230	0.890	0.223	0.007	0.000	0.000	20	18
Maize	<2200	N	5.443	2.945	0.980	1.339	0.730	0.398	0.217	102	69
Sorghum	<2200	N	3.176	0.744	0.989	0.210	0.151	0.108	0.078	36	18
Barley	>2000	N	1.811	0.546	0.975	0.291	0.136	0.064	0.030	40	41
Faba bean	>2000	N	2.400	0.100	0.963	0.068	0.022	0.007	0.002	11	18
Wheat HP>3t	>2000	N	3.777	1.279	0.974	0.699	0.317	0.144	0.065	83	69
Wheat LP<3t	>2000	N	2.497	1.229	0.978	0.598	0.307	0.157	0.081	89	69
Irish potato	>2000	N	23.175	13.646	0.980	6.203	3.383	1.846	1.007	184	92
						0-5	5-10	10-15	15-20		
Faba bean	<2200	P	2.23	0.594	0.920	0.203	0.133	0.088	0.058	28	20
Rice	<2200	P	2.743	0.285	0.850	0.159	0.070	0.031	0.014	15	20
Teff	<2200	P	1.006	0.840	0.900	0.344	0.203	0.120	0.071	28	20
Bean	<2200	P	2.510	0.405	0.885	0.185	0.101	0.055	0.030	19	20
Maize	<2200	P	4.498	1.117	0.918	0.389	0.253	0.165	0.108	30	20
Faba bean	>2000	P	2.387	0.751	0.825	0.464	0.177	0.068	0.026	18	20
Barley	>2000	P	3.194	0.945	0.880	0.446	0.236	0.124	0.066	20	20
Wheat HP>3t	>2000	P	4.023	1.458	0.812	0.943	0.333	0.118	0.041	18	20
Wheat LP<3t	>2000	P	2.320	0.683	0.940	0.182	0.133	0.098	0.072	29	20
Irish potato	>2000	P	21.486	2.745	0.825	1.696	0.648	0.248	0.095	21	20

†The following grain values and fertilizer costs were used to calculate EOR values. Grain values used were (EtB/kg): bean, 12; faba bean, 12; tef, 12; wheat, 8; barley, 6; sorghum, 5.5; maize, 4; finger millet, 10; soybean, 9; Irish potato, 6. Fertilizer use costs for 50 kg were (EtB/kg): 700 for urea; 850 for DAP; and 1500 for KCl.

a profitable response to N only in the tepid to cold moist mid-highland <2200 masl and soybean did not have a response to N. All targeted crops had an economic response to P except sorghum in the tepid to cold moist and sub-moist mid-highlands <2200 masl. The only economical responses to applied K were determined for hot to warm moist lowlands for maize and teff.

The EOR for N averaged over all crops in all AEZ was 63 kg/ha compared with 51 kg/ha for the average of the RECs with a standard error (SE) of 3.3 (Table 5.4a-g). High EOR of N determined for Irish potato compared with REC N contributed much to difference and SE. The EOR for P averaged over all crops in all AEZ was 18 kg/ha compared with 20 kg/ha for average of recommended rates with a SE of difference of 2.1. The REC P rate was 20 kg/ha in most cases while the EOR P determined from the results of field research was much more variable.

Table 5.4b: Tepid to cold humid mid-highland, differentiated by altitude

	Altitude range (masl)	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Maize	>1700	N	5.596	2.256	0.961	1.572	0.477	0.144	0.044	61	69
Sorghum	<2200	N	4.880	0.870	0.975	0.463	0.217	0.101	0.047	53	41
Teff	<2200	N	2.753	1.049	0.955	0.785	0.197	0.050	0.012	63	69
Barley	>1700	N	2.053	0.753	0.979	0.355	0.188	0.099	0.053	52	41
Faba bean	>1700	N	2.350	0.100	0.900	0.096	0.004	0.000	0.000	20	18
Wheat HP>3T	>2000	N	4.009	1.698	0.940	1.433	0.224	0.035	0.005	54	41
Wheat LP<3T	>2000	N	2.238	0.947	0.977	0.476	0.237	0.118	0.059	57	41
						0-5	**5-10**	**10-15**	**15-20**		
Maize HP>5t	>1700	P	6.928	2.832	0.833	1.696	0.680	0.273	0.109	20	30
Maize LP<5t	>1700	P	3.521	1.515	0.940	0.403	0.296	0.217	0.159	30	20
Sorghum	<2200	P	4.645	1.550	0.850	0.862	0.383	0.170	0.075	17	10
Teff	<2200	P	1.401	0.514	0.898	0.214	0.125	0.073	0.043	19	20
Barley	>1700	P	2.687	0.438	0.901	0.178	0.106	0.063	0.037	15	10
Faba bean	>1700	P	2.753	1.392	0.850	0.774	0.344	0.152	0.068	21	20
Wheat HP>3T	>2000	P	4.154	1.415	0.867	0.722	0.354	0.173	0.085	23	20
Wheat LP<3T	>2000	P	2.313	0.576	0.930	0.175	0.122	0.085	0.059	24	20
Wheat	>2000	K	2.369	0.056	0.899	0.023	0.014	0.008	0.005	0	0

5.7 Conclusion

Nutrient management is very critical to maximize crop yield and to sustain soil productivity. Poor farmers need to achieve high net returns on their investment with little risk while wealthier farmers may strive to maximize profit per hectare. Profit potential from fertilizer use varies greatly with crop-nutrient choices. The profit potential is generally much greater with application of N and P compared with K and the secondary and micro nutrients. Consistent with findings elsewhere worldwide, farmers need adequate access to single nutrient and di-nutrient compound fertilizers to maximize profit. Evidence-based FOTs were developed for optimization of fertilizer use by Ethiopian farmers of any economic class. The EOR determined from the results of field research often differed from RECs.

5.8 References

CSA (Central Statistics Agency) (2013) Agricultural Sample Survey 2012/2013 Volume I. Report on area and production of major crops (private peasant holdings, meher season). Statistical Bulletin 532, Addis Ababa

Dercon S and Hill RF (2009) Growth from agriculture in Ethiopia. Identifying key constraints. Paper prepared as part of a study on agriculture and growth in Ethiopia. DFID, UK.

Dubale P (2001) Soil and water resources and degradation factors affecting their productivity in the Ethiopian highland agro-ecosystems. International Conference on the Contemporary Development Issues in Ethiopia, CADPR, and Western Michigan University.

Fantaye KT (2016) Ethiopia: description of cropping systems, climate, and soils in Ethiopia. http://www.yieldgap.org/ethiopia

Table 5.4c: Tepid to cold sub-humid mid-highland, differentiated by altitude

	Altitude range (masl)	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Sorghum	<2200	N	4.770	0.611	0.973	0.342	0.151	0.066	0.029	41	41
Teff HP>2t	<2200	N	2.877	1.220	0.955	0.913	0.230	0.058	0.014	66	69
Teff LP<2t	<2200	N	1.015	0.458	0.963	0.310	0.100	0.032	0.010	49	41
Maize HP>5t	<2200	N	6.306	3.025	0.975	1.610	0.753	0.352	0.165	88	87
Maize LP<5t	<2200	N	4.082	1.400	0.971	0.821	0.340	0.140	0.058	55	64
Barley	>2000	N	1.811	0.546	0.975	0.291	0.136	0.064	0.030	40	32
Wheat HP>3t	>2000	N	3.777	1.279	0.974	0.699	0.317	0.144	0.065	83	87
Wheat LP<3t	>2000	N	2.350	1.229	0.978	0.598	0.307	0.157	0.081	89	64
Faba bean	>2000	N	2.400	0.100	0.963	0.068	0.022	0.007	0.002	11	18
Irish potato	>2000	N	23.176	13.646	0.980	6.203	3.383	1.846	1.007	184	110
						0-5	**5-10**	**10-15**	**15-20**		
Sorghum	<2200	P	4.766	1.166	0.882	0.544	0.290	0.155	0.083	20	20
Teff	<2200	P	1.401	0.514	0.898	0.214	0.125	0.073	0.043	20	20
Maize HP>5t	<2200	P	6.865	2.761	0.819	1.744	0.642	0.237	0.087	17	20
Maize LP<5t	<2200	P	4.195	1.219	0.94	0.324	0.238	0.175	0.128	23	20
Barley	>2000	P	3.194	0.945	0.880	0.446	0.236	0.124	0.066	18	10
Wheat HP>3t	>2000	P	4.023	1.458	0.812	0.943	0.333	0.118	0.041	17	20
Wheat LP<3t	>2000	P	2.320	0.683	0.940	0.182	0.133	0.098	0.072	24	20
Faba bean	>2000	P	2.387	0.751	0.825	0.464	0.177	0.068	0.026	16	20
Irish potato	>2000	P	21.486	2.745	0.825	1.696	0.648	0.248	0.095	19	20

GYGA (2016) Global Yield Gap Atlas. http://www.yieldgap.org/

Spielman DJ, Dawit K and Dawit A (2011) Seed, fertilizer, and agricultural extension in Ethiopia. Addis Ababa, Ethiopia, ESSP Working paper

Table 5.4d: Tepid to cold sub-moist mid-highland, differentiated by altitude

	Altitude range (masl)	Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Bean	<2200	N	2.000	0.015	0.930	0.013	0.002	0.000	0.000	0	0
Faba bean	<2200	N	2.148	0.376	0.966	0.243	0.086	0.030	0.011	46	18
Maize	<2200	N	3.385	1.601	0.973	0.897	0.394	0.174	0.076	64	64
Teff	<2200	N	1.602	0.989	0.988	0.300	0.209	0.146	0.101	107	64
Sorghum	<2200	N	3.107	0.654	0.966	0.422	0.150	0.053	0.019	41	41
Barley	>2000	N	1.811	0.546	0.975	0.291	0.136	0.064	0.030	40	64
Wheat HP>3t	>2000	N	3.777	1.279	0.974	0.699	0.317	0.144	0.065	83	64
Wheat LP<3t	>2000	N	2.350	1.229	0.978	0.598	0.307	0.157	0.081	89	64
Faba bean	>2000	N	2.400	0.100	0.963	0.068	0.022	0.007	0.002	11	18
Irish potato	>2000	N	23.176	13.646	0.980	6.203	3.383	1.846	1.007	184	110
						0-5	**5-10**	**10-15**	**15-20**		
Bean	<2200	P	2.509	0.404	0.88	0.191	0.101	0.053	0.028	17	0
Faba bean	<2200	P	2.238	0.902	0.922	0.301	0.201	0.134	0.089	30	20
Maize	<2200	P	4.498	1.117	0.918	0.389	0.253	0.165	0.108	19	20
Teff	<2200	P	1.148	0.212	0.955	0.044	0.035	0.028	0.022	10	20
Sorghum	<2200	P	2.664	0.232	0.97	0.033	0.028	0.024	0.021	0	20
Barley	>2000	P	3.194	0.945	0.880	0.446	0.236	0.124	0.066	18	20
Wheat HP>3t	>2000	P	4.023	1.458	0.812	0.943	0.333	0.118	0.041	17	20
Wheat LP<3t	>2000	P	2.320	0.683	0.940	0.182	0.133	0.098	0.072	24	20
Faba bean	>2000	P	2.387	0.751	0.825	0.464	0.177	0.068	0.026	16	20
Irish potato	>2000	P	21.486	2.745	0.825	1.696	0.648	0.248	0.095	19	20
Maize	<2200	K	3.659	0.120	0.800	0.081	0.026	0.009	0.003	0	0

Table 5.4e: Hot to warm moist lowlands, differentiated by latitude

	Altitude range (masl)	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Maize <9°N	N	3.462	1.782	0.978	0.868	0.445	0.228	0.117	71	32	
Maize >9°N	N	2.600	0.384	0.955	0.288	0.072	0.018	0.005	74	32	
Sorghum <9°N	N	4.400	1.714	0.979	0.807	0.427	0.226	0.120	86	32	
Sorghum >9°N	N	2.504	0.297	0.920	0.273	0.022	0.002	0.000	89	32	
Rice, lowland paddy	N	3.006	0.787	0.958	0.570	0.157	0.043	0.012	62	64	
Bean	N	2.000	0.015	0.950	0.012	0.003	0.001	0.000	0	0	
Teff	N	1.912	1.013	0.962	0.696	0.218	0.068	0.021	30	64	
					0-5	**5-10**	**10-15**	**15-20**			
Maize <9°N	P	2.923	0.344	0.95	0.078	0.060	0.047	0.036	7	20	
Maize >9°N	P	2.800	0.559	0.897	0.234	0.136	0.079	0.046	4	20	
Sorghum <9°N	P	4.696	0.913	0.8	0.614	0.201	0.066	0.022	30	20	
Sorghum >9°N	P	2.419	0.089	0.900	0.036	0.022	0.013	0.008	13	20	
Bean	P	2.497	0.392	0.940	0.104	0.077	0.056	0.041	22	20	
Teff	P	1.564	0.155	0.750	0.118	0.028	0.007	0.002	8	20	
Soybean	P	1.476	0.346	0.880	0.163	0.086	0.046	0.024	13	10	
					0-5	**5-10**	**10-15**	**15-20**			
Maize	K	3.383	0.282	0.85	0.157	0.070	0.031	0.014	12	0	
Teff	K	1.595	0.157	0.700	0.131	0.022	0.004	0.001	9	0	

Table 5.4f: Hot to warm sub-moist and drier lowlands, differentiated by altitude

	Altitude range (masl)	Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Rice	>1000	N	4.579	1.822	0.979	0.858	0.454	0.240	0.127	132	110
Sorghum	>1000	N	4.229	0.810	0.957	0.593	0.159	0.042	0.011	42	64
Maize	>1000	N	3.654	1.674	0.985	0.610	0.388	0.246	0.157	80	64
Teff	>1000	N	1.912	1.013	0.962	0.696	0.218	0.068	0.021	71	64
Maize	<1000	N	4.272	2.025	0.963	1.372	0.443	0.143	0.046	61	64
Sorghum	<1000	N	4.159	0.619	0.890	0.600	0.018	0.001	0.000	22	18
Rice	<1000	N	2.779	1.162	0.973	0.651	0.286	0.126	0.055	95	87
Finger millet	<1000	N	1.528	0.282	**0.904**	**0.268**	**0.013**	**0.001**	0.000	22	18
Teff	<1000	N	2.735	1.235	0.948	0.986	0.199	0.040	0.008	61	64
						0-5	**5-10**	**10-15**	**15-20**		
Rice	>1000	P	2.500	0.300	0.700	0.250	0.042	0.007	0.001	8	20
Sorghum	><1000	P	4.037	0.715	0.830	0.433	0.171	0.067	0.026	12	20
Maize	>1000	P	3.892	0.711	0.700	0.592	0.099	0.017	0.003	7	20
Teff	>1000	P	0.916	0.044	0.800	0.030	0.010	0.003	0.001	2	20
Maize	<1000	P	3.803	1.267	0.910	0.476	0.297	0.185	0.116	20	20
Rice	<1000	P	3.790	0.556	**0.947**	**0.133**	**0.101**	**0.077**	0.059	31	20
Finger millet	<1000	P	1.559	0.325	0.937	0.090	0.065	0.047	0.034	16	20
Soybean	<1000	P	1.827	0.352	0.750	0.268	0.064	0.015	0.004	9	20
Teff	<1000	P	1.118	0.250	0.795	0.171	0.054	0.017	0.005	10	20

Table 5.4g: Cold to very cold sub-Afro alpine.

	Altitude range (masl)	Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crops		**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
				t/ha			**t/ha**			**kg/ha**	
Barley	N	2.179	0.625	0.982	0.263	0.152	0.088	0.051	44	73	
Faba bean	N	2.550	0.060	0.940	0.051	0.008	0.001	0.000	16	18	
Wheat	N	3.284	1.303	0.964	0.869	0.289	0.096	0.032	69	73	
					0-5	**5-10**	**10-15**	**15-20**			
Barley	P	3.525	0.881	0.871	0.439	0.220	0.110	0.055	18	30	
Faba bean	P	3.040	1.434	0.847	0.809	0.353	0.154	0.067	22	20	
Wheat	P	4.656	1.468	0.837	0.865	0.355	0.146	0.060	20	30	

6. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Ghana

Francis M. Tetteh[1] fmarthy2002@yahoo.co.uk, Gabriel W. Quansah[1], Samuel O. Frempong[1], Abdul Rahman Nurudeen[2], Williams K. Atakora[3], Godwin Opoku[4]

[1]*CSIR-Soil Research Institute, Academy Post Office, Kwadaso-Kumasi, Ghana*
[2]*IITA/Africa RISING, P.O. Box TL 06, Tamale, Ghana*
[3]*Savanna Agricultural Research Institute, P.O. Box TL 52, Tamale, Ghana*
[4]*Savanna Agricultural Research Institute, P.O. Box 494, Wa Station, Wa, Ghana*

6.1 Soil nutrient management, including fertilizer use in Ghana

Ghana's agriculture is characterized by low crop yields due to low soil fertility, soil erosion, inappropriate land use and nutrient depletion through crop harvest and exports without corresponding replacement of these nutrients by fertilizer use, leading to soil degradation. Food security is therefore at risk, with increased dependence on imported food and expenditure of Ghana's foreign exchange reserves.

The important food crops in Ghana are maize, rice, sorghum, millet, cassava and legumes. Among the cereals, maize is the most important with about 750,000 ha/year of production. Cowpea is a very important legume food crop and soybean is becoming important as a cash crop. The yields of these crops are, however, low because of low soil fertility and low input use. The Abuja summit on fertilizer declared that Sub-Saharan Africa (SSA) can only increase food production and alleviate poverty when fertilizer use is increased.

However, the mean maize yield is 1.5 t/ha compared to potential yield of 6 t/ha. Two major reasons for low crop productivity include low soil

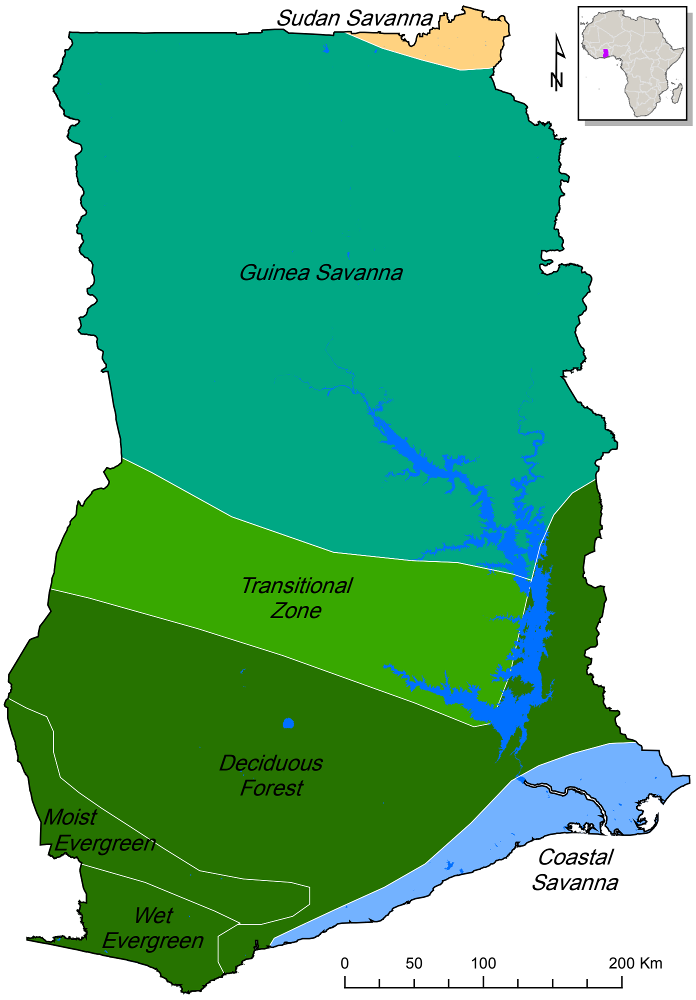


Figure 6.1: Agro-ecological zones (AEZ) of Ghana.

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

fertility and low input use. The soils of the major maize growing areas are low in organic carbon (<1.5%), total nitrogen (<0.2%), exchangeable potassium (<100 ppm) and available phosphorus (< 10 ppm) (Benneh et al., 1990; Adu 1995). A large proportion of the soils are also shallow with iron and magnesium concretions (Adu 1969).

Despite these shortcomings, soil fertility management receives little attention from farmers. Fertilizer nutrient application in Ghana is approximately 12 kg/ha (FAO 2005) while depletion rates, which range from about 40 to 60 kg of nitrogen, phosphorus and potassium (NPK) per ha/yr (FAO 2005), are among the highest in Africa. FAO estimates show negative nutrient balance for all crops in Ghana. The escalating rates of soil nutrient mining are a serious threat to sustainability of agriculture and poverty reduction.

Ghana's farming systems vary with agro-ecological zones although certain agricultural practices cut across all zones (Figure 6.1). The bush fallow system prevails wherever there is ample land to permit a plot to replenish its fertility after one to three years of cultivation (Ofori and Stern 1987; MoFA 1998). Staple food crops are often mixed-crop while cash crops are usually monocropped.

In the forest zone, tree crops are significant with cocoa, oil palm, coffee and rubber being the dominant crops. Food crops in these areas are mainly intercropped mixtures of maize, plantain, cocoyam and cassava.

The middle belt is characterized by mixed or sole cropping of maize, legumes, cocoyam or yam with tobacco and cashew being the predominant cash crops.

The food crops in the northern sector are mainly sorghum, maize, millet, cowpeas, groundnuts and yam with tobacco and cotton as the predominant cash crops.

Table 6.1: Mean monthly rainfall (mm), maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of selected AEZ of Ghana

	J	F	M	A	M	J	J	A	S	O	N	D
Deciduous, Abourtem												
Rainfall	19	62	140	151	180	223	146	91	173	194	89	34
Tmax	31.8	33.2	33.1	32.3	31.6	29.7	28.1	28.3	29.0	30.3	31.5	30.7
Tmin	20.6	27.3	27.4	27.2	27.0	25.8	24.7	24.3	25.2	25.8	26.6	25.8
Derived Transitional, Wenchi												
Rainfall	6	30	106	143	163	171	115	83	187	182	46	14
Tmax	32.1	33.7	33.4	32.4	31.2	28.9	27.4	26.5	27.8	28.6	29.7	29.6
Tmin	19.8	21.5	21.9	22.0	21.6	21.1	20.7	20.4	20.7	20.5	20.6	19.8
Guinea Savanna, Nyankpala												
Rainfall	2	8	43	86	123	149	156	185	225	99	11	4
Tmax	35.9	37.5	37.3	36.0	33.9	31.6	30.1	29.9	30.4	32.6	35.2	35.3
Tmin	20.7	23.2	24.8	24.7	24.0	22.8	22.4	22.1	22.0	22.2	21.8	20.2
South Sudan Savanna, Navrongo												
Rainfall	1	3	14	43	92	122	181	259	172	47	4	2
Tmax	35.2	37.1	38.3	37.6	35.2	32.2	30.3	29.7	30.4	33.2	36.1	35.0
Tmin	19.4	21.5	24.4	25.3	24.6	23.0	22.2	22.0	21.9	21.9	20.5	18.8
North Sudan Savanna, Wa												
Rainfall	2	5	34	79	125	129	161	201	195	80	9	6
Tmax	34.6	36.1	36.2	35.3	32.9	30.9	29.5	29.1	29.7	32.3	34.9	34.2
Tmin	19.5	21.6	23.7	24.1	23.0	22.0	21.5	21.4	21.2	21.5	20.9	19.4

Source: climatedata.org/Ghana

In the Guinea savanna zone about 88% of farmers intercropped cowpea with sorghum or millet (GGDP 1991).

Rice is grown in all the ecological zones. The traditional method of land clearing and preparation is the use of rudimentary tools for slashing and burning of the debris.

Poultry production is the main livestock sector in the south while cattle production is concentrated in the savanna zones. Sheep and goat production is important throughout the country (MoFA 1998). Manures from poultry, cattle, sheep and goats are used by smallholder farmers in home gardens especially in the northern savanna zone.

Ghana is divided into six major agro-ecological zones: these are Rain Forest, Deciduous Forest, Forest-savanna Transition, Coastal Savanna and Northern (interior) Savanna which comprises Guinea and Sudan Savannas (Figure 6.1; Table 6.1).

Ghana's climate ranges from equatorial bimodal rainfall in the south to the tropical unimodal monsoon type in the north. The mean monthly temperature over most of the country never falls below 25°C, a consequence of low latitude and low altitude. Mean annual temperature average is 27°C. Absolute maxima approach 40°C, especially in the north, with absolute minima descending to about 15°C. In the coastal areas, with the influence of the sea breeze, monthly annual mean temperatures differ by 5 to 6°C. In the interior, this temperature range is about 7 to 9°C (Dickson and Benneh, 1988; Benneh et al., 1990). The rainfall generally decreases from the south to the north. The wettest area is the extreme southwest where the mean rainfall is over 2000 mm/yr. In the extreme north, the annual rainfall is less than 1100 mm/yr.

Most of the soils of Ghana are developed on thoroughly weathered parent materials, with alluvial soils (Fluvisols) and eroded shallow soils (Leptosols) common to all the ecological zones. Generally most of the soils are affected with inherently or humanly induced infertility (MoFA 1998).

The soils in the forest zone are grouped under Forest Oxysols and Forest Acid Gleysols. These are porous, well drained and generally loamy and are distinguished from those of the savanna zones by the greater accumulation of organic matter in the surface resulting from higher accumulation of biomass. They occur in areas underlain by various igneous, metamorphic and sedimentary rocks, which have influenced the nature and properties of the soil.

Soils of the savanna zones, especially in the interior savanna, are low in organic matter (less than 2% in the topsoil), have high levels of iron concretions and are susceptible to severe erosion. Thus well-drained upland areas tend to be droughty and when exposed to severe incident sunshine, tend to develop cement-like plinthite. These conditions make it imperative that manure be incorporated regularly into the soils in the savanna zones (MoFA 1998).

6.2 Fertilizer use and recommendations

Current recommended rates of fertilizer application on food crops were formulated about 30 years ago. At that time, long fallow periods and less intensive cropping coupled with crop varieties with low response to nutrients resulted in low to medium rates of recommended nutrient levels of application.

With agriculture developing fast and improved crop varieties with high nutrient requirements, there is the need to improve nutrient supply to crops if the full yield potential of the crop is to be realized. Even with subsidization, fertilizer use is expensive to the smallholder farmers who form the bulk of production force. However, it is in the interest of farmers to invest in fertilizer rates that are economically and scientifically sound so as to derive benefit and keep the soil productive. More so, the price of maize is steadily high and attractive to make farmers invest in fertilizer to increase production. A key limitation to farmers' use of fertilizer in Ghana is also lack of fertilizer recommendations that could result in good profits for farmers.

Soil fertility and productivity conditions vary considerably between geographic areas and among farms and fields in the same soil area, so blanket fertilizer-use recommendations may be entirely unprofitable for a whole region or area while profitable in a few areas. This is because fertilizer-use recommendations are site- and situation-specific. That is why several general fertilizer-use recommendations in Ghana have been inconsistent and not popular among farmers and agricultural scientists.

6.3 Current fertilizer use

Cost-effective soil fertility management and increased agricultural productivity goes with good soil information and fertilizer recommendations that are current and specific for crops and agro-ecologies. This has been inadequate in Ghana. Fertilizer recommendations were made for maize, rice, cassava, cotton and groundnut. The fertilizer recommendation for maize was updated in 1974 and since then only sporadic and inconclusive attempts have been made to update these recommendations.

For example, from 2002 to 2005, an attempt was made under the Ghana Soil Fertility Management Action Plan to update the fertilizer recommendation for maize but no specific recommendations have been made for the different agro-ecologies. The old and blanket fertilizer recommendation is two bags of blended fertilizer and one bag of sulphate of ammonium per acre for maize, irrespective of the AEZ.

Currently there is no effective soil test service for farmers and as a result fertilizer application is not based on soil test information. Soil conditions have changed over the years and the old recommendations are not the most efficient today. There is need to update fertilizer recommendations for maize and other crops in Ghana and provide soil analysis service to farmers.

In 2008, the government re-introduced fertilizer subsidies through a voucher-based system to promote fertilizer use and improve crop productivity of smallholder farmers. The vouchers were worth 50% of the price of fertilizer on selected fertilizers for use on staple food crops (urea, 15-15-15 NPK, 23-10-5 NPK and sulphate of ammonia). The subsidy on fertilizer has, however, declined over the years from 50% in 2008 to 20% in 2015 as a way of equalizing fertilizer price in Ghana and the neighboring countries to discourage smuggling of subsidized fertilizer. Farmers were encouraged to use the fertilizers on mainly the key food crops – maize, rice, millet and sorghum. The total cost of the subsidy was valued at GH₵ 20.7 million and GH₵ 80 million in 2008 and 2015, respectively.

The performance of the subsidy programme has so far been commendable. It is estimated that yields of major food crops have increased by 4% in targeted areas. Fertilizer use has also increased thereby stimulating fertilizer supplies in the country. For example, fertilizer imports in 2009 were estimated at about 223,000 t/yr compared with 113,000 and 150,000 t/yr in 2007 and 2008, respectively. This is expected to grow in the coming years.

Over the period of the implementation of the fertilizer subsidy programme from 2008 to 2013, a total of 737,248 metric tons of fertilizer was subsidized at a total cost of GH₵ 341,239,000 (US$ 183,334,000). After successfully implementing the fertilizer subsidy, seeds of maize, rice and soybean were added to the programme in 2012. After four years of implementation the fertilizer application rate increased from 8 to 10 kg per hectare. This has led to increased productivity of the country's major staple food crops. The target is to increase application rate to at least 50 kg per hectare as recommended in the Medium Term Agricultural Sector Investment Programme (METASIP), the policy document of the Ministry of Food and Agriculture.

The Ministry of Food and Agriculture implemented targeted measures in the 2013 subsidy programme to ensure maximum reach to resource poor farmers and greater efficiency of distribution and value for money. Instead of universal fertilizer subsidy, the 2013 subsidy programme targeted smallholder farmers cultivating maize, rice, sorghum and millet with priority on food crop farmers in the savanna area of the country, out-grower farmers registered under recognized nucleus farmers/companies, food crop farmers, either on their own or as members of an out-grower scheme, and women farmers. The package for a hectare of land was four bags (50 kg each) of compound fertilizer (NPK-15-15-15 or 23-10-5) and two bags of sulphate of ammonia or urea.

6.4 Fertilizer use integrated with other practices

Integrated soil fertility management (ISFM) is the approach advocated by the Alliance for a Green Revolution in Africa (AGRA) to improve the soil fertility status of African soils. ISFM is the application of soil fertility management practices, and the knowledge to adapt these to local conditions, which optimize fertilizer and organic resource use efficiency and crop productivity. ISFM practices include appropriate fertilizer and organic input management in combination with the utilization of improved crop varieties.

Substantial knowledge on soil management practices and technologies has been accumulated over the last 20 years, enabling the project to adequately address the intensification of maize-legume rotation and intercropping systems among small-scale Ghanaian farmers in a sustainable and environmentally beneficial manner. For example, ISFM in maize-cowpea rotation/intercropping is a proven success in northern Ghana with strong synergies between the cereal and legume phases.

Soil fertility management relies upon retention of legume residues, judicious application of mineral fertilizer, targeting fertilizer to specific phases of the rotation/intercrop (e.g. P fertilizer to the cowpea phase and N fertilizer to the maize phase).

Soybean cultivation has also caught on fairly well in Ghana and significant rotation effect has been demonstrated where soybean residues were returned to the soil.

In general farmers are aware of the beneficial effects of maize-legume rotation but in most cases, farmers tend to keep cereals or maize for the best soils under continuous cropping as maize is the major staple. Farmers have not developed the confidence of routine rotation with reliance on legumes as cash crop to purchase the cereals that they need in the years they will keep a legume crop in place of a cereal. Intercropping has always been the closest compromise.

The main limitation to the widespread adoption of maize-legume rotation/intercropping systems is lack of financial and physical access to fertilizer and availability of high-yielding legume varieties that are also well adapted to intercrop conditions. Under the Challenge Program on Water and Food (CPWF), the Savanna Agricultural Research Institute (SARI) developed a number of cowpea varieties that are high yielding under intercrop conditions.

There are inefficiencies and bottlenecks in the fertilizer distribution network which limit access and add to the cost of fertilizer in the farming communities. Farmer-based organizations (FBO) are few and weak and therefore unable to acquire credit, fertilizer and other inputs in bulk to reduce cost. SARI, the Ministry of Food and Agriculture (MoFA) and NGOs have promoted the formation of FBOs, but these need to be strengthened and trained. Agro-dealerships are rudimentary in Ghana and lack the skills to support a vibrant agricultural growth.

6.5 Diagnosis of nutrient deficiencies in Ghana

In 2015, five trials were conducted on maize, cowpea, sorghum and groundnut in two agro-ecological zones in Ghana to compare the effect of micronutrients on yields. The diagnostic treatment (N+P+K+Mg+S+Zn+B) was compared with the treatment of the same N+P+K rate to determine if one or more of the secondary or micro nutrients resulted in increased yield. The initial results obtained from the Navrongo location showed an inconsistent but mean increase of 4.8% in maize yield due to the diagnostic package of nutrients. More diagnostic research is needed to verify this increase, to better determine the conditions under which a response is likely to occur, and to better determine which of the four secondary and micro nutrients are most deficient.

6.6 Optimizing fertilizer use in Ghana

Fertilizer use in Ghana is low and the recommended rates are usually blanket and out-moded. Even when fertilizers are subsidized they are still expensive to the smallholder farmer.

The typical crop response to applied nutrient is curvilinear to plateau. Such a yield response (vertical axis or y-axis) of maize to applied N (horizontal axis or x-axis) is displayed in Figure

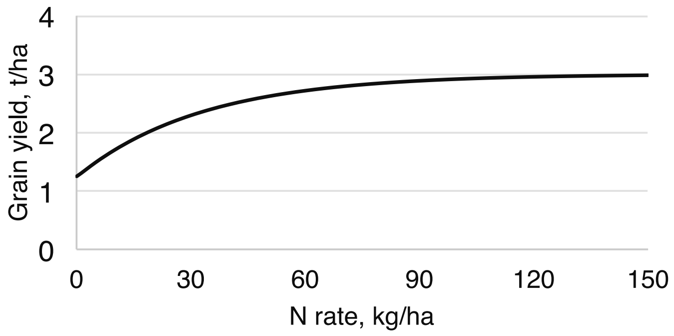


Figure 6.2: Response of maize to N application in South Sudan Savanna of Ghana.

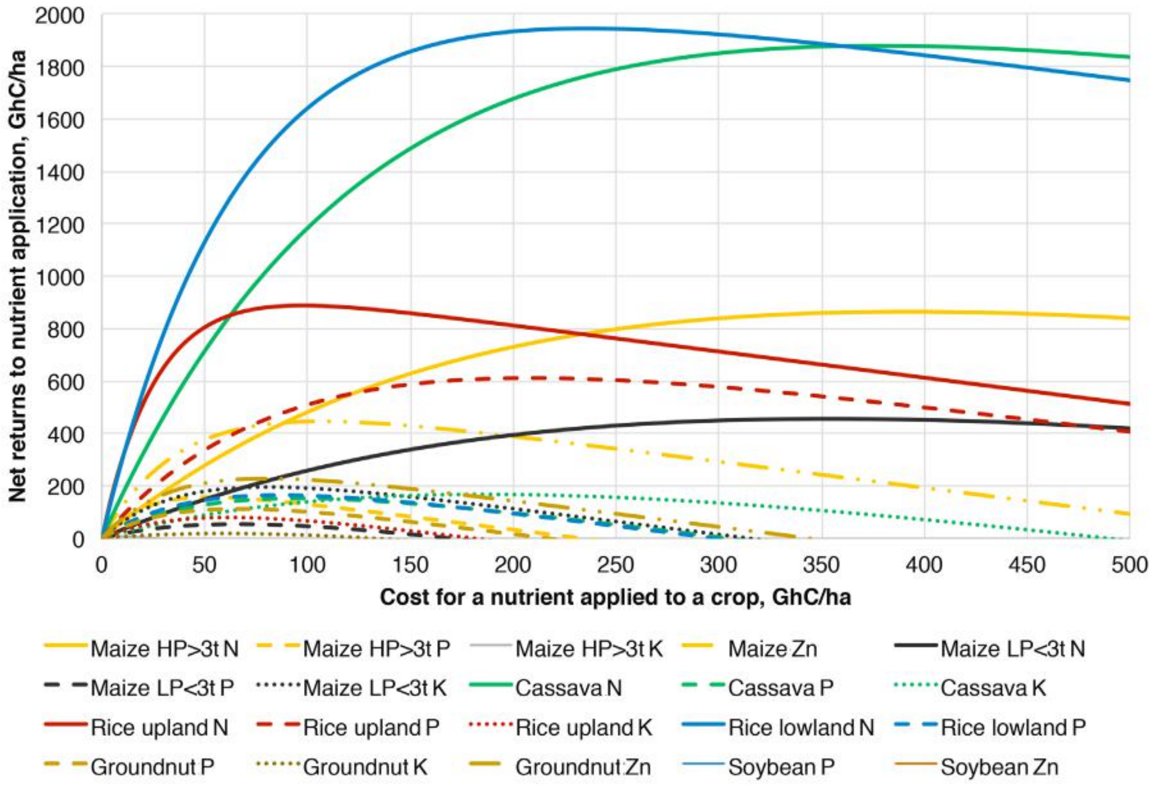


Figure 6.3: Net return from fertilizer use in the Derived Savanna Transitional Zone of Ghana. Less profitable and unprofitable nutrient applications were excluded from the figure. This graphic is dependent on grain values and fertilizer use costs. Grain and tuber values used were: 0.75, 1.52, 1.22, 2.78, 1.77 and 0.20 for maize, sorghum, rice, groundnut, soybean and cassava respectively. Fertilizer use costs were: urea = 100; TSP = 150; KCl = 150 and $ZnSO_4$ = GH₵ 600 per 50 kg.

6.2 with a large yield increase with increasing N at low rates, a lower rate of yield increase at higher N rates, until yield reaches a plateau with no more yield increase. This tells us that the net returns to low rates of nitrogen application are greater than with higher rates. Such response curves are typical for most crops and nutrients and are essential to determining the profitability of fertilizer use. These show that the financially constrained farmer will make more profit on a limited amount of fertilizer by applying at lower nutrient rates to more land than by applying higher rates over less land.

Another important aspect of achieving high profit from fertilizer use for financially constrained farmers is that profit potential varies with nutrients and the crops to which these are applied (Figure 6.3). In this figure, each curve represents the profit potential of a nutrient applied to a crop. When the slope of the curve is steep, net returns to investment are very high. As the amount invested increases (the x-axis) the slope decreases but if still upward, profit is increasing. The steepest slope for the Derived Savanna Transitional Zone is with about GH₵ 20/ha (x-axis) of K applied to cassava with an expected net return of approximately GH₵ 1230/ha (y-axis). When the same amount (GH₵ 20) is invested in P applied to groundnut (on x-axis), the expected mean net return is approximately GH₵ 950 (on the y-axis) to farmers in the Derived Transitional Zone. The peak of the curves is the point of maximum profit per hectare for that nutrient applied to that crop. When slopes decline, profit is declining. The financially constrained farmer wants first to take advantage of the most profitable crop-nutrient combinations for crops in the cropping system. Making decisions in consideration of these curves for the amount of nutrient to apply to each crop is, however, very complex. Not only the agronomy of the responses to applied nutrients of the different crops of interest to farmers, but also the farmer's land allocation to different crops, the value of the commodity, the costs of fertilizer use and the money available for fertilizer use need to be considered in optimizing fertilizer use for high profit. Therefore, fertilizer optimization tools were developed using Excel Solver© (Frontline Systems Inc.) that use complex mathematics to integrate economic and agronomic information, but which are easy to use (https://agronomy.unl.edu).

6.7 Fertilizer use optimization tools (FOT) for Ghana

Fertilizer Optimization Tools (FOTs) were developed to integrate the economic and agronomic aspects of the farmer's situation with the crop nutrient response functions determined from field research trials through complex calculations involving linear optimization. Fertilizer use optimization as mentioned here refers to maximizing profit from fertilizer use, including profit per hectare for the farmer with adequate finance and also profit on the small investment in fertilizer use by the financially constrained farmer. These easy to use tools were designed to make decisions to maximize profits from fertilizer use.

The FOTs were developed for four zones in Ghana as shown in the FOT input screen (Figure 6.4) for the Derived Savanna Transitional Zone. It considers high and low potential maize, cassava, upland and lowland rice, groundnut and soybean. To use the FOT, the Excel add-in Solver needs to be activated and macros need to be enabled; see the step-by-step instructions in the 'Help and Instructions' worksheet of the FOTs and more detailed instructions (Extension Materials and FOT Manual) are available at http//:agronomy.unl.edu/OFRA.

Once Solver has been activated and macros enabled, the user enters the land areas in hectares 'Area Planted, ha' for each crop to be planted. The expected on-farm value of the commodity considering the expected value of that kept for home consumption and that to be marketed is entered 'Excepted Grain Value/kg'. If a crop is not planted, '0' is entered for hectares. Next, the cost of using available fertilizers are entered considering the purchase price, and transport and application costs under 'Cost/50 kg bag'; if the fertilizer is not available,'0' is entered for the cost. An optional fertilizer can be added under the KCl row with the nutrient concentrations. Finally, the amount of money that the farmer has for fertilizer use is entered 'Budget Constraint'; in the example, GH₵ 500 is entered, an affordable budget for many smallholders. A left click on 'Optimize' runs the optimization.

The FOT output is in three tables (Figure 6.5). The upper table 'Application rate - kg/ha' gives the recommended fertilizer rates for each crop. Some recommended rates are less than 20 kg/ha and too low for feasible application; that fertilizer or money can be allocated by the user to another fertilizer application. Total fertilizer amounts recommended are 256 kg/ha of urea, 33 of kg/ha of TSP, 0 kg/ha DAP as this was not selected in the Input screen, 56 kg/ha of KCl, and just 6 kg of NPK which was generally not economically competitive with the single nutrient fertilizers.

The next table 'Expected Average Effects per ha' addresses expected average yield increases and net return per acre due to the recommended fertilizer use (Figure 6.5). This table indicates the relative profitability associated with fertilizer applied to the different crops; in the table the most profitable fertilizer use is with cassava suggesting that the farmer may want to increase area planted to cassava; this high profit potential with cassava is consistent with information in Figure 6.3.

The third table 'Total Expected Net Returns to Fertilizer' is an average estimate, adjusted for land allocated to each crop, but expecting that the net returns will be more in some years and less in other years. These results can only be expected if the farmer adheres to good agronomic practices of variety selection, planting and control of weeds, disease and pests.

Crop options are to a large extent determined by physiographic and climatic conditions, such as with sorghum and cowpea generally in drier areas and maize and beans in more humid areas. The choice of crops is done by the farmer considering crop suitability, home consumption needs, local market opportunities, credit availability and market access.

The FOTs help the farmers make decisions to maximize profit from fertilizer use. The FOTs can be used in decision making at district level so as to ensure the fertilizers that are most cost effective for the farmer are adequately available on a timely basis. For example, the results in Figure 6.5 indicate the strong need for timely availability of urea but also that TSP and KCl supply should have priority over supply of NPK.

AEZ Derived Savanna/Transitional

Producer Name:	xxx
Prepared By:	
Date Prepared:	**August 3, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Ha)***	**Expected Grain Value/kg †**
Maize HP>3t	1	0.75
Maize LP<3t	0.5	0.75
Cassava	0.5	0.2
Rice upland	0.5	1.22
Rice lowland	0.5	1.22
Groundnut	1	2.71
Soybean	0.3	1.77
Total	**4.3**	

Fertilizer Selection and Prices					
Fertilizer Product	**N**	**P2O5**	**K2O**	**Zn**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	100
Triple super phosphate, TSP	0%	46%	0%	0%	150
Diammonium phosphate, DAP	18%	46%	0%	0%	0
Murate of potash, KCL	0%	0%	60%	0%	150
NPK	15%	15%	15%	0%	120

Budget Constraint	
Amount available to invest in fertilizer	500

Figure 6.4: Input data options for the computer generated FOT.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**NPK**
Maize HP>3t	45	9	0	0	0
Maize LP<3t	0	0	0	7	0
Cassava	87	0	0	20	6
Rice upland	90	0	0	19	0
Rice lowland	35	0	0	5	0
Groundnut	0	24	0	5	0
Soybean	0	0	0	0	0
Total fertilizer needed	151	33	0	30	3

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
Maize HP>3t	916	571
Maize LP<3t	177	112
Cassava	14,952	2,740
Rice upland	1,800	1,961
Rice lowland	739	816
Groundnut	297	717
Soybean	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	4,101

Figure 6.5: Output after optimizing the tool showing fertilizers needed and the expected returns.

Table 6.2: An example paper Fertilizer Optimization

GHANA SOUTH GUINEA AEZ FERTILIZER USE OPTIMIZER:
Paper Version: March 2016

The below assumes:
Calibration measurement is with a: Voltic water bottle cap (cap) of 8 ml, 5.6 g urea, 8.8 g DAP, TSP, or KCl, or 8 g NPK; and with a Gino tomato can (Gino) of 70 ml to hold 49 g urea and 77 g DAP, TSP, or KCl and 70 g NPK.
Plant spacing: maize and sorghum, 75 x 40 cm; pearl millet, 100 x 40 cm; cowpea, groundnut and soybean, 40 x 20 cm and rice, 20 x 20 cm.
Grain values per kg (GH₵): Pearl millet 3; sorghum 1.52; maize 0.75; rice 1.22; groundnut unshelled 2.71; cowpea 2.43; soybean 1.77.
50 kg of fertilizer costs in GH₵: urea 100; TSP 150; KCl 150; NPK (15-15-15) 120.
Broadcast width: 2.0 m; WAP = Weeks After Planting, WAT = Weeks After Transplanting. Application rate is kg/ha. Point apply at least 5 cm from plants.

Level 1 financial ability.	
Maize	point apply and cover 33 kg/ha TSP (cap for 9 hills) at 2 WAP; point apply and cover 60 kg/ha urea at 6 WAP (cap for 3.1 hills)
Lowland rice	broadcast 50 kg/ha urea at panicle initiation (Gino for 4.6 m)
Cowpea	82 kg/ha TSP 2 WAP point apply and cover (cap for 13 hills)
Sorghum	45 kg/ha TSP (cap for 7 hills) at 2 WAP
Soybean	29 kg/ha TSP at 2 WAP point apply and cover (cap for 38 hills)
Groundnut	31 kg/ha TSP (cap for 36 hills)
Level 2 financial ability.	
Maize	point apply and cover 65 kg/ha urea (cap for 3 hills) and 9 kg/ha $ZnSO_4$ (cap for 50 hills) at 2 WAP; point apply and cover 65 kg/ha urea at 6 WAP (cap for 3 hills). Or mix 5 Gino urea and 1 Gino $ZnSO_4$ (a cap of mix for 4.5 hills)
Lowland rice	broadcast 39 kg/ha urea at 2 WAT and 39 kg/ha urea at panicle initiation (Gino for 6 m each time)
Upland rice	broadcast 38 kg/ha urea at panicle initiation (Gino for 1.2 m). Broadcast 28 kg/ha KCl at 2 WAT (cap for 1.6 m)
Cowpea	point apply and cover 110 kg/ha TSP at 2 WAP (cap for 10 hills)
Sorghum	point apply and cover 45 kg/ha urea (cap for 4 hills) and 73 kg/ha TSP (cap for 4.5 hills) at 2 WAP; point apply 45 kg/ha urea at panicle initiation (cap for 4 hills)
Soybean	point apply and cover 83 kg/ha TSP at 2 WAP (cap for 13 hills)
Groundnut	apply 43 TSP kg/ha at 2 WAP (cap for 26 hills)
Level 3 financial ability (maximize profit per hectare).	
Maize	point apply and cover 75 kg/ha urea (cap for 2.5 hills) and 30 kg/ha TSP (cap for 10 hills) and 15 kg/ha $ZnSO_4$ (1 cap for 32 hills) at 2 WAP; point apply and cover 75 kg/ha urea at 6 WAP (cap for 25 hills). Or mix 6 Gino TSP and 5 Gino $ZnSO_4$ (cap for 6 hills)
Lowland rice	broadcast 50 kg/ha urea at 2 WAT (Gino for 94.6 m). Broadcast 50 kg/ha urea at panicle initiation (Gino for 3.2 m)
Upland rice	broadcast 64 kg/ha urea at panicle initiation (Gino for 3.5 m). Broadcast 106 kg/ha TSP (cap for 0.4 m) and 33 kg/ha KCl at 2 WAT (cap for 1.3 m)
Groundnut	point apply and cover 53 kg/ha TSP at 2 WAP (cap for 21 hills)
Cowpea	point apply and cover 133 kg/ha TSP at 2 WAP (cap for 8 hills)
Sorghum	point apply and cover 93 kg/ha TSP (cap for 3.5 hills) at 2 WAP
Soybean	point apply and cover 121 kg/ha TSP (cap for 9 hills) and 9 kg/ha $ZnSO_4$ at 2 WAP (cap for 200 hills). Or mix 8 Gino TSP and 1 Gino $ZnSO_4$ (cap for 7.3 m)

Optimizing fertilizer use implies that other good agronomic practices are applied and therefore adequate availability of other agricultural inputs. Therefore, for the district the FOT does not stop at making decisions for fertilizer use but decisions at a broader scale of agricultural production.

Each Excel Solver© FOT has a corresponding paper FOT to be used when a computer is not available and directly by farmers themselves (Table 6.2). These are available at http://agronomy.unl.edu/OFRA. The paper FOT is designed for three financial ability levels. Financial ability level 1 is for the farmer who has not more than one-third the amount required to apply fertilizer to all cropland at the rate to maximize profit per ha. Financial ability level 2 is for farmers with not more than two-thirds the amount required to apply fertilizer to all cropland at rates to maximize profit per hectare. Financial ability level 3 is for farmers with enough money to apply fertilizer at rates to maximize profit per hectare.

The paper tool makes assumptions about:

- measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer as in Table 6.2 where the measuring units are the Voltic brand water bottle lid with a volume of 7 ml and the Gino brand tomato sauce can giving a volume of 70 ml
- crop row and plant spacing
- fertilizer use costs per 50-kg bag
- expected grain values on-farm at harvest, considering the value both for home consumption and for market
- application guidelines.

The paper FOTs address the 4Rs, advising on the right product, rate, time and method of application (Table 6.2). It also advises on calibration, that is the length of band or the number of plants/planting hills for the recommended fertilizer rate with one measuring unit.

Consider as an example from the South Guinea Savanna paper FOT the level 2 financial ability recommendation “Sorghum point apply 45 kg urea (1 lid per 8 hills) and TSP 73 kg (1 lid per

Table 6.3: Fertilizer substitution value of good agronomic practices and soil test implications

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT CONTEXT

FERTILIZER SUBSTITUTION AND SOIL TEST IMPLICATIONS

ISFM practice	Urea	DAP or TSP	KCl	NPK 15-15-15
	Fertilizer reduction, % or kg/ha			
Previous crop was a green manure crop (mucuna for maize)	100%	70%	70%	70%
Farmyard manure per 1 t of dry material (low quality)	22 kg	10 kg	10 kg	70 kg
Residual value of FYM applied for the previous crop, per 1 t	10 kg	5 kg	5 kg	35 kg
Poultry manure, per 1 t dry material	65 kg	22 kg	17 kg	200kg
Residue value of poultry manure, per 1 t dry material	32 kg	10 kg	8 kg	100 kg
Compost, per 1 t	11 kg	1 kg	1 kg	33 kg
Maize-cowpea intercropping	TSP by 22 kg/ha, but no change in N and K compared with sole maize rates			
Maize-groundnut intercropping	Increase DAP/TSP by 52 kg/ha, no change in N and K compared with maize rates			
Maize-cowpea rotation	0% reduction but more yield expected			
Rice-cowpea rotation	0% reduction but more yield expected			
If Bray-Kurtz I P > 20 ppm, or Olsen P > 30 ppm	Apply no P			
If soil test K < 100 ppm	Band apply 15 kg/ha KCl			

Table 6.4a: Derived Savanna Transitional Zone. Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations by agro-ecological zones in Ghana. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**A**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
		t/ha			**t/ha**				**kg/ha**	
Maize HP>3t	N	3.787	1.936	0.978	0.955	0.484	0.245	0.124	89	90
Maize LP<3t	N	2.526	1.399	0.982	0.588	0.341	0.198	0.115	72	60
Cassava	N	44.810	11.935	0.967	7.573	2.676	1.011	0.370	98	60
Rice, upland	N	4.650	1.900	0.980	0.864	0.471	0.257	0.140	72	60
Rice, lowland	N	3.104	0.746	0.953	0.570	0.135	0.032	0.007	50	90
					0-5	**5-10**	**10-15**	**15-20**		
Maize HP>3t	P	2.820	0.310	0.520	0.424	0.188	0.084	0.037	24	26
Maize LP<3t	P	0.910	0.240	0.780	0.171	0.049	0.014	0.004	0	17
Cassava	P	28.790	1.527	0.770	1.114	0.301	0.082	0.022	12	26
Rice, upland	P	1.830	0.420	0.910	0.158	0.099	0.061	0.038	0	17
Rice, lowland	P	3.210	0.150	0.700	0.125	0.021	0.004	0.001	0	26
Groundnut	P	4.430	0.830	0.800	0.270	0.069	0.017	0.004	23	13
Soybean	P	1.740	0.110	0.880	0.153	0.098	0.063	0.040	37	13
Maize HP>3t	K	3.759	0.036	0.550	0.035	0.002	0.000	0.000	0	50
Maize LP<3t	K	2.565	0.419	0.855	0.227	0.104	0.047	0.022	0	33
Cassava	K	34.000	6.966	0.813	4.234	1.504	0.534	0.190	23	50
Rice, upland	K	4.430	0.830	0.800	0.558	0.183	0.060	0.020	0	33
Groundnut	K	1.740	0.110	0.880	0.052	0.027	0.014	0.008	0	17
					0-1	**1-2**	**2-3**	**3-4**		
Maize	Zn	4.010	0.790	0.310	0.545	0.169	0.052	0.016	1.7	ND
Groundnut	Zn	1.060	0.080	0.300	0.056	0.017	0.005	0.002	0.8	ND
Soybean	Zn	1.774	0.194	0.270	0.142	0.038	0.010	0.003	1.2	ND

† EOR was determined with the cost of using 50 kg: urea 100 Gh cedis; TSP and KCl at GH cedis 150; and zinc sulphate at 600. Commodity values (GH cedis/kg) used were: rice 1.22; maize 0.75; cassava 0.20; cowpea 2.43; groundnut 2.71; soybean 1.77; and pearl millet 1.69.

‡CSIR-Soil Research Institute (SRI)

9 hills) at 2 WAP; urea 45 kg (1 lid per 8 hills) at panicle initiation.” Therefore, urea and TSP are to be applied at least 5 cm to the side of planting hills of sorghum at rates of 45 and 73 kg/ha, respectively. One Voltic bottle lid is sufficient for 8 planting hills with urea and 9 planting hills with TSP. Another 45 kg/ha urea is to be topdress applied at panicle initiation by point applying at least 5 cm away from the plant; one bottle lid is sufficient for 8 planting hills.

6.8 Adjusting fertilizer rates for other practices and soil test information

Fertilizer use decisions need to consider the effects of other practices that supply soil nutrients as well as soil test information (Table 6.3). Manure application to a field calls for adjustment in the fertilizer rate applied according to the fertilizer substitution value of the manure, which varies with the quality of manure. Manure of confined poultry, dairy, sheep and goats manure has greater fertilizer substitution value than farmyard manure.

Other practices with fertilizer substitution value considered in Table 6.3 include having a green manure crop and a cereal following a legume in rotation. Intercropping may require more fertilizer than the sole crop. Soil test values are considered. Soil test P is commonly low for smallholder fields not near the household and P should be applied according to the FOT unless the soil test P value is above 20 mg/kg by Bray 1 for soils with pH of less than 7 or above 30 mg/kg by Olsen for soils with pH greater than 7. Fertilizer K should be applied as recommended by the FOT unless the soil test K is less than 100 ppm when 15 kg/ha muriate of potash or potassium sulphate should be applied.

6.9 Targeted crops and cropping systems by AEZ

Crop responses to nutrients were determined for important food crops in each agro-ecological zone using results of past and recent field research trials (Tables 6.4 a - d). The first two columns are for crop and nutrient. Columns 3-5 have the a, b, c coefficients for the curvilinear to plateau response function, $Y = a - bc^r$. The next four columns report the expected yield increase with increased nutrient rates compared with the lower rate and the right-most columns report the optimized nutrient rate for maximizing profit per hectare due to fertilizer use (EOR) compared with the current recommended rate (REC). The commodity values and fertilizer

Table 6.4b: South Guinea Savanna, Ghana

	Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate, kg/ha				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
		t/ha			t/ha				kg/ha	
Maize	N	3.130	1.680	0.980	0.955	0.484	0.245	0.124	69	90
Rice, lowland	N	3.100	0.750	0.950	0.588	0.341	0.198	0.115	46	90
Rice, upland	N	2.500	0.300	0.955	0.225	0.056	0.014	0.004	29	60
Sorghum	N	1.720	0.570	0.980	0.259	0.141	0.077	0.042	46	60
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.160	0.340	0.880	0.161	0.085	0.045	0.024	6	26
Rice, upland	P	3.160	0.770	0.970	0.109	0.093	0.080	0.069	21	17
Groundnut, unshelled	P	1.580	0.360	0.760	0.269	0.068	0.017	0.004	11	13
Cowpea	P	1.060	0.185	0.890	0.082	0.046	0.025	0.014	27	13
Sorghum	P	2.190	0.800	0.890	0.353	0.197	0.110	0.062	19	17
Soybean	P	2.010	0.680	0.930	0.207	0.144	0.100	0.070	24	13
Rice, lowland	K	1.950	0.090	0.810	0.059	0.020	0.007	0.002	6	50
Rice, upland	K	4.430	0.840	0.800	0.565	0.185	0.061	0.020	16	33
Groundnut, unshelled	K	1.770	0.100	0.750	0.076	0.018	0.004	0.001	9	17
Cowpea	K	0.820	0.130	0.800	0.087	0.029	0.009	0.003	11	17
Cassava	K	34.000	6.966	0.813	4.234	1.504	0.534	0.190	23	50
Rice, upland	K	4.430	0.830	0.800	0.558	0.183	0.060	0.020	0	33
Groundnut	K	1.740	0.110	0.880	0.052	0.027	0.014	0.008	0	17
					0-1	**1-2**	**2-3**	**3-4**		
Maize	Zn	4.010	0.790	0.310	0.545	0.169	0.052	0.016	1.7	ND
Groundnut	Zn	1.060	0.080	0.300	0.056	0.017	0.005	0.002	0.8	ND
Soybean	Zn	1.774	0.194	0.270	0.142	0.038	0.010	0.003	1.2	ND

costs used in determining EOR are given in the footnote of Table 6.4.

Nutrient applications exceeding the field research based EOR is expected to result in loss of profit. Any nutrient application at less than EOR means less than maximum potential profit per acre to fertilizer use but lower rates are typically most profitable with financially constrained fertilizer use.

The greatest yield increase, the b value, occurred in the Derived Savanna Transitional Zone with cassava for N application (Table 6.4 a). High potential maize (HP>3t) and upland rice also had a large response to N. High potential maize, cassava, groundnut and soybean had profitable responses to applied P. Only cassava had a profitable response to K. Maize, soybean and groundnut responded well to 1 kg/ha Zn applied. The field research based EOR was: similar to the REC N for high potential maize; more than the REC for low potential maize, cassava, and upland rice; and less than the REC for lowland rice. The EOR for P was less than the REC for most crops but higher for groundnut and soybean. The EOR for K was less than the REC for all crops and zero for most crops.

For the South Guinea Savanna, maize, upland and lowland rice, sorghum, cowpea, groundnut and soybean were considered (Table 6.4 b). Maize responded especially well to applied N but all cereals had a profitable response to N. All crops had an economical response to applied P. Upland and lowland rice, groundnut and cowpea had profitable responses to K but maize, sorghum and soybean did not. The EOR for N was always less than the REC N rates. The EOR of P for maize was less than REC rate but otherwise EOR of P was similar to REC for groundnut and sorghum, and greater than REC for the remaining crops. The EOR for K was always less than the REC.

Maize, upland rice and sorghum were especially responsive to applied N in the North Guinea Savanna (Table 6.4 c). All crops had an

Table 6.4c: North Guinea Savanna, Ghana

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
		t/ha			t/ha				kg/ha	
Cowpea	N	0.963	0.357	0.762	0.357	0.000	0.000	0.000	9	20
Maize LP <3t	N	2.493	1.601	0.972	0.918	0.392	0.167	0.071	73	60
Maize HP >3t	N	3.513	1.808	0.981	0.791	0.445	0.250	0.141	92	90
Rice, lowland	N	2.729	0.214	0.963	0.145	0.047	0.015	0.005	22	90
Rice, upland	N	4.665	1.908	0.988	0.580	0.404	0.281	0.196	92	60
Sorghum	N	4.154	1.338	0.906	1.269	0.066	0.003	0.000	40	13
					0-5	**5-10**	**10-15**	**15-20**		
Cowpea	P	0.961	0.052	0.600	0.048	0.004	0.000	0.000	3	13
Groundnut	P	1.589	0.362	0.760	0.270	0.069	0.017	0.004	11	13
Maize LP <3t	P	2.678	1.653	0.980	0.159	0.144	0.130	0.117	25	17
Maize HP >3t	P	3.541	1.799	0.978	0.189	0.169	0.152	0.136	24	26
Rice, lowland	P	3.058	0.738	0.969	0.108	0.092	0.078	0.067	20	26
Rice, upland	P	3.165	0.770	0.908	0.295	0.182	0.112	0.069	19	17
Sorghum	P	1.721	0.576	0.980	0.055	0.050	0.045	0.041	14	17
Cowpea	K	0.821	0.134	0.800	0.090	0.030	0.010	0.003	11	17
Groundnut	K	1.776	0.102	0.630	0.092	0.009	0.001	0.000	7	17
Rice, lowland	K	1.951	0.091	0.810	0.059	0.021	0.007	0.003	6	50
Rice, upland	K	2.500	0.300	0.945	0.074	0.056	0.042	0.032	20	33

Table 6.4d: South Sudan Savanna, Ghana

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC ‡
		t/ha			t/ha				kg/ha	
Maize	N	3.000	1.760	0.970	1.054	0.423	0.170	0.068	69	90
Rice, upland	N	4.655	1.908	0.988	0.580	0.404	0.281	0.196	69	90
Sorghum	N	4.067	1.530	0.860	1.513	0.016	0.000	0.000	23	60
Rice, lowland	N	2.482	0.428	0.970	0.256	0.103	0.041	0.017	42	90
Cowpea	N	1.860	0.168	0.770	0.168	0.000	0.000	0.000	12	20
Pearl millet	N	1.111	0.110	0.930	0.098	0.011	0.001	0.000	16	60
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	16	26
Rice, upland	P	3.633	0.979	0.904	0.388	0.234	0.141	0.085	20	26
Sorghum	P	2.770	1.470	0.910	0.553	0.345	0.215	0.134	10	26
Cowpea	P	0.929	0.040	0.700	0.033	0.006	0.001	0.000	0	9
Soybean	P	1.319	0.141	0.855	0.077	0.035	0.016	0.007	5	9
Pearl millet	P	1.520	0.129	0.900	0.053	0.031	0.018	0.011	13	17
Rice, upland	K	4.439	0.838	0.800	0.563	0.185	0.060	0.020	16	33
Sorghum	K	2.016	0.114	0.900	0.047	0.028	0.016	0.010	10	33
Rice, lowland	K	1.950	0.091	0.961	0.016	0.013	0.011	0.009	6	50
Cowpea	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	10	17
					0-1	**1-2**	**2-3**	**3-4**		
Maize	Zn	3.590	0.560	0.250	0.420	0.105	0.026	0.007	1.7	ND
Sorghum	Zn	4.300	0.100	0.500	0.050	0.025	0.013	0.006	1.3	ND
Soybean	Zn	1.614	0.348	0.397	0.210	0.083	0.033	0.013	0.8	ND

economical response to P and all but maize and sorghum had a profitable response to applied K. The EOR N rate was often high compared with the REC with exceptions for lowland rice and cowpea. The EOR and REC for P were similar except that EOR was much lower for cowpea. The EORs of K were always less compared with REC.

In South Sudan Savanna Zone, all crops including cowpea but excluding soybean had an economic response to applied N. All crops had a profitable response to applied P and K application was profitable for upland and lowland rice, sorghum and cowpea but not for maize, pearl millet or soybean. Recommended rates were also higher than EOR for N, P and K. The EOR of Zn was determined for maize, sorghum and soybean but there was a lack of evidence for response to Zn by pearl millet, upland and lowland rice, and cowpea.

With the exception of N in the Derived Savanna and the North Guinea Savanna where the relationship was inconsistent, the REC compared to the field research derived EOR were on average 44 to 130% higher, and more so for K than for N and P. In 54 of the 69 crop nutrient responses considered across the four agro-ecological zones, the REC is high compared with EOR. Therefore, farmers applying fertilizer at REC are generally over-applying fertilizer with loss in profit potential. Finance-constrained farmers should generally be applying fertilizer at rates well below the EOR, gaining the profit potential typically associated with relatively steep crop yield increases with lower rates of nutrient application. The results demonstrate the importance of providing farmers with a choice of fertilizers as the most profit potential typically lies with wise use of single nutrient fertilizers.

6.10 References

Adu SV (1969) Soils of the Navrongo – Bawku Area, Upper Region, Ghana. Memoir No. 5. Soil Research Institute, Kumasi

Adu SV (1995) Soils of the Nasia Basin. Memoir No. 6. Soil Research Institute, Kumasi

Benneh G, Agyepong GT and Allotey JA (1990) Land degradation in Ghana. Food Production and Rural Development Division. Commonwealth Secretariat, London

Dickson KB and Benneh G (1988) A new geography of Ghana. Longman Group UK Limited, Harlow, UK

FAO (2005) Fertilizer Use by Crop in Ghana. FAO, Rome

GGDP (1991) Ghana Grains Development Project. Thirteenth Annual Report. Part 2. Research Results

MoFA (Ministry of Food and Agriculture) (1998) National Soil Fertility Management Action Plan. Directorate of Crop Services, Accra, Ghana

Ofori F and Stern WR (1987) Cereal – legume intercropping systems. Advances in Agronomy 41:41-89

7. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Kenya

Catherine N. Kibunja[1] catherine.kibunja@yahoo.com, Keziah W. Ndungu-Magiroi[2], Dixon K. Wamae[3], Teresa J. Mwangi[4], Leonard Nafuma (Deceased)[5], Mary N. Koech[2], Jacob Ademba[4] and Erastus M. Kitonyo[1]

[1]KALRO-Kabete, P.O. Box 14733- 00800, Nairobi
[2]KALRO-Kitale, P.O. Box 450-30200, Kitale
[3]KALRO-Muguga, P.O. Box 32- 0902, Kikuyu
[4]KALRO-Kisii, P.O. Box 523-40200, Kisii
[5]KALRO-Njoro, Private Bag 20-107, Njoro

7.1 Agricultural systems of Kenya

7.1.1 Introduction

Agriculture is essential for sustainable development, poverty reduction and enhanced food security in many sub-Saharan African (SSA) countries. The economic pillar of Kenya's Vision 2030 Strategy puts the agricultural sector among the six key growth drivers of the economy (GoK 2014). Agricultural productivity contributes about 30% to its Gross Domestic Product (GDP) and 60% to foreign exchange earnings. About 75% of Kenya's population of approximately 42 million works in the agricultural sector. Only about one third of Kenya's total land area, from the Kenyan highlands, the coastal plains and the lake region, is used for crop production (Fig. 7.1). The rest of the land area, which is semi-arid to arid, is used for pastoralism.

7.1.2 Agro-ecological zones (AEZ)

The zonation most used in Kenya for economic planning and agricultural development is by Jaetzold and Schmidt (1983). Kenya is divided

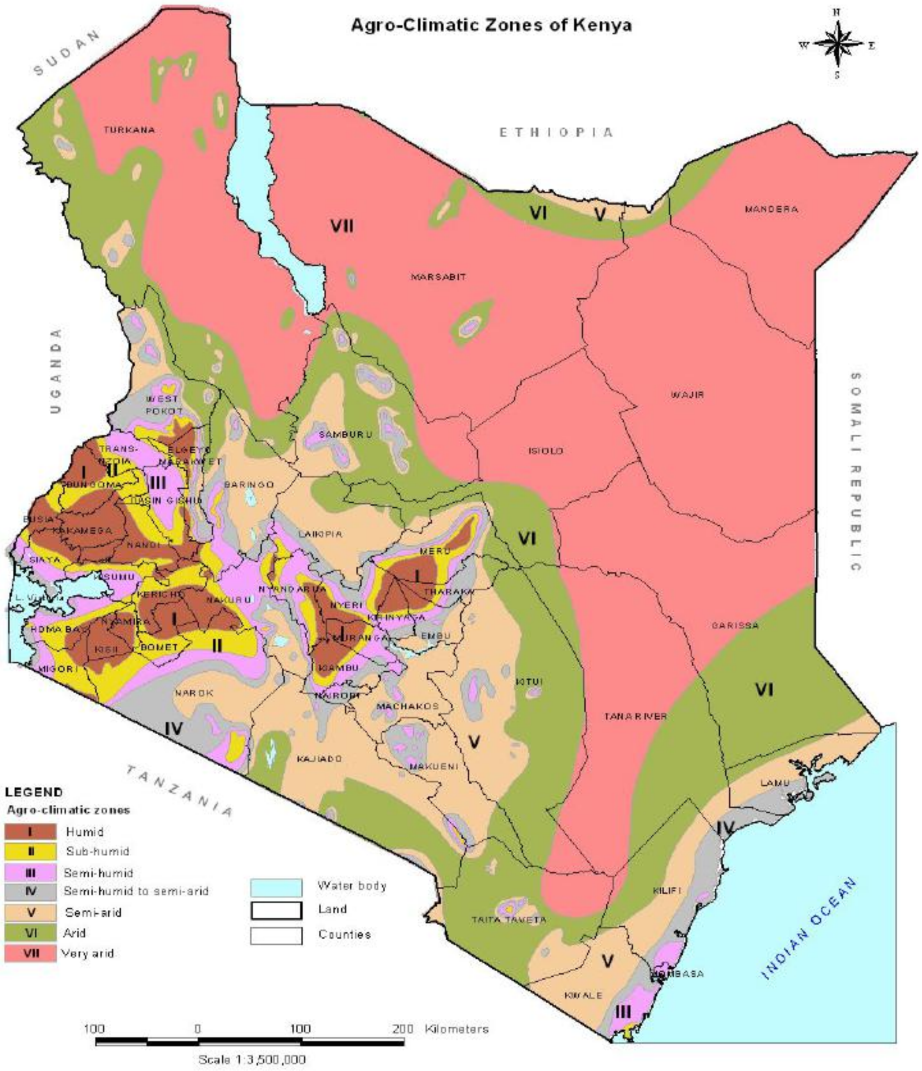


Figure 7.1: Agro-ecological zones (AEZ) of Kenya (Source: Kenya Soil Survey 2007).

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

Table 7.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Kenya for year 2015

	J	F	M	A	M	J	J	A	S	O	N	D
Eastern Upper												
Rainfall	27	26	113	278	164	32	29	38	41	171	234	53
Tmax	29	30	32	31	29	27	26	26	29	30	29	28
Tmin	10	10	11	10	10	9	9	9	10	10	10	9
Eastern Lower												
Rainfall	39	29	65	120	28	3	1	1	3	39	192	99
Tmax	35	37	37	35	34	32	31	31	34	36	35	34
Tmin	12	12	12	12	11	11	10	10	11	12	12	11
Central												
Rainfall	44	50	94	212	167	50	18	27	29	65	145	88
Tmax	27	28	27	25	24	22	22	22	25	26	25	25
Tmin	12	13	14	15	14	12	11	11	12	13	14	13
Rift Valley Upper												
Rainfall	20	30	63	121	148	86	79	92	88	69	78	49
Tmax	28	28	29	29	27	27	26	26	26	27	26	27
Tmin	9	9	10	10	9	9	9	9	9	9	9	9
Rift Valley Lower												
Rainfall	85	80	96	152	94	34	22	21	26	32	71	84
Tmax	26	26	27	27	26	23	23	23	25	26	25	25
Tmin	9	9	9	9	**9**	**8**	**8**	**8**	8	9	8	9
Western Upper												
Rainfall	28	57	91	162	187	107	139	168	105	99	89	37
Tmax	28	30	30	29	28	27	26	27	27	28	28	28
Tmin	10	10	10	10	10	9	9	9	9	9	9	9
Western Lower												
Rainfall	105	190	297	292	111	99	156	169	158	179	87	29.3
Tmax	30.0	30.4	30.0	28.7	27.9	27.4	27.2	27.7	27.0	29.1	28.4	29.3
Tmin	15.9	15.7	15.7	16.5	16.3	15.8	15.6	15.5	14.7	16.0	15.9	15.8
Coastal												
Rainfall	34	16	56	153	223	87	69	64	68	103	105	75
Tmax	41	42	43	41	39	37	36	36	37	39	40	41
Tmin	14	14	14	14	13	12	12	12	12	13	13	14

into seven agro-climatic zones using a moisture index (Sombroek et al. 1982) based on annual rainfall expressed as a percentage of annual potential evaporation (Figure 7.1).

The humid highlands, with a moisture index greater than 50% and with high potential for crop production, are designated as Zone I (humid with a moisture index of >80% and annual rainfall of 1100-2700 mm), Zone II (sub-humid with a moisture index of 65-80% and annual rainfall of 1000 -1600 mm) and Zone III (semi-humid with a moisture index of 50-65% and annual rainfall of 800-1400 mm). Together they account for 12% of the land area. The remaining land has a moisture index of less than 50% and a mean annual rainfall

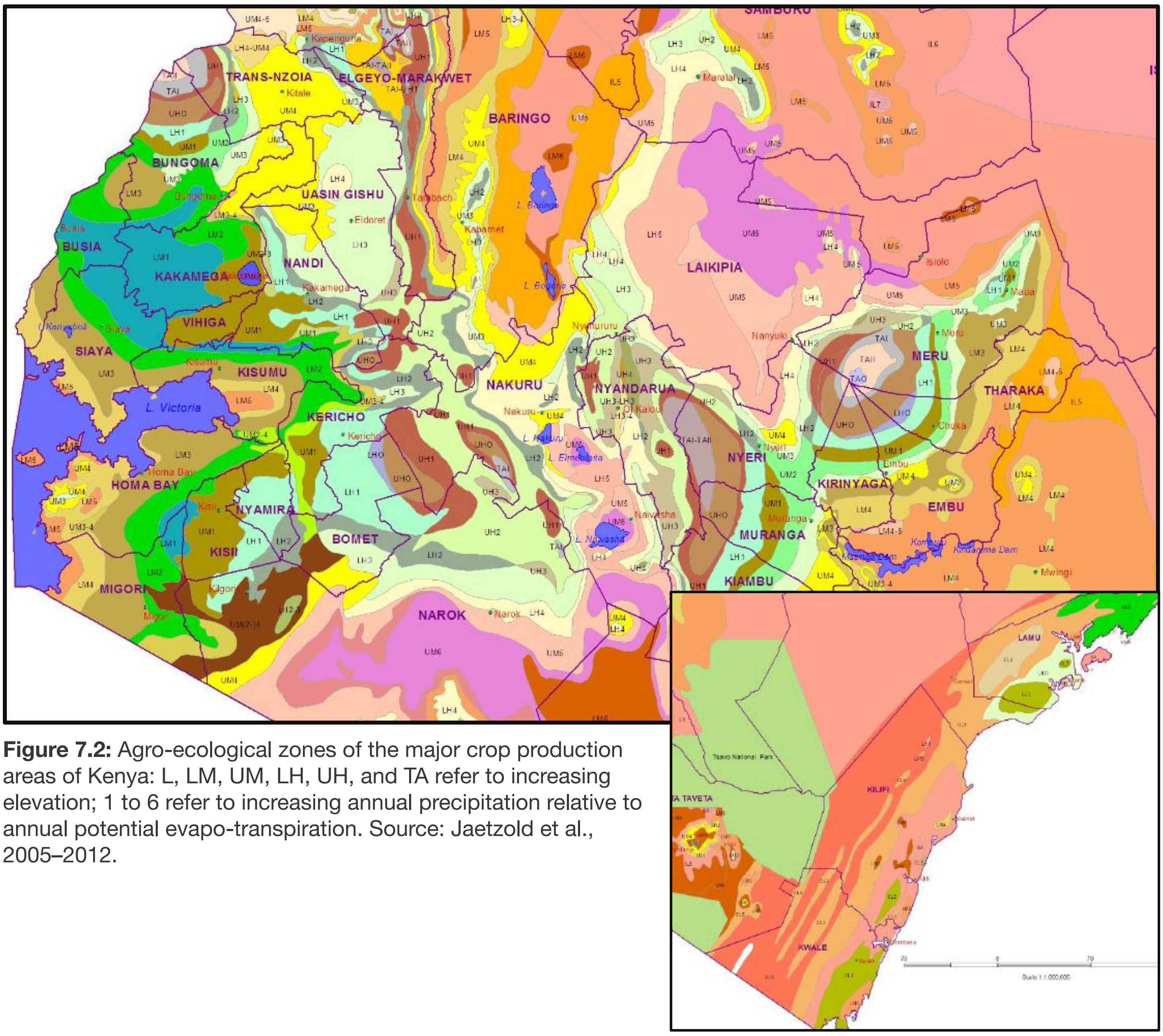


Figure 7.2: Agro-ecological zones of the major crop production areas of Kenya: L, LM, UM, LH, UH, and TA refer to increasing elevation; 1 to 6 refer to increasing annual precipitation relative to annual potential evapo-transpiration. Source: Jaetzold et al., 2005–2012.

of less than 1100 mm, including Zone IV (the semi-humid to semi-arid transitional zone), Zone V (semi-arid), Zones VI (arid) and VII (very arid). These four zones are generally referred to as the Kenyan rangelands and account for 88% of the land area, which is mainly used for livestock rearing.

The seven agro-climatic zones are further sub-divided according to mean annual temperature to identify areas suitable for growing each of Kenya's major food and cash crops (Figure 7.2). Most of the high and medium potential areas, representing about 70% of the agricultural land, are located at an altitude of 1000 to 2800 m above sea level (masl) with mean annual temperatures ranging from 10-24°C (Jaetzold and Schmidt 1983). The dominant agricultural soils are Ferralsols, Vertisols, Acrisols, Lixisols, Luvisols and Nitisols (Jaetzold and Schmidt 1983).

The Tropical Alpine (TA) environments are humid highlands above 2800 masl with an average temperature of 2-10°C and an annual rainfall of 1100-2700 mm with a moisture index of >80% (Table 7.1). The natural vegetation is evergreen rainforest. The main agricultural activities include husbandry of sheep and cattle at the lower altitudes. The AEZ is comprised mainly of forest reserves and national parks.

The Upper Highlands (UH1 and UH2) or Sub-Humid Highlands at 2350 to 2800 masl has mean annual temperatures of 10-15°C, annual rainfall of 900 to 1600 mm with one or two dry months and a moisture index of 65-80%. These areas have underlying volcanic rocks with loamy soils and include the highlands east and west of the Rift Valley including the Rift Valley bottom. The natural vegetation is seasonal rainforest. The major crops include maize, wheat, pyrethrum, Irish potato, kale, cabbage and temperate fruits. Crops are slow to mature due to low temperature. Sheep and dairy cattle are major livestock enterprises and are grazed on natural pastures of Kikuyu grass. In some regions, the AEZ has forest reserves and national parks.

The Lower Highlands (LH) or Semi-humid Highlands are highly productive lands at 2000-2350 masl with an average temperature of 15-18°C, an annual rainfall of 900-1600 mm and a moisture index of 50-65%. The AEZ covers about 30% of the arable land. The natural vegetation corresponds to seasonal semi-deciduous moist forest or tall grass-broad-leaved trees savanna. The major agricultural activities include maize, wheat, barley, seed maize, tea, kale and cabbage. Dairy cattle and sheep are the main livestock enterprises.

The Upper Midlands (UM) are semi-humid to semi-arid, very productive and occupy about 5% of the total land area. It is at 1500-2000 masl with an average temperature of 18-21°C, an annual rainfall of 600-1350 mm and a moisture index of 40-50%. The original vegetation was deciduous woodland. The main agricultural enterprises include maize, maize-bean intercrop, sunflower, wheat, sweet potato, finger millet, sorghum, kale and cabbage. Crop residues are fed to dairy cattle and sheep.

The Lower Midlands (LM) are semi-arid lands of 1000-1500 masl with an average temperature of 21-24°C, annual rainfall ranging from 450-900 mm and a moisture index of 25-40%. The agriculture is a mix of livestock and crop production. The AEZ occupies about 15% of the total land area. The main agricultural enterprises are rainfed maize, sorghum, millet, cassava, bean, pigeonpea, cowpea, green gram, groundnut, citrus and mango. Banana is produced under furrow irrigation. Livestock types include cattle, goats, sheep, camels, donkeys and bees while forages used include acacia and grasses. The major soil types are Luvisols, Acrisols and Vertisols.

The Inner Lowlands (IL) are arid and very arid lands at 750-1000 masl with an average temperature of more than 24°C, less than 550 mm/yr of rainfall and a moisture index of 15-25% or less. The area occupies about 66% of Kenya's land area and is not suitable for rainfed crops. It is important for goats which are grazed on acacia and grasses but is commonly overgrazed resulting in land degradation.

The Coastal Lowlands (CL) include the Kenyan coastlands which have well-drained sandy soils with a loamy, sandy clay texture and other humid lowlands of less than 1500 masl, such as the Taita Hills with fertile loamy soils and the Tana and Sabaki river valleys with alluvial soils (silts). The coastal lands are characterized by sand dunes and mangrove swamps with deep, grey, saline and poorly drained soils which are not suitable for crop production.

7.2 Soil fertility management

Most of the agricultural soils in Kenya have inherently low soil fertility, low soil moisture retention and high erodibility, but have been intensively farmed by smallholders. There has been a general decline in crop and pasture yields, soil physical properties, vegetation cover and biological diversity but an increase in noxious weeds. The most critical limiting nutrients are N and P while K, S and some micronutrient deficiencies are often diagnosed.

Soil fertility research in East Africa began in the 1930s and addressed the restoration of soil fertility through the combined use of vegetative fallows and animal manures. Traditional farming systems in sub-Saharan Africa were supported by shifting slash-and-burn cultivation, a low input sustainable agricultural farming system that allowed for several years of native vegetative and woody plant growth that resulted in nutrient cycling, restoration of soil organic matter, and improved soil physical properties to restore soil productivity. However, population growth has increased demand for food, feeds and fuel which has led to decreased fallow with resultant soil fertility decline.

Manure is commonly used by most smallholders who practise mixed crop-livestock farming especially in maize, potatoes and vegetables but its widespread usage is limited by low availability. Other organic materials used are liquid manure, composts, green manures, crop residues and municipal wastes (Gachene and Kimaru 2003). Other sources of replenishment included use of rotation with grain legumes, cereal-legume intercropping systems, mulch, agroforestry trees for litter fall and shifting livestock holding pens periodically.

Substantial research in soil fertility status and restoration was carried out under the Fertilizer Use Recommendation Project (FURP) (1987-1993), which resulted in 24 district-based fertilizer recommendations for major crops including maize, sorghum, bean, cowpea, finger millet and other crops.

Other uncoordinated fertilizer use studies in various parts of the country have given rise to numerous fertilizer use practices targeting maize, which include soil nutrient replenishment with rock phosphate (PREP), fortified composting (COMP), relay intercropping with *Lablab purpureus* (LABLAB), staggered-row intercropping (MBILI, an acronym for managing beneficial interactions in legume intercrops) and short-term improved *Crotolaria grahamiana* fallows (IMPFAL).

Most fertilizer is applied to maize, rice and horticultural crops in Kenya (GoK 2014). Fertilizer use in these and other crops is still low. For example, Kenyan farmers apply an average of 50 kg/ha of nutrients to maize compared to 125, 180 and 300 kg/ha in South America, India and the European Union, respectively (Ariga and Jayne 2010; Jama et al. 2013).

Agro-ecological potential affects fertilizer use decisions with much more fertilizer applied to maize in the high-potential areas compared with the semi-arid areas, such as the lower eastern region where fertilizer used is often unprofitable for farmers unless highly subsidized (Ariga et al. 2008). Fertilizer price levels, household income and education level of the household head also affect fertilizer use.

The main fertilizer types used for maize production are calcium ammonium nitrate, urea, compound fertilizers like diammonium phosphate (DAP) and ammonium sulphate, and NPK blends such as 23:23:0 and 17:17:17.

Fertilizer is a costly input to crop production and efficient use is needed to improve profitability, minimize loss of nutrients to the environment and reduce soil acidification due to N application.

The 4Rs of nutrient management are important, that is to apply the right product, the right rate, at the right time and using the right method. This is especially important for N, which is easily lost, e.g. most of the fertilizer nitrogen should be applied at the start of and/or during the period of rapid crop growth when the rate of N uptake is high and N should be incorporated to minimize ammonia volatilization. With maize, for example, this means that at least 50% of the fertilizer N should be applied six weeks after planting (6 WAP). However, when the recommended rate of N is low, it is advisable to apply all at 6 WAP. Fertilizer N should not be applied during dry periods. Also important to good response to fertilizer is to have a healthy and well managed crop with good choice of variety, timely planting, and good weed and pest control.

7.3 Diagnosis of soil nutrient deficiencies

In the Optimizing Fertilizer Recommendations in Africa (OFRA) project, 37 trials were conducted for various crops in four regions of Kenya. The mean responses to N, P and K across these trials were 39, 5 and 17%, respectively. Treatments were included to compare the diagnostic package of N+P+K+Mg+S+Zn+B with a treatment with the same N, P, and K rates for effect on grain yield. Any yield increase with the diagnostic treatment would indicate that deficiency of Mg, S, Zn and/or B may limit yield at that location. The mean yield increase was 10% in Rift Valley upper region, but mean effect of the diagnostic treatment was not different from zero in the other regions (Figure 7.3). Further investigation is needed to determine which nutrient is most deficient in the Rift Valley upper region such as with more nutrient specific trials and/or foliar tissue analysis.

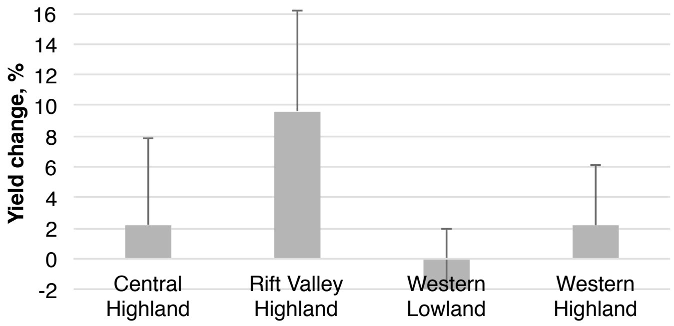


Figure 7.3: Yield change (%) due to secondary and micro-nutrient (diagnostic treatment) application in OFRA trials.

7.4 Optimizing fertilizer use in Kenya

Crop response to fertilizer application tends to be curvilinear to plateau with positive yield

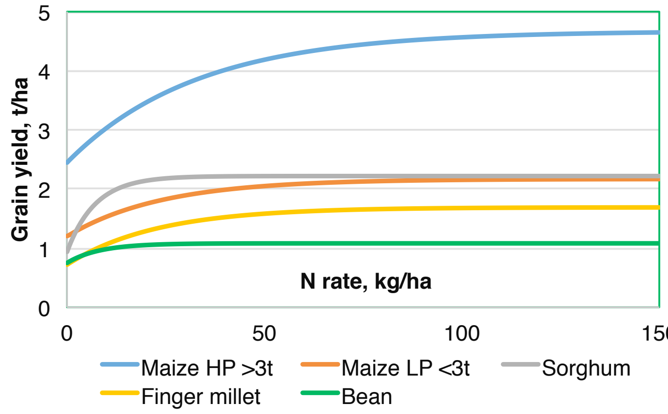


Figure 7.4: The curvilinear to plateau yield responses of five crops to fertilizer N in the Central Highlands of Kenya. HP and LP refer to high and low potential maize production situations

increases until a plateau (Fig. 7.4). Exceptions do occur as when the response is linear or when crop yield declines at high application rates. However, over many trials, curvilinear to plateau functions, such as the Mitscherlich 1909 function, capture crop response well.

Response functions can be derived using a simple asymptotic function: Yield = $a - bc^r$ where a is near maximum yield, b is gain in yield due to nutrient application, c determines the shape of the curve and r is the nutrient application rate.

The nature of the curvilinear response varies as in Fig 7.4 for five crops produced in the Central Region with differing responses to applied N. The magnitude of yield increase is relatively great for high potential (HP > 3 t/ha grain yield expected) maize but more gradual compared with some of the other displayed responses and continuing to relatively high N rates. In contrast, sorghum shows a substantial but steep response to N and is near the plateau with only 25 kg/ha N applied. Bean also has a steep response and a >40% yield increase with a very low N rate. Finger millet and low potential (LP < 3 t/ha grain yield expected) maize have similar magnitudes and shapes of response although maize has the higher yield potential. In all cases, there is a relatively steep yield increase with increasing N rate at low N rates and a reduced rate of yield increase at higher rates until yield reaches a plateau with no more yield increase. Therefore, the benefit to cost ratio of fertilizer use is expected to be greater at relatively low application rates.

Another aspect of the economics of fertilizer use for financially constrained fertilizer use is that some nutrients applied to some crops

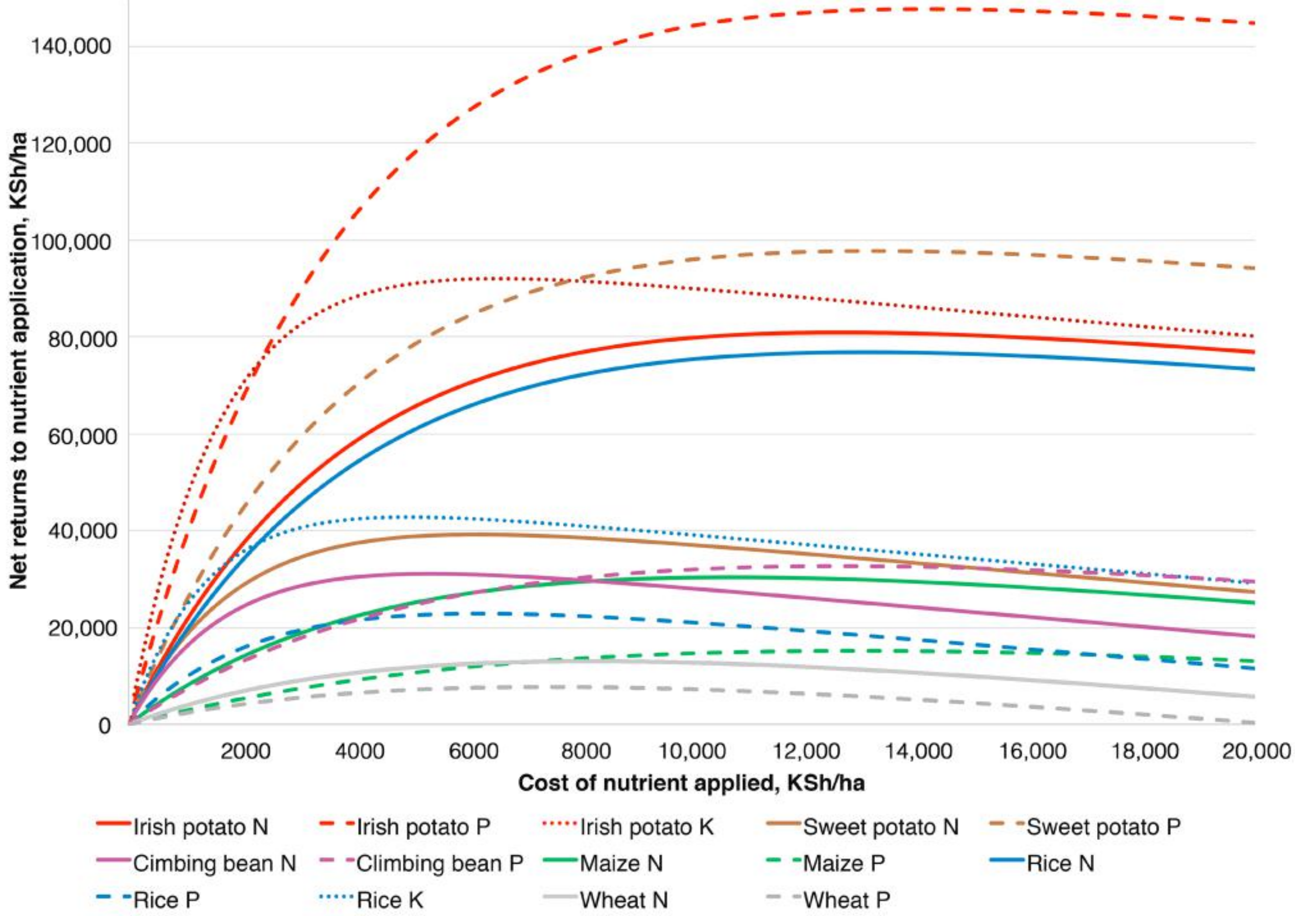


Figure 7.5: Net returns to investment in nutrient application in Western Kenya (>1400 masl).

have more profit potential than other nutrients applied to the same or other crops (Figure 7.5). The amount of money invested in one nutrient applied to one crop is on the x-axis. The y-axis shows net returns to investment for the nutrient applied. For each curve, the profit potential of the nutrient applied to a crop is displayed. The steeper the curve, the higher the net rate of return to investment. The slope decreases with higher investments, but profit is increasing if the slope is still upward. At the peak of a curve, the point of maximum profit per hectare is reached; this rate is often referred to as the economically optimum rate (EOR).

In this example from western Kenya, the expected yield increases are especially substantial for P and K applied to Irish potato and P applied to sweet potato, indicating these two options to have the most profit potential for a limited investment in fertilizer use (Table 7.2e). Nitrogen applied to Irish potato, rice, sweet potato and climbing bean, and K applied to rice also have high profit potential, at least at low rates of application. The lower curves represent profit potential but less potential compared with the upper curves with current commodity prices and fertilizer costs, and should be addressed by financially constrained farmers only after the more profitable options are addressed. Therefore, the choice and rate of nutrients applied to a crop is very important to fertilizer use profitability.

Table 7.2a: Central Highlands of Kenya. Response functions coefficients (col. 3-5), expected yield increases (t/ha) for crop-nutrient increments (col. 6-9), and OFRA economically optimal rate (EOR) to maximize profit per hectare (col 10) compared to current or recent (REC) recommendations (col. 11). P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
		t/ ha			**Yield increase t/ ha**				**kg/ ha**	
Maize HP >5t	N	6.558	1.633	0.963	1.106	0.357	0.115	0.037	67	75
Maize LP <5t	N	4.061	1.242	0.961	0.865	0.262	0.080	0.024	58	75
Bean	N	0.955	0.125	0.798	0.125	0.000	0.000	0.000	12	NA
Maize-bean	N	5.210	1.830	0.960	0.338	0.275	0.225	0.183	66	75
Rice, lowland	N	5.248	2.397	0.967	1.522	0.556	0.203	0.074	104	NA
Wheat HP >3t	N	3.922	1.232	0.968	0.768	0.289	0.109	0.041	70	NA
Wheat LP <3t	N	2.563	1.160	0.969	0.710	0.276	0.107	0.042	69	NA
					0-5	**5-10**	**10-15**	**15-20**		
Maize HP >5t	P	3.762	0.281	0.934	0.191	0.166	0.144	0.125	16	11
Maize LP <5t	P	4.078	0.683	0.940	0.182	0.133	0.098	0.072	23	11
Bean	P	0.990	0.185	0.867	0.094	0.046	0.023	0.011	16	NA
Maize-bean	P	4.860	0.810	0.890	0.358	0.200	0.112	0.062	19	0
Rice, lowland	P	5.395	0.572	0.885	0.261	0.142	0.077	0.042	22	NA
Wheat HP >3t	P	4.000	0.671	0.941	0.176	0.130	0.096	0.071	26	NA
Wheat LP <3t	P	2.048	0.437	0.94	0.116	0.085	0.063	0.046	19	NA
Wheat	K	3.763	0.282	0.934	0.081	0.058	0.041	0.029	22	NA
Rice	K	6.253	0.984	0.898	0.409	0.239	0.140	0.082	35	NA

† EOR was determined with the cost of using 50 kg urea and DAP at KSh 2850 and 3600, respectively. Commodity values (KSh/kg) used were: rice 50; maize 25; bean 60; wheat 30; green gram 90; cowpea 50; groundnut unshelled 50; soybean 30; finger millet 50; cassava 30; sorghum 30; Irish potato 30; sweet potato 30; banana 30. NA - data not available.

‡ Fermont et al. (2010)

7.5 Crops targeted for optimization by region

The OFRA determined crop-nutrient response functions for important food crops and applied the functions in development of fertilizer use optimization tools (FOTs). Priority crops for different regions were chosen: maize, bean, Irish potato, lowland rice and wheat were common in most regions while banana, sweet potato, cowpea, green gram, sorghum and finger millet were selected for one or more regions (Table 7.2a-h).

Irish potato, lowland rice, green gram, soybean and wheat are mainly grown as sole crop in all the regions. However, maize-bean intercropping is common. Finger millet and sorghum, commonly grown in Rift Valley and Western regions, are grown on small land areas during the short rains due to high labour requirement.

In the Central Highlands (LU and UM), all crops except for bean had large responses to applied N with most of the yield gain with 30 kg/ha N applied and not much additional gain with more than 60 kg/ha applied (Table 7.2a). There were also good responses to applied P and not much response to applying P beyond the 10 kg/ha rate.

The available field research results did not show any of these crops to be generally responsive to applied K and Zn which agrees with the results of the diagnostic treatments (section 7.3). For the Central Highlands, the EOR compared with REC were lower for N but higher for P.

In the Coastal Lowlands, all crops responded well to applied N and P (Table 7.2b). Cassava yield increases were high with N, P and K applied. Cowpea responded to applied N and more so to applied P. Maize and cowpea had responses to applied K. The EOR compared with REC were lower for N applied to maize but higher for N applied to cassava, finger millet and sorghum, and lower for P and K rates. In six cases, EOR were determined from field research results where RECs were missing.

Table 7.2b: Coastal Lowlands

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
		t/ ha			**Yield increase t/ ha**				**kg/ ha**	
Cassava	N	41.361	12.546	0.972	7.194	3.069	1.309	0.558	151	100‡
Maize HP >3t	N	4.374	2.130	0.980	0.968	0.528	0.288	0.157	90	150
Maize LP <3t	N	2.056	0.399	0.950	0.313	0.067	0.014	0.003	28	75
Rice, lowland	N	4.569	1.868	0.985	0.681	0.433	0.275	0.175	159	NA
Sorghum	N	3.993	1.436	0.974	0.785	0.356	0.162	0.073	84	50
Finger millet	N	1.692	1.003	0.961	0.699	0.212	0.064	0.019	70	0
Cowpea	N	1.222	0.382	0.920	0.351	0.029	0.002	0.000	31	NA
					0-5	**5-10**	**10-15**	**15-20**		
Cassava	P	25.905	6.787	0.882	3.164	1.689	0.902	0.481	37	22‡
Maize HP >3t	P	2.815	1.113	0.914	0.403	0.257	0.164	0.105	26	66
Maize LP <3t	P	2.815	1.113	0.914	0.403	0.257	0.164	0.105	26	33
Rice, lowland	P	3.773	0.862	0.875	0.420	0.215	0.110	0.057	24	NA
Sorghum	P	3.590	1.178	0.891	0.516	0.290	0.163	0.091	24	0
Finger millet	P	1.776	0.221	0.8	0.149	0.049	0.016	0.005	10	50
Cowpea	P	1.495	0.702	0.9	0.287	0.170	0.100	0.059	26	NA
Cassava	K	29.171	8.9499	0.878	4.280	2.233	1.165	0.608	43	83‡
Maize	K	3.143	0.177	0.911	0.066	0.041	0.026	0.016	13	NA
Cowpea	K	1.110	0.168	0.850	0.093	0.041	0.018	0.008	15	NA

In the Eastern Upper region (LM and UM), all crops except bean had large responses to N, with the highest yield gain occurring with 30 kg/ha N applied while application of N above 60 kg/ha gave less yield increments (Table 7.2c). Responses to applied P occurred in lower P application rates (up to 10 kg/ha). In this region, high responses to applied K only occurred in bananas, Irish potato and lowland rice. Bananas had the highest responses to K application, with high yield gains when 20 kg/ha was applied. The EOR compared with REC were lower for N applied to Irish potato and maize but higher for N applied to banana. The EOR compared with REC was inconsistent for P but EOR were higher than REC for K.

Table 7.2c: Eastern Upper (>1200 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
			t/ ha			**Yield increase t/ ha**			**kg/ ha**	
Banana	N	46.500	7.900	0.896	7.607	0.282	0.010	0.000	49	0
Irish potato	N	12.378	3.960	0.952	3.055	0.698	0.160	0.036	78	150
Maize HP	N	5.398	1.679	0.964	1.120	0.373	0.124	0.041	69	75
Maize LP	N	2.410	0.770	0.875	0.756	0.014	0.000	0.000	23	75
Rice, lowland	N	5.030	1.612	0.981	0.705	0.397	0.223	0.125	132	NA
Bean	N	0.940	0.086	0.8	0.086	0.000	0.000	0.000	10	NA
					0-5	**5-10**	**10-15**	**15-20**		
Banana	P	24.531	1.681	0.874	0.824	0.420	0.214	0.109	25	33
Irish potato	P	16.195	5.289	0.903	2.113	1.269	0.762	0.457	41	33
Maize HP	P	5.680	1.280	0.940	0.341	0.250	0.183	0.135	34	33
Maize LP	P	2.609	0.709	0.940	0.189	0.138	0.102	0.075	24	33
Rice, lowland	P	5.241	2.329	0.964	0.390	0.325	0.270	0.225	32	NA
Bean	P	0.997	0.187	0.860	0.099	0.047	0.022	0.010	13	9
Banana	K	38.200	9.750	0.913	3.565	2.261	1.435	0.910	59	0
Irish potato	K	14.158	2.190	0.913	0.801	0.508	0.322	0.204	42	0
Rice, lowland	K	6.187	0.89	0.873	0.439	0.222	0.113	0.057	28	0

Table 7.2d: Eastern Lower (<1200 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC ‡**
			t/ ha			**Yield increase t/ ha**			**kg/ ha**	
Maize	N	2.260	1.135	0.945	0.927	0.170	0.031	0.006	45	60
Bean	N	1.000	0.500	0.899	0.479	0.020	0.001	0.000	31	NA
Sorghum	N	2.050	0.000	0.000	0.000	0.000	0.000	0.000	0	NA
Irish potato	N	39.444	16.914	0.949	13.397	2.786	0.579	0.120	102	NA
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.027	0.079	0.885	0.036	0.020	0.011	0.006	0	NA
Bean	P	1.140	0.350	0.824	0.217	0.082	0.031	0.012	14	NA
Sorghum	P	2.500	0.207	0.750	0.158	0.037	0.009	0.002	7	NA

Table 7.2e: Western Upper (>1400 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases			Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	EOR†	REC ‡
		t/ ha			Yield increase t/ ha			kg/ ha	
Maize	N	5.290	1.830	0.974	1.000	0.454	0.206	86	60
Irish potato	N	12.899	3.898	0.969	2.383	0.927	0.360	108	90
Sweet potato	N	9.750	1.577	0.938	1.346	0.197	0.029	50	0
Rice, lowland	N	5.006	1.882	0.971	1.104	0.456	0.189	106	NA
Maize-bean	N	7.360	2.530	0.970	1.533	0.605	0.239	90	75
Climbing bean	N	2.293	0.636	0.931	0.562	0.066	0.008	43	0
Wheat	N	3.521	0.871	0.975	0.464	0.217	0.102	66	NA
					0-5	5-10	10-15		
Maize	P	5.396	1.496	0.962	0.263	0.217	0.179	36	26
Irish potato	P	16.095	5.517	0.908	2.112	1.303	0.805	43	33
Sweet potato	P	13.257	3.828	0.912	1.413	0.891	0.562	42	0
Rice, lowland	P	5.487	0.631	0.863	0.329	0.157	0.075	16	NA
Maize-bean	P	7.280	1.790	0.890	0.790	0.441	0.246	26	22
Climbing bean	P	2.199	0.852	0.940	0.227	0.166	0.122	41	NA
Wheat	P	4.000	0.700	0.940	0.186	0.137	0.100	27	NA
Irish potato	K	16.881	3.338	0.913	1.220	0.774	0.491	47	0
Rice, lowland	K	6.253	0.983	0.902	0.396	0.236	0.141	31	0

Table 7.2f: Western Lower (<1400 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC ‡
		t/ ha			Yield increase t/ ha				kg/ ha	
Maize HP >3t	N	4.672	2.224	0.970	1.332	0.534	0.214	0.086	86	70
Maize LP <3t	N	2.170	0.970	0.959	0.694	0.198	0.056	0.016	50	60
Sorghum	N	2.220	1.281	0.870	1.261	0.019	0.000	0.000	27	NA
Finger millet	N	1.691	0.969	0.957	0.710	0.190	0.051	0.014	26	NA
Bean	N	1.082	0.331	0.885	0.322	0.008	0.000	0.000	24	NA
					0-5	5-10	10-15	15-20		
Maize HP >3t	P	4.310	0.848	0.940	0.226	0.166	0.121	0.089	27	NA
Maize LP <3t	P	2.624	0.744	0.940	0.198	0.145	0.107	0.078	25	NA
Sorghum	P	2.272	1.072	0.750	0.818	0.194	0.046	0.011	13	NA
Finger millet	P	1.776	0.221	0.800	0.149	0.049	0.016	0.005	10	NA
Bean	P	0.730	0.180	0.840	0.105	0.044	0.018	0.008	12	NA
Groundnuts, unshelled	P	1.230	0.288	0.904	0.114	0.069	0.042	0.025	14	NA
Maize	K	3.878	0.209	0.934	0.060	0.043	0.031	0.022	15	NA
Bean	K	2.117	0.264	0.889	0.118	0.065	0.036	0.020	23	NA
Groundnut	K	1.391	0.151	0.890	0.067	0.037	0.021	0.012	17	NA

Table 7.2g: Rift Valley Upper (>2000 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC ‡
		t/ ha			Yield increase t/ ha				kg/ ha	
Maize HP	N	7.490	2.640	0.903	2.516	0.118	0.006	0.000	39	75
Maize LP	N	3.700	0.200	0.886	0.195	0.005	0.000	0.000	13	75
Irish potato	N	10.883	2.342	0.988	0.712	0.495	0.345	0.240	159	0
Bean	N	0.783	0.122	0.963	0.744	0.027	0.009	0.003	21	0
Wheat	N	6.147	1.562	0.976	0.808	0.390	0.188	0.091	91	NA
Maize-bean	N	5.770	1.490	0.990	0.530	0.342	0.221	0.142	110	50
Green gram	N	1.159	0.324	0.860	0.320	0.003	0.000	0.000	20	0
					0-5	**5-10**	**10-15**	**15-20**		
Maize HP	P	6.087	0.738	0.904	0.292	0.177	0.107	0.064	20	0
Maize LP	P	4.663	0.792	0.990	0.039	0.037	0.035	0.033	0	NA
Irish potato	P	10.303	1.103	0.857	0.593	0.274	0.127	0.059	20	33
Bean	P	0.793	0.122	0.630	0.110	0.011	0.001	0.000	7	0
Wheat	P	6.859	1.104	0.809	0.721	0.250	0.087	0.030	16	NA
Maize-bean	P	6.542	1.084	0.887	0.489	0.268	0.147	0.081	21	17
Green gram	P	1.260	0.542	0.700	0.451	0.076	0.013	0.002	12	0

Table 7.2h: Rift Valley Lower (<2300 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC ‡
		t/ ha			Yield increase t/ ha				kg/ ha	
Maize	N	5.717	1.084	0.969	0.663	0.258	0.100	0.039	61	75
Irish potato	N	25.748	8.936	0.948	7.135	1.438	0.290	0.058	46	NA
Bean	N	1.218	0.112	0.899	0.107	0.004	0.000	0.000	16	NA
Wheat	N	2.825	0.838	0.952	0.646	0.148	0.034	0.008	47	NA
Maize-bean	N	6.870	1.670	0.970	1.077	0.382	0.135	0.048	76	50
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	6.564	1.109	0.898	0.461	0.269	0.157	0.092	23	NA
Soybean	P	1.012	0.157	0.878	0.075	0.039	0.020	0.011	7	NA
Irish potato	P	24.027	6.868	0.919	2.366	1.551	1.017	0.666	50	33
Bean	P	1.207	0.185	0.800	0.124	0.041	0.013	0.004	10	NA
Wheat	P	2.874	0.572	0.839	0.334	0.139	0.058	0.024	13	NA
Maize-bean	P	7.350	1.230	0.890	0.556	0.305	0.167	0.092	22	17
Green gram	P	1.301	0.601	0.803	0.400	0.134	0.045	0.015	11	NA
Maize	K	6.518	0.835	0.835	0.496	0.201	0.082	0.033	18	NA
Maize-bean	K	7.300	0.960	0.890	0.432	0.237	0.130	0.071	25	NA

In the Eastern Lower (LM) zone, all crops except sorghum had responses to applied N with more of the yield gain from application of 30 kg/ha N and small increases with applications beyond 60 kg/ha (Table 7.2d). Higher responses to applied P were only found in beans and sorghum but the response was low beyond the 10 kg/ha rate. The results did not show any of the crops to be generally responsive to applied K, which agrees with the results of the diagnostic treatments (section 7.3). The EOR compared with REC were lower for N applied to maize. The EOR for N and P were determined for several crop that did not have EOR.

The Western Upper (LM and UM) zone had high responses to N in all the crops with the highest yield gain occurring with 30 kg/ha N applied and lesser yield gains when more than 60 kg/ha was applied (Table 7.2e). Responses to 10 kg/ha of P occurred for all crops with the great yield responses for Irish potato and sweet potato. Only Irish potato and lowland rice benefitted from added K (up to 10 kg/ha), but the other crops did not respond to K. The EOR compared with REC were high for N, P and K in the Western Upper Altitude zone. No RECs were available for lowland rice, climbing beans and wheat despite these crops having responses to nutrient addition.

The Western Lower (LM) zone had high responses to applied N in all crops with more of the yield gains from application of 30 kg/ha N and small yield increments with applications beyond 60 kg/ha (Table 7.2f). Groundnuts did not respond to N application, while beans required applications of of less than 30 kg/ha. All crops responded to applied P but response was small to P rates greater than 10 kg/ha. High responses at 15 kg/ha of K occurred in three crops, but yield gains were lower beyond 20 kg/ha. For Western Lower, the EOR compared with REC were high for N, P and K.

In the Rift Valley Upper (UH, LH) zone, there were high responses to applied N in all the crops with the 30 kg/ha application having the highest yield gain but lower yield gains at applications beyond 60 kg/ha (Table 7.2g). All the crops responded to applied P but at modest rates of up to 10 kg/ha. No response to K occurred in all the crops. For Rift Valley Upper, the EOR compared with REC were low for N applied to maize but high for N applied to Irish potato, bean, wheat and green gram, and low for P applied to Irish potato but high for P applied to other crops.

In the Rift Valley Lower (UM) zone, all crops except soybean and green gram had responses to applied N with more of the yield gain from application of 30 kg/ha and small yield increments with applications beyond 60 kg/ha (Table 7.2h). All crops responded to applied P but the response was small to rates above 10 kg/ha except for Irish potato that responded well up to 20 kg/ha of P. Responses to applied K only occurred in maize and maize-bean intercrops, with more yield gain from applications up to 10 kg/ha. The EOR rates were mainly less than the REC, but in most crops, EOR was determined in crops that had no RECs.

The EOR determined from field research results varied inconsistently compared with REC (Table 7.2a-h). For 49 crop-nutrients across the eight recommendation domains, field-research-based EOR were determined where the REC was not available or was 0 kg/ha. In all regions, all non-legumes had an economic response to applied N and most of the yield gain was achieved with 30 kg/ha applied, and little additional gain with more than 60 kg/ha applied (Table 7.2a-h). Similarly, in all regions, all crops had an economic response to applied P with the exceptions of Irish potato in Eastern and low-potential maize in the Rift Valley Region. Responses to K occurred in less than one-third of the cases and most often with Irish potato, rice, groundnut and banana. Due to financial constraints, farmers can expect higher benefit to cost ratios when applying at less than EOR, particularly in the low-potential areas where fertilizer use is considered risky (Ariga and Jayne 2010). The results indicate good profitability with some fertilizer use on most crops.

7.6 Fertilizer use optimization tools (FOT) for Kenya AEZ

Optimization of profit from fertilizer use requires good choice of nutrient rates for each crop. Response to applied nutrients of different crops of interest, amount of land allocated to different crops, value of the produce, cost of fertilizer used and the money available for fertilizer use need to be considered in optimizing fertilizer use for high profit.

Considering these complex factors, fertilizer use optimization tools (FOTs) were developed using Excel Solver© (Frontline Systems Inc., Incline Village, NV, USA). The Solver function in the FOTs uses complex mathematics of linear optimization in the integration of the farmer's economic and agronomic information with up to 28 crop-nutrient response functions to develop recommendations. The design makes the FOTs easy to use. The choice of crop-nutrient-rate combinations is expected, on average, to maximize returns on investment in fertilizer use.

Eight FOTs were developed for recommendation domains in Kenya and are available at http://agronomy.unl.edu/OFRA. To use a FOT, Solver needs to be added on in Excel and the macros need to be enabled; see the Help and Instructions worksheet of the FOT for instructions.

Data input requires the farmer to estimate how much land will be planted to each crop of interest under 'Area Planted, Ac'. Next, the on-farm value at harvest time per kg of the produce is determined, considering the value of that kept for home consumption and the value of marketed surplus, and entered under 'Expected Grain Value' (Figure 7.6). The cost of using different fertilizers, including purchase price and costs of transport and application, is entered under 'Price/ 50 kg fertilizer'. The farmer's available money for fertilizer use is also entered as the 'Budget Constraint'.

The results are given in three sections (Figure 7.7) including the amount of each fertilizer to apply to each crop, the expected average yield increases and net returns, and the expected average total net returns to fertilizer use for the farm.

Differences in net returns to fertilizer use by crop are revealing. In this example, fertilizer use with Irish potato is estimated to have very high returns. The farmer should not increase the amount of fertilizer applied per acre above the recommended amount but should consider allocating more land to Irish potato production while decreasing land for another crop with low net returns, realizing that the return to fertilizer use is only one factor in the total profitability of a crop.

A farmer investing KSh 50,000 in fertilizer for seven crops is expected to get an average total return on investment of about KSh 362,400. For a farmer with lower investment potential of KSh 10,000 with the same crops and land allocation, the expected average net returns decline to KSh 210,000. These are partial budget net returns to fertilizer investment, without considering other production costs. Due to seasonal variation in input output prices, access to current information on fertilizer prices and grain market prices are required to most accurately optimize fertilizer use recommendations for the current season.

Paper versions of all FOTs were developed for county extension officers, agro-dealers and farmers without easy access to computers (Table 7.3; available at http://agronomy.unl.edu/OFRA). These are easy to use but need to be updated, maybe annually, with major changes in fertilizer costs relative to commodity prices.

Paper FOTs are developed with the farmer's ability for fertilizer use divided into three financial levels: level 1) for a poor farmer who has no more than one-third the amount of money required to apply fertilizer to all cropland at EOR; level 2) for a farmer with more money but with no more than two-thirds the amount required to apply fertilizers to all cropland at EOR; and level 3) for the farmer with enough money to apply fertilizer to at least some cropland at EOR.

The paper FOTs advise on the 4Rs, i.e. right product, rate, time and method of application. Mode of calibration is also given for guiding the farmer to calibrate his/her sense of feel and visual impression of the correct rate, e.g. the length of the band or the number of holes per measuring unit. The paper FOTs assume that the farmer will use the Keringet brand water bottle lid which has a volume of 4 ml, or for broadcast application, a Keringet or Aqua brand water bottle cut at 4 cm high from the bottom which has a volume of 78 ml. These measuring units were selected because of easy availability in rural areas.

Consider the use of the paper FOT (Table 7.3). If the farmer has only a small amount of money for fertilizer use, he/she is likely to be in financial level 1. This level has recommendations for five of the seven crops as the profit potential for

AEZ Western
Elevation >1400

Producer Name:	
Prepared By:	
Date Prepared:	**July 6, 2016**

Crop Selection and Prices			
Crop	**Area Planted (Ac)***	**Expected Grain Value/kg †**	
Maize	1	25	
Irish potato	1	30	
Potato, sweet	1	30	
Rice, lowland	1	60	
Maize-bean	1	[redacted]	Enter grain values for maize and bean sole crop.
Beans, climbing	1	60	
Wheat	1	40	
Total	**7**		

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
P-mazao	10%	26%	10%	3250

Budget Constraint	
Amount available to invest in fertilizer	50,000

Figure 7.6: Input data options of crop prices and fertilizer costs in Upper western Region, Kenya.

Fertilizer Optimization					
	Application Rate - kg/Ac				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**P-ma**
Maize	43	0	61	0	0
Irish potato	59	0	61	31	23
Potato, sweet	16	5	61	0	0
Rice, lowland	61	0	43	27	0
Maize-bean	52	0	48	0	0
Beans, climbing	11	0	61	0	0
Wheat	37	0	55	0	0
Total fertilizer needed	280	5	388	58	23

Expected Average Effects per Ac		
Crop	**Yield Increases**	**Net Returns**
Maize	1,060	19,647
Irish potato	5,003	138,669
Potato, sweet	2,079	56,640
Rice, lowland	1,336	71,638
Maize-bean	1,621	34,090
Beans, climbing	534	27,044
Wheat	519	14,679

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	362,407

Figure 7.7: Output data of optimized fertilizer rates and returns to fertilizer investment in Upper Western Region, Kenya.

Table 7.3: An example of a paper tool

Western Kenya Upper (>1400 m) Fertilizer Use Optimizer

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 4 cm has approx. 80 ml to hold 56 g urea, and 88 g DAP and MOP.
Row spacing: maize, Irish potatoes, sweet potatoes and climbing bean have 75 cm; bean at 50 cm; wheat at 25cm.
Grain values per kg (Ksh): 25 maize, 30 Irish potatoes, 30 sweet potatoes, 50 rice, 60 bean, 30 wheat.
Cost of using 50 kg fertilizer (Ksh): 2850 urea; 3600 DAP; 3600 MOP.
Application rates are in kg/ac. Minimum rates are 10 kg/ac.

Level 1 financial ability.	
Maize HP (>3t)	at planting band 10 kg DAP (1 lid for 2.2 m)
Irish potato	at planting band 60 kg DAP (1 lid for 0.4 m) and 20 kg MOP (1 lid for 1 m)
Sweet potato	at planting band 39 kg DAP (1 lid for 0.6 m)
Maize-bean intercropping	at planting band 19 kg DAP (1 lid for 1.1 m) and sidedress by banding 15 kg urea at 6 WAP (1 lid for 0.9 m)
Climbing bean	at planting band 28 kg DAP (1 lid for 0.8 m)
Level 2 financial ability	
Maize HP (>3t)	at planting band 36 kg DAP (1 lid for 0.6 m) and sidedress by banding 26 kg urea at 6 WAP (1 lid for 0.5 m)
Irish potato	at planting band 61 kg DAP (1 lid for 0.3 m) and 30 kg MOP (1 lid for 0.8 m)
Sweet potato	at planting band 61kg DAP (1 lid for 0.3 m)
Rice, lowland	broadcast 25 kg DAP (one cut bottle for 6.7 m @ 2 m wide) and 20 kg MOP (one cut bottle for 5.6 m @ 2 m wide) at planting and sidedress by broadcast 51 kg urea (one cut bottle for 2.0 m @ 2 m wide) at panicle initiation
Maize-bean intercropping	at planting band 34 kg DAP (1 lid for 0.7 m) and sidedress by banding 35 kg urea at 6 WAP (1 lid for 0.4 m)
Climbing bean	at planting band 55 kg DAP (1 lid for 0.4 m)
Wheat	band at planting 19 kg DAP (1 lid for 3.5 m) and sidedress by banding 14 kg urea at panicle initiation (1 lid for 2.2 m)
Level 3 financial ability (maximize profit per acre).	
Maize HP (>3t)	at planting band 61 kg DAP (1 lid for 0.3 m) and sidedress by banding 52 kg urea at 6 WAP (1 lid for 0.25 m)
Irish potato	at planting band 61 kg DAP (1 lid for 0.3 m) and 30 kg MOP (1 lid for 0.7 m)
Sweet potato	at planting band 61kg DAP (1 lid for 0.3 m)
Rice, lowland	broadcast 45 kg DAP (one cut bottle for 3.7 m @ 2 m wide) and 28 kg MOP (one cut bottle for 1.8 m @ 2 m wide) at planting and sidedress by broadcast 61 kg urea (one cut bottle for 1.6 m @ 2 m wide) at panicle initiation
Maize-bean intercropping	at planting band 53 kg DAP (1 lid for 0.4 m) and sidedress by banding 58 kg urea at 6 WAP (1 lid for 0.25 m)
Climbing bean	at planting band 61 kg DAP (1 lid for 0.3 m) and sidedress by banding 14 kg urea at 6 WAP (1 lid for 1 m)
Wheat	band at planting 54 kg DAP (1 lid for 1.2 m or broadcast with cut bottle for 5 m) and sidedress by banding 37 kg urea at panicle initiation (1 lid for 1.1 m or broadcast with cut bottle for 2.9 m)

fertilizer use on wheat and lowland rice were inadequate to qualify for this financial level at the higher elevations of western Kenya. The recommendations for each crop in this level have somewhat similar potential for profit from fertilizer use. Therefore, the farmer can opt to use any or all of the options according to financial ability. If money for fertilizer is remaining, he/she may advance to one or more options in level 2.

One option in level 1 is 'For Irish potato, at planting band 60 kg DAP (1 lid for 0.4 m) and 20 kg MOP (1 lid for 1.0 m)'. Therefore, DAP and MOP fertilizers are to be applied to Irish potato at planting in a band passing near the row. The farmer calibrates him/herself to apply 60 kg/ac DAP by using the Keringet water bottle lid with one level full lid sufficient for 0.4 m of band. The calibration for the 20 kg/ac MOP is similarly done with one level full lid sufficient for 1.0 m of band. The instructions for all other options are also easy to follow.

Another aspect of optimizing fertilizer use is to account for the effects of other soil management practices and to consider soil test values. Organic inputs available at the farm level are generally inadequate to supply all the nutrients required, however, when used in combination with inorganic fertilizers, within the integrated soil fertility management (ISFM) framework, they improve crop productivity and profitability. Some of these materials include farmyard manure and composts, fresh vegetative materials such as tithonia and grevillea prunings, as well as green manures such as mucuna and Azolla.

Table 7.4 is a guideline to giving fertilizer substitution values to some common practices. For example, if the farmer applies 1 ton (dry weight) of low quality farmyard manure, this will substitute for about 5 kg urea, 3 kg DAP or TSP, and 2 kg KCl, or 10 kg NPK fertilizer during planting. On the other hand, if the previous crop was a green manure crop such as mucuna for maize and Azolla for lowland rice, then organic inputs substitute up to 100% of N and 70% of the P, K and NPK required for crop

Table 7.4: Fertilizer substitution guidelines using commonly available organic materials

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT CONTEXT

FERTILIZER SUBSTITUTION AND SOIL TEST IMPLICATIONS

ISFM practice	**Urea**	**DAP/TSP**	**KCl**	**NPK 17-17-17**
	Fertilizer reduction, % or kg/acre			
Previous crop was a green manure crop e.g. mucuna and crotalaria for maize or Azolla for lowland rice	100%	70%	70%	70%
Fresh vegetative material (e.g. prunings of *tithonia, Lantana camara, grevillea, Leucaena, Sesbania sesban,* banana leaves, coffee husks) per 1 t of fresh material	4 kg	2 kg	2 kg	8 kg
Farmyard manure per 1 t of dry material	5 kg	3 kg	2 kg	10 kg
Residual value of FYM applied for the previous crop, per 1 t	2 kg	1 kg	1 kg	3 kg
Dairy or poultry manure, per 1 t dry material	9 kg	4 kg	5 kg	16 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	2 kg	2 kg	1 kg	3 kg
Compost, per 1 t	8 kg	3 kg	3 kg	15 kg
Residual value of compost applied for the previous crop, per 1 t	3 kg	2 kg	1 kg	5 kg
Rotation	0% reduction but more yield expected			
Cereal-bean intercropping	Increase DAP/TSP by 7 kg/ac, but no change in N and K compared with sole cereal fertilizer			
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 11 kg/ac, reduce urea by 9 kg/ac, and no change in K compared with sole cereal fertilizer			
If Mehlich III P >15 ppm	Apply no P			
Avail. P (Olsen) > 10 ppm	Apply no P			
If soil test K <100 ppm	Band apply 20 kg/ac KCl			

production leading to enhanced profitability. The instructions for other options are given in Table 4 and are also easy to follow.

It is recommended that soil tests be done every 4 years to assess the soil nutrient levels and optimize the fertilizer requirement by applying only what is deficient and hence improve on-farm profitability. For example, when the soil test for P is above 15 ppm, then it is recommended that no fertilizer P should be added. On the other hand, if the K soil gives a value of less than 100 ppm, then K should be applied at the rate of 20 kg/ac of KCl in a band at planting (Table 7.4).

7.7 Conclusions

Increased fertilizer use by smallholder farmers is essential to reversing the declining trend of food production in SSA. The combined application of organic inputs and inorganic fertilizers normally give improved yields, particularly when farmers apply the right fertilizer at the right rate, time and placement, and in consideration of other good agronomic practices.

Fertilizer usage is often limited by lack of sound knowledge required to develop and disseminate sustainable integrated fertilizer recommendations that are soil and crop specific and that are profitable to the farmer. The overall objective of OFRA was to provide farmers with decision tools which would allow them to choose the fertilizer rates and types for different crops in various agro-ecological zones to maximize their profits based on their economic constraints.

A total of 37 replicated trials were conducted for various crops in four regions of Kenya. The mean responses to N, P and K across these trials were 39, 5 and 17%, respectively and 49 crop-nutrient response functions for various recommendation domains were developed. In all regions, all non-legumes had an economic response to applied N and most of the yield gain was achieved with 30 kg/ha N applied and little additional gain with more than 60 kg/ha N applied. Similarly, in all regions, all crops had an economical response to applied P with the exceptions of Irish potato in Eastern and low potential maize in the Rift Valley Region. Responses to K occurred in less than one-third of the cases and most often with Irish potato, rice, groundnut and banana.

The optimal choice of crop-nutrient-rate combinations is expected, on average, to maximize returns on investment in fertilizer use. Eight fertilizer optimization tools (FOTs) were developed for eight recommendation domains in Kenya and are available at http://agronomy.unl.edu/OFRA. Paper versions of all FOTs were developed for use by county extension officers, agro-dealers and farmers without easy access to computers, which may need to be updated when situations like crop and fertilizer prices change.

In addition to the above, optimizing fertilizer use accounts for the effects of other soil management practices and soil test values. Organic inputs, such as farmyard manure and composts, and fresh vegetative materials, such as tithonia and grevillea prunings, may be used within an ISFM framework to improve crop productivity and profitability. Soil tests may be done every 4 years to assess soil nutrient availability and optimize the fertilizer requirement by applying only what is deficient and hence improve on-farm profitability.

7.8 Acknowledgements

The authors are very grateful for support and collaboration received from various parties during the duration of the project. We particularly thank the farmers and extension staff of the Ministry of Agriculture in the counties of Busia, Embu, Machakos, Migori, Muranga, Nakuru, Trans Nzoia and Uasin Gishu. This work is part of the Optimizing Fertilizer Recommendations in Africa conducted in 13 sub-Saharan African countries, funded by AGRA and coordinated by CABI with Prof Charles Wortmann, University of Nebraska-Lincoln, USA as the Science Director. We are grateful for all the support and facilitation received. We appreciate Prof. Wortmann for his commitment and guidance during the implementation of the project and manuscript preparation. We are also grateful to the Director-General, Kenya Agricultural and Livestock Research Organization (KALRO) for permission to publish this work.

7.9 References

Ariga J and Jayne TS (2010). Factors driving the increase in fertilizer use by smallholder farmers in Kenya, 1990-2007. Egerton University, Tegemeo Agricultural Monitoring and Policy Analysis (TAMPA) project, funded by USAID/ Kenya. Draft Report 2: June 10, 2010

Ariga J, Jayne TS, Kibaara B and Nyoro JK (2008). Trends and patterns in fertilizer use by smallholder farmers in Kenya, 1997-2007. Working Paper Series No. 28 Tegemeo Institute, Nairobi, Kenya

Fermont AM, Tittonell PA, Baguma Y, Ntawuruhunga P and Giller KE (2010) Towards understanding factors that govern fertilizer response in cassava: lessons from East Africa. Nutr Cycl Agroecosyst 86:133-151

Gachene KK and Kimaru G (2003) Soil fertility and land productivity. A guide for extension workers in the eastern Africa region. RELMA

Government of Kenya (GoK) (2014) Soil suitability evaluation for maize production in Kenya. A report by National accelerated Agricultural Inputs Access Programme (NAAIAP) in collaboration with Kenya Agricultural Research Institute (KARI), Department of Kenya Soil Survey, February 2014. Available at: http://kenya.soilhealthconsortia.org/?wpfb_dl=3

Jaetzold R and Schmidt H (1983) Farm management handbook of Kenya. Vol/C. Natural conditions and farm management information. Ministry of Agriculture/GAT, Nairobi, Kenya

Jaetzold R, Hornetz B, Shisanya CA and Schmidt H (Eds) (2005-2012) Farm Management Handbook of Kenya. Vol. I-IV (Western, Central, Eastern, Nyanza, Southern Rift Valley, Northern Rift Valley, Coast), Nairobi. Available at: https://www.uni-trier.de/index.php?id=58581

Jama B, Harawa R, Kiwia A, Rarieya M, Kimani D, Zeila A and Scarpone AJ (2013) Chapter 4: Improving soil health in Africa: challenges and promising solutions, pp 44-50. In Annual Report, AGRA

Kenya Soil Survey (2007) Soil and Terrain Database for Kenya. Available at: http://www.isric.org/data/soil-and-terrain-database-kenya-ver-20-kensoter

Sombroek WG, Braun HMH and van der Pouw BJA (1982) Exploratory Soil Map and Agro-Climatic Zone Map of Kenya, 1980. Scale: 1:1,000,000. Exploratory Soil Survey Report No. E1. Kenya Soil Survey Ministry of Agriculture, National Agricultural Laboratories, Nairobi, Kenya

8. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Mali

Mohamed Dicko mkdicko@gmail.com, Mama Koné, Lamine Traoré, Cheick H. Diakité, Nianankoro Kamissoko, Baba Sidibé, Zoumana Kouyaté, Diakalia Sogodogo, Lassana Dioni, Hamidou Konaré and Amadou Gakou

Institut d'Economie Rurale, B.P.258, Rue Mohamed V, Bamako, Mali

8.1 Agricultural systems of Mali

Mali is a vast country of 1,241,000 km^2 in the semi-arid zone of West Africa (10 ° to 25 °N and 4 °E to 12 °W; Diarra 1993; MEATEU 2000). Agriculture is the principal occupation of about 80% of the population. It accounts for 34% of GDP and 23% of exported products.

Subsistence farming dominates with agricultural produce largely consumed locally by the producers. Cropland has increased while fallow has decreased and crop mean yields, except for rice, have not increased.

Generally, smallholders readily adopt new good agricultural practices (GAP), including new varieties, use of fertilizers and good husbandry methods. Where appropriate, double cropping is practised and fertilizer use varies according to farmers' financial capacity. In the south and west of the country, inputs may be provided for cotton and maize production and fertilizers are used more in the cereal-cotton rotation than cropping systems that do not include cotton. The value of complementing fertilizer use by manure application is recognized. Farmers welcome herdsmen to 'overnight-park' livestock on their fields during the dry season to gain the excreted urine and faeces.

A law called 'Loi d'Orientation Agricole' (LOA: Agricultural Orientation Law), enacted in 2006, has enabled government subsidies on seeds and fertilizers, mechanization of agriculture, structuring and strengthening the technical capabilities of producers and their organizations, and the establishment of an institutional framework called the High Council of Agriculture.

Mali has a dry tropical climate with an annual rainfall ranging from less than 100 mm to about 1200 mm (Table 8.1). Mali has four bioclimatic based agro-ecological zones (AEZ): Sahara,

Table 8.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Mali

	J	F	M	A	M	J	J	A	S	O	N	D
Sahara, Kidal												
Rainfall	1	0	0	1	5	12	37	46	23	3	0	0
Tmax	28	31	35	39	42	42	40	38	39	38	33	29
Tmin	13	15	19	23	27	29	27	26	26	23	18	14
Sahel, Niono												
Rainfall	2	0	1	4	20	56	131	171	76	17	0	0
Tmax	30	34	38	41	43	40	37	34	35	35	32	29
Tmin	15	20	24	28	30	27	25	24	24	23	18	14
Northern Sudan Savanna, Kolombada, Samanko												
Rainfall	2	1	3	22	52	119	215	268	169	55	2	0
Tmax	33	37	38	40	39	36	33	32	33	34	34	32
Tmin	15	20	22	25	26	24	24	22	22	23	18	14
Southern Sudan Savanna, Bougouni, Longorola, Finkolo												
Rainfall	2	1	7	39	98	144	242	292	206	77	9	1
Tmax	31	33	35	35	33	31	28	28	29	31	33	30
Tmin	18	24	27	28	**27**	**25**	**24**	**23**	24	24	23	21

Fertilizer Use Optimization in sub-Saharan Africa (2016) Charles S. Wortmann and Keith Sones (ed). Published by CABI.

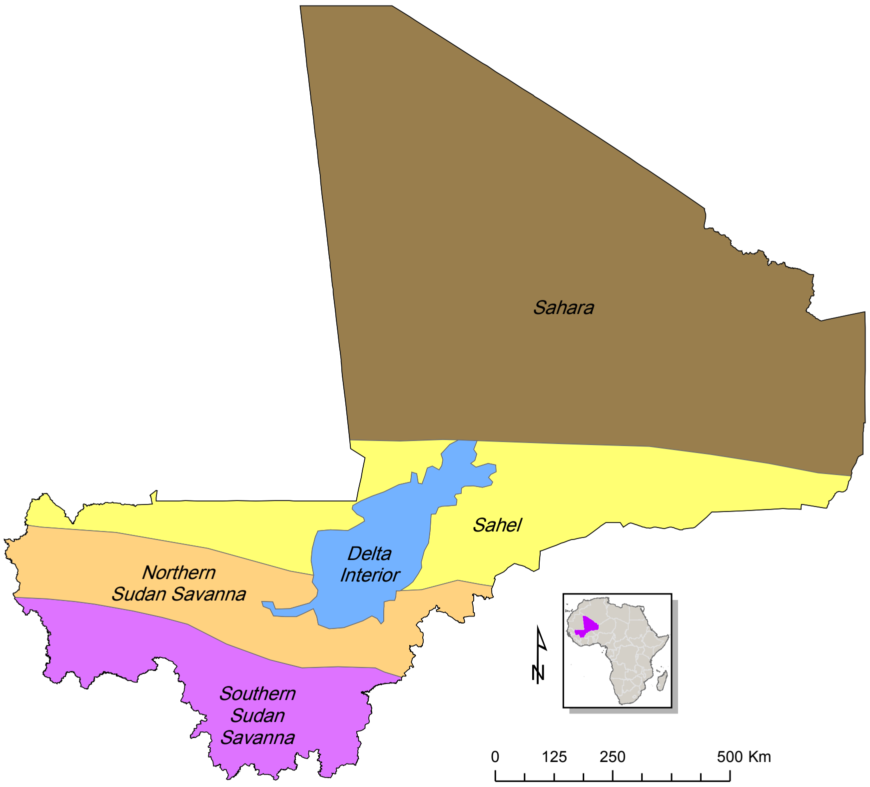


Figure 8.1: Natural regions of Mali.

Sahel, Northern Sudan Savanna, pre-Guinean zone considered here as Southern Sudan Savanna and a transverse area called the Niger River Delta (Figure 8.1).

The Sahara covers more than 50% of the country. It has an extreme spatial and temporal variability of precipitation. The annual rainfall is less than 200 mm and the temperature ranges from less than 14 to more than 42°C. The soils are sandy with low water retention capacity and much wind erosion occurs. Livestock can complement crops as the manure produced is a valuable resource if well used for crop production.

In the Sahel, the average annual rainfall is 200 to 600 mm with a rainy season from July to September during which 79% of the rainfall is received (Table 8.1). Soils are generally low in organic matter and available nutrients. Soil erosion, especially by wind is of major concern. Cereals production is hampered by frequent drought occurrence. Cattle are the main livestock but sheep and goats are also important in the northern Sahel. Manure is important for soil fertility management in this zone, but the amounts produced are insufficient for farmers' needs.

The North Sudan Savanna is characterized by annual rainfall of 600 mm to 1100 mm. The rainy season ranges from about 3 months in the north to 4 months in the south during which 90% of the rainfall is received (Table 8.1). Heavy rainfall causes leaching of nutrients. The most fertile soils are alluvial soils found in the lowlands (Soumaré 2004). This AEZ has the most agricultural potential in Mali. In addition to a relatively long rainy season and high rainfall, good soil water holding capacity in the lowlands allow for adaptation of many crops.

The South Sudan Savanna corresponds to ecosystems of open forests and woodlands. This is the most humid climatic AEZ in Mali with an annual rainfall ranging from 1100 to 1200 mm (Table 8.1). The rainy season is of 5 to 7 months duration and has some torrential rains which are major soil erosion factors. The soils consist of loam and sandy loam in the lowlands and there are areas of ferralitic soil. The wooded land covers 40 to 90% of the AEZ . Furthermore, favourable natural conditions allow the cultivation of several crop types including tubers, citrus, cereals and pulses. Major biotic constraints of this AEZ for agricultural productivity include insects, mites and birds.

8.2 Current soil fertility management

Extensive and unsustainable exploitation of natural resources has resulted in soil degradation in Mali (Koné and Doumbia 1997). Each cropping system is experiencing intensification and sustainability challenges. Increased crop yields on soils of low natural fertility requires a more intensive and effective use of fertilizer combined with manure. Most fertilizer used in Mali is imported.

Crop production is mostly rainfed and crops are grown from June to October and harvested between November and December. Over the years, farmers have adopted GAP for soil fertility management that fit their production systems. Some examples of GAP are:

- Fallowing to restore soil fertility: although traditionally very important (Wane 2009) fallows are becoming shorter and disappearing in some places (Dixon et al., 2001) because of population growth of 3% per year and a high pressure on lands.
- Intercropping: sorghum-cowpea and sorghum-peanut in the North Sudan Savanna and lowlands of the Sahel; pearl millet-cowpea in the Sahel; and annual crops with trees such as shea tree in the North Sudan Savanna and *Acacia albida* in the Sahel add to land productivity while the trees contribute to the maintenance of soil fertility.
- Application of manure on the fields by three traditional manure delivery systems: (a) the 'overnight-parking' arrangement with nomads with consequent deposition of faeces and urine in the fields, (b) moving night pens from one point to another in which the deposition and trampling of faeces by animals contribute to their incorporation into the soil, and (c) fixed night pens from which the manure is transported and applied to fields (Landais and Lhoste 1993). Dry season feeding of crop residues is common with the unconsumed residue serving as bedding and eventually absorbing urine and entering into manure.

To achieve fertilizer use efficiency, recommendations should be adapted to cropping systems and rainfall amounts and distribution with rates decreasing from south to north. Good fertilizer nutrient management is referred to as the 4Rs of Nutrient Stewardship implying application of the right source of nutrients at the right rate, at the right time for efficient uptake by the crop, and with the right placement to be accessible to plant roots (Johnston and Bruulsema 2014).

Fertilizer use in Mali has increased from 84,800 tons in 1994 to 175,000 tons in 2009 and 250,000 tons in 2011, despite the unusually high fertilizer costs, or fertilizer price inflation, of 2007 and 2008. In 2012, fertilizer sales reached about 300,000 tons. This increase in imports and sales of fertilizer is mainly due to subsidies and more efficient fertilizer distribution with about 2000 input shops supplying quality fertilizers to farmers (CNFA 2010). Fertilizer blending facilities, which include Toguna Agro-Industry, Sogefert and ADP, respectively, in Bamako, Sikasso and Ségou, attempt to match blends with crop needs.

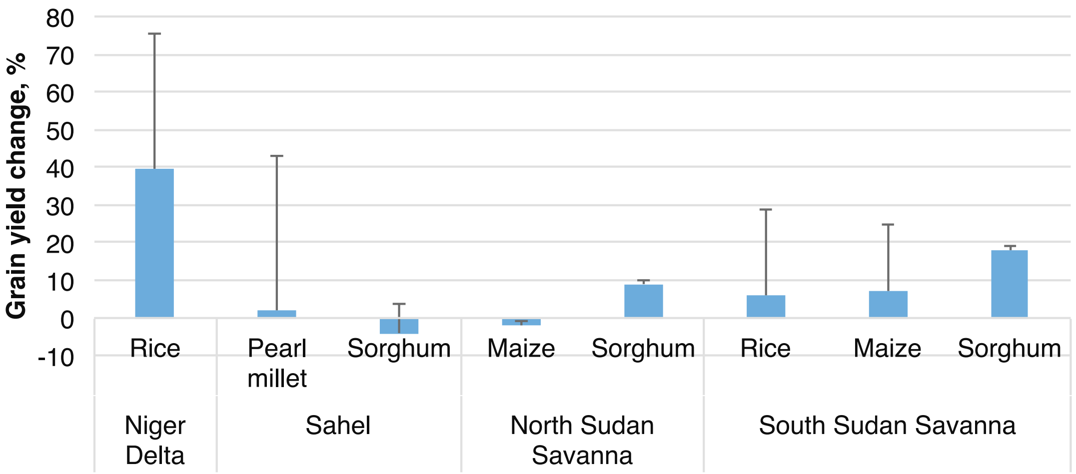


Figure 8.2: Crop response to added secondary and micronutrients (Mg, S, Zn, B) at field research sites of 2014-15 in Mali.

A concern with fertilizer supply is the low availability to farmers of single nutrient and two-nutrient compound fertilizers, with the exception of urea and DAP, although the same are imported and used to create blends. Limiting the fertilizer choice and emphasis on blends is expected to add to fertilizer cost and reduce the farmers' profit potential.

There has been some commercialization of organic resources. Companies such as Profeba, Orgafert and Elephant Vert produce municipal and industrial compost but the supply is small relative to farmer demand.

The combined use of fertilizer, organic resources and soil and water conservation techniques (Mason et al., 2014) are needed to restore and improve soil fertility (AGRA 2013). Examples of GAP integration include use of manure, micro-dose fertilizer application, improved sorghum and maize varieties, the basin tillage practice of zai and reducing runoff and erosion with stone barriers or earthen bunds. Micro-dose fertilizer use with improved cereal varieties is practised, often complemented by application of manure. Other encouraged GAP include mulching, crop rotation, managed fallow, simple and tied ridging and intercropping. In valleys, dams are sometimes used to store water for irrigation of rice and vegetable crops.

8.3 Diagnosis of nutrient deficiencies in Mali

Trials conducted in 2014-2015 included a diagnostic treatment to determine the importance of secondary and micronutrients to crop performance. This treatment contained Mg, S, Zn and B in addition to N, P and K and was compared with a treatment of the same N, P and K rates. The diagnostic treatment resulted in a mean yield increase of 39% for irrigated rice yield. However, there was not a consistent yield increase with other crops in the Sahel, North Sudan and South Sudan Savannas indicating that other biotic or abiotic factors are more constraining to yield than any of these secondary or micro-nutrients (Figure 8.2). Further investigation is needed to determine which of these nutrients are most important to irrigated rice production.

8.4 Optimizing fertilizer use in Mali

In spite of the government subsidy programme for fertilizer many poor farmers cannot afford fertilizer use or apply inconsistently at low levels. To overcome this pitfall, optimization of fertilizer use is aimed at maximizing farmer profit from fertilizer use. Determining the economics of fertilizer use requires crop nutrient response functions. Results of numerous studies from different AEZ were used to capture crop responses to applied nutrients with a curvilinear to plateau relationship of nutrient rate with yield. This response is represented mathematically as: Yield = a - bc^{r}, where a is near maximum yield for application of that nutrient, b is the gain in yield due to application of that nutrient, and c^{r} determines the shape of the curvilinear response where c is a curvature coefficient and ^{r} is the nutrient rate. A response function has been established for each targeted crop-nutrient combination of three AEZ. Once such a response function has been determined, economics can be applied to estimate the profit potential for different nutrients applied to different crops.

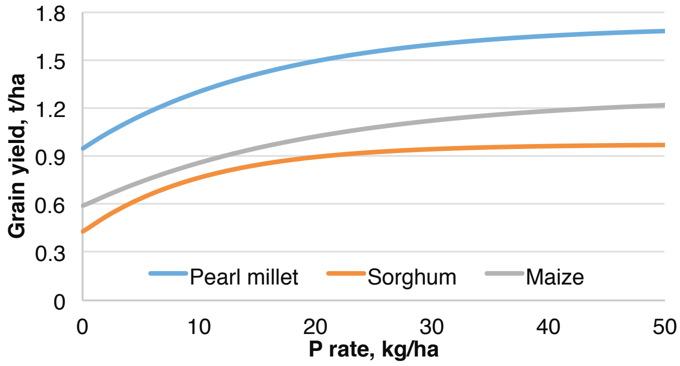


Figure 8.3: Crop responses to fertilizer P in the Sahel.

The fertilizer P response curves of maize, sorghum and pearl millet in Figure 8.3 illustrate how rate of application is important to profitability. With all curves, there is a higher rate of yield gain per kg/ha of P applied at lower compared with higher rates, especially for sorghum. Sorghum yield has a steep rate of increase as P is increased from 0 to 10 kg/ha and therefore potential for a relatively high rate of return on investment, a lesser rate for 10 to 20 kg/ha, eventually reaching a point of insufficient yield value increase to justify the cost of applying additional P. The financially constrained farmer can obtain the best returns on a limited investment in fertilizer use by applying at a rate where the response curve is relatively steep.

Another important economic consideration in fertilizer use, especially for the financially

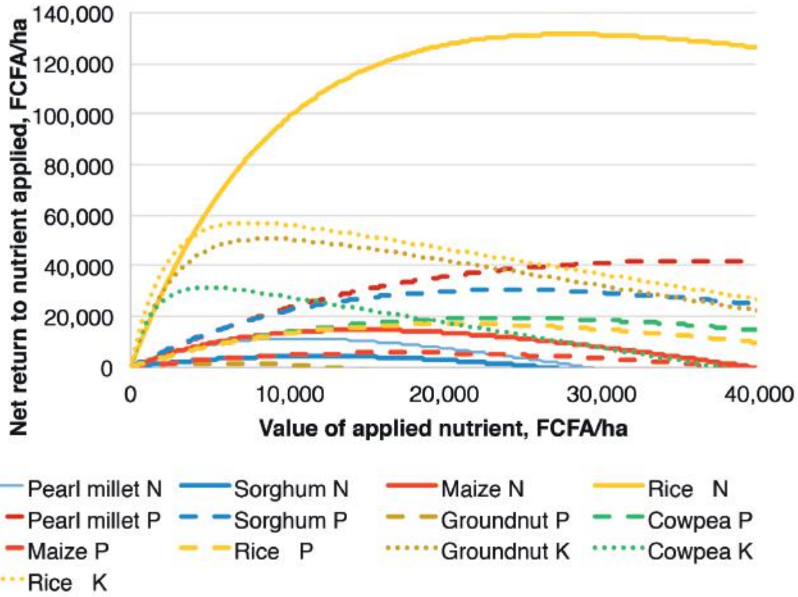


Figure 8.4a: Net return from fertilizer use in the Sahel Zone of Mali. This graphic assumes that grain values used were (in XOF) 330 for rice, 80 for maize, 130 for sorghum, 135 for pearl millet, 600 for cowpea and groundnut. Fertilizer use costs were: 13,500 for urea, 20,000 for DAP, 16,000 for TSP, 16,000 for KCl, and 13,500 for 15-15-15.

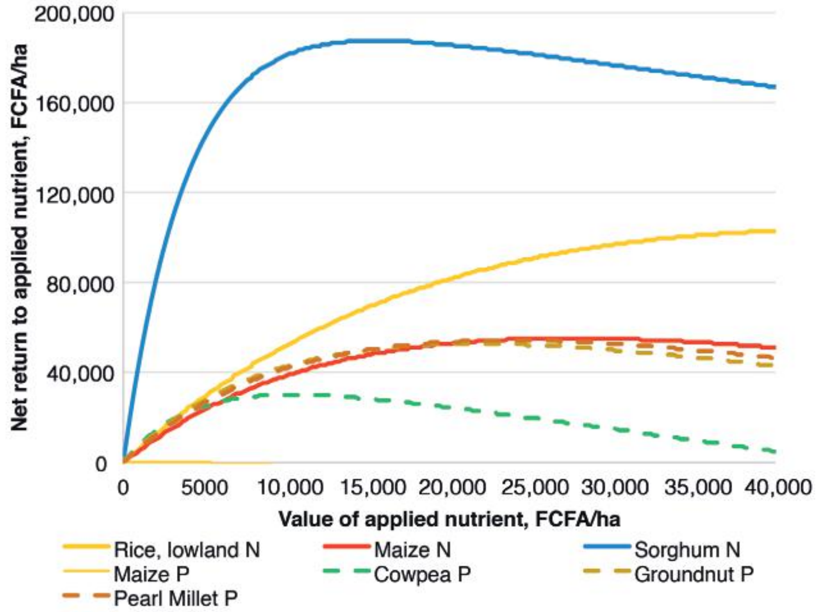


Figure 8.4b: Net return from fertilizer use in the North Sudan Savanna of Mali.

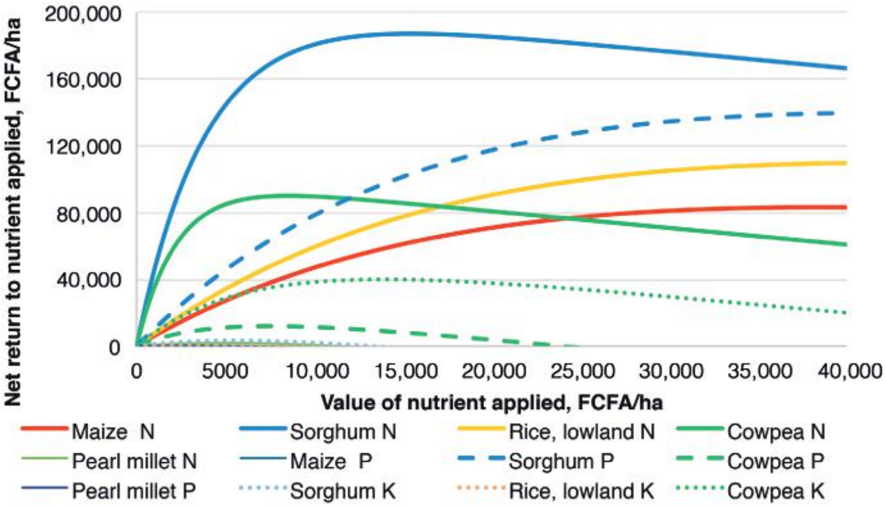


Figure 8.4c: Net return from fertilizer use in the South Sudan Savanna of Mali.

constrained farmer, is that not all nutrients applied to the same or different crops have the same profit potential. In Figures 8.4a-c, each curve represents the profit for a nutrient applied to a particular crop. The horizontal axis shows the amount invested in a nutrient applied to a crop. The vertical axis shows the net revenue resulting from the application of each nutrient to a crop. The net income tends to increase as one invests more in an applied nutrient until a peak before net income begins to decrease. The rate at the peak is referred to in this chapter as the economically optimal rate (EOR), that is the rate to maximize net returns per hectare and the targeted rate of the farmer with adequate financing. With the optimization of fertilizer use approach, the farmer's financial constraint affects the choices of fertilizer amounts to apply to different crops as the farmer wants to apply fertilizer to maximize net returns on the limited investment. When the curves are steep, the expected net returns to application of that nutrient to the crop are high.

In the Sahel region, there is high profit potential, at least at low rates of application, for N and P applied to rice, P applied to groundnut and K applied to cowpea (Figure 8.4a). The point where the yield gain is insufficient to pay for the cost of additional nutrient is at the peak of the curve and the EOR, after which profit is lost with more nutrient application. There the value of P applied to rice and of K applied to cowpea should be less than 7000 and 5000 CFCA/ha, respectively. There is good profit potential, however, with applying more P to groundnut and more N to rice. The lower lying curves also have the potential for profit, but much less potential compared with the steeper curves.

In the North Sudan Savanna, the big profit opportunity is with N applied to sorghum (Figure 8.4b). Below that, with good but less profit potential are with N applied to maize and rice, and P applied to cowpea and pearl millet. The relatively low grain price for maize reduces its profit potential. In the South Sudan Savanna, the better profit opportunities are with N applied to sorghum, P applied to rice and sorghum, and K applied to cowpea (Figure 8.3c). Therefore, the financially constrained farmer needs to choose crop-nutrient-rate combinations appropriate to the choice of crops that have the greatest potential to maximize net returns per hectare.

8.5 Fertilizer use optimization tools for Mali

Decisions on investing in fertilizer use to optimize profit on the investment must consider a great deal of information and is potentially overwhelming, especially if the decisions are finance constrained. A farmer in the South Sudan Savanna has the implications of 14 crop-nutrient response functions to consider while accounting for their choice of crops, land allocation, expected value of commodities, the fertilizer use costs, and the amount of money to invest in fertilizer use. Therefore, fertilizer optimization tools (FOTs) were developed that work with macros created in Excel with the add-on Solver © (Frontline Systems Inc., Incline Village, NV, USA). These Excel FOTs use complex mathematics of linear programming which integrate crop-nutrient response information with other agronomic and economic information relevant to the farmer's specific situation (agronomy.unl.edu/OFRA). In spite of this mathematical complexity, use of the FOTs is easy. Before the FOTs can be used, the add-on Solver needs to be activated and macros need to be enabled; the steps to doing this are given in the 'Help and Instructions' worksheet of the FOT. The FOTs and instructional materials are available at (https://agronomy.unl.edu/OFRA).

In the input panels (Figure 8.5a), the user enters the land area allocated to each crop and expected value of the harvest, accounting for the value of that which will be kept for home consumption and the surplus to be marketed. He/she then enters the cost of using, considering purchase costs and the costs of transport and application, 50 kg bags of each fertilizer likely to be available. If a fertilizer is not available, its cost is replaced by zero. He/she finally enters the amount available for use of fertilizers; this is the budget or financial constraint. After fully informing the tool, the user left-clicks on the optimize button to launch the calculation.

The amount of each fertilizer to be applied to each crop to maximize profit is reported in the upper panel of the output (Figure 8.5b). Sometimes the recommended rates are too

AEZ_SAHEL

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	July 6, 2016

Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Pearl millet	3	135
Sorghum	2	130
Groundnuts, unshelled	0.5	600
Cowpea	0.5	600
Maize	0.5	80
Rice	0.25	300
Total	6.75	

Fertilizer Selection and Prices					
Fertilizer Product	N	P2O5	K2O	xx	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	13500
Triple super phosphate, TSP	0%	46%	0%	0%	16000
Diammonium phosphate, DAP	18%	46%	0%	0%	20000
Murate of potash, KCL	0%	0%	60%	0%	16000
NPK	15%	15%	15%	0%	13500

Budget Constraint	
Amount available to invest in fertilizer	100000

Figure 8.5a: Input panel for the Excel FOT.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**TSP**	**DAP**	**KCl**	**NPK**
Pearl millet	0	0	48	0	0
Sorghum	0	22	10	0	0
Groundnuts, unshelled	0	0	0	20	0
Cowpea	0	18	0	11	0
Maize	31	0	0	0	0
Rice	65	0	21	18	0
0	0	0	0	0	0
Total fertilizer needed	32	53	170	20	0

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
Pearl millet	449	41,439
Sorghum	271	24,032
Groundnuts, unshelled	93	49,319
Cowpea	82	40,053
Maize	351	19,733
Rice	751	193,591
0	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	275,331

Figure 8.5b: Excel FOT output panel after optimization showing fertilizers needed and the expected returns.

Table 8.2: The paper fertilizer optimization tool for the South Sudan Savanna

MALI-South Sudan-AEZ Fertilizer Use Optimizer

The below assumes:
Calibration measurement is with: Diago water bottle lid that holds about 8 ml, 5.6 g urea, 8.8 g DAP, 8.8 g of TSP, 8.0 g NPK and 8.8 g KCl; Gino tomato can of 70 ml to hold 49 g urea, 77 g DAP, 77 g TSP, and 77 g KCl.
Planting: It is assumed maize and cowpea: 0.8 x 0.4 m; sorghum 0.8 x 0.8 m; pearl millet 1 x 0.8 m; groundnut 0.4 x 0.4 m; rice 20 cm.
Crop values: It is assumed grain prices per kg (CFA): 80 maize; 130 sorghum; 300 rice; 135 pearl millet; 600 Groundnut; 600 cowpea.
Fertilizer use costs for 50 kg: It is assumed 50 kg of fertilizer use costs (CFA): 13,500 urea; 20,000 DAP; 13,500 NPK; 16,000 TSP; 16,000 KCl.
Broadcast width: 3 m; WAP=weeks after planting, WAT=weeks after transplanting. Application rate is kg/ha.

Level 1 financial ability.	
Cowpea	Point apply 35 kg NPK (1Diago lid for 7 plants) at emergence
Maize	Point apply 11 kg urea (1 Diago lid for 20 plants) at 6 WAP
Rice, lowland	Broadcast 78 kg urea in 2 applications : 28 kg urea (1 Gino can for 7.5 m) at transplanting and 50 kg urea (1 Gino can for 4.1 m) at panicle initiation and 106 kg NPK (1 Gino can for 2 m) at transplanting, and 106 kg NPK at transplanting (1 Gino can of 70 ml for 2 m)
Sorghum	Point apply 66 kg NPK (1 Diago lid for 2 plants) at emergence
Level 2 financial ability.	
Maize	Point apply 32 kg urea (1 Diago lid for 6.8 plants) at emergence and 50 kg urea (1 Diago lid for 4.8 plants) 6 WAP
Cowpea	Point apply 50 kg NPK at emergence (1 Diago lid for 5 plants)
Rice, upland	Broadcast 49 kg urea (1 Gino can for 3.3 m) at transplanting and 50 kg urea (1 Gino can lid for 7 plants) at panicle initiation and broadcast 162 kg NPK at emerging or transplanting (1 Gino can for 1 m)
Sorghum	Point apply 135 kg of NPK (1 Diago lid for 1 plant) at emergence
Rice, lowland	Broadcast 26 kg urea (1 Gino can for 6.3 m) at transplanting and 50 kg urea (1 Gino can for 3.3 m) at panicle initiation
Level 3 financial ability (maximize profit per acre).	
Millet	Point apply 10 kg urea at emergence (1 Diago lid for 14 plants) and 26 kg NPK at emergence (1 Diago lid for 4 plants)
Maize	Point apply 31 kg urea (1 Diago lid for 7.5 plants) at emergence and 100 kg urea (1 Diago lid for 2 plants) 6 WAP and 33 kg NPK (1 Diago lid for 8 plants) at emergence and point apply 33 kg NPK at emergence (1 Diago lid for 8 plants)
Cowpea	Point apply 66 kg NPK at emergence (1 Diago lid for 9 plants) and 12 kg KCl at emergence (1 Diago lid for 23 plants)
Rice, upland	Broadcast 200 kg NPK at transplanting (1 Gino can for 1 m) and 50 kg at panicle initiation (1 Gino can for 3.3 m)
Sorghum	Point apply 187 kg of NPK (1 Diago lid for 1plant) at emergence
Rice, lowland	Broadcast 35 kg Urea at transplanting (1 Gino can for 4.7 m and 100 kg urea at panicle initiation (1 Gino can for 1.6 m), and broadcast 26 kg KCl at land preparation (1 Gino can for 9.9 m)

small to be feasible, such as 10 kg/ha DAP applied to sorghum or 11 kg/ha KCl applied to cowpea. For such small rates, the money or fertilizer should be allocated to another option. The second panel shows the expected average increases in yield and net profits due to the recommended fertilizer application for each crop. The very high net return to fertilizer applied on rice might cause the farmer to allocate more land to rice production. Finally, the total expected net return due to fertilizer use is reported.

Note that the budget constraint was FCFA 100,000 which was allocated to 32, 53, 170, 20 and 0 kg of urea, TSP, DAP, KCl and NPK 15-15-15 (Figure 8.5b). The NPK blended fertilizer is likely the most expensive to produce, but has the lowest price because of unbalanced subsidies on fertilizer types. Even though it has a low price, it was not found to be economically competitive with other fertilizers because farmers would have to pay for the three nutrients even if the crop does not have an economic response to all nutrients. The added cost would mean profit lost. It would be even more harmful to the financially constrained farmer as purchase of the NPK would mean less money available for purchase of a fertilizer that has high profit potential. In some situations where the crop has an economic response to all three nutrients, the NPK blend may be economically competitive if adequately subsidized. When the scenario of Figure 8.4 is optimized with only urea and NPK available, the expected average total net returns are only CFA 184,524 compared with CFA 275,331, and only 67% of expected profit to the farmer who has the wider choice of fertilizer. The results illustrate the importance of enabling farmer access to a choice of fertilizers if the intent is to maximize farmer profit potential.

For each Excel FOT, a companion paper FOT is developed realizing that farmers and extension workers often will not have a readily available computer (Table 8.2). The paper FOT has three financial capacity levels. Financial level 1 is the most constrained for a farmer who cannot invest more than one-third of the total amount required to apply fertilizer to all cropland at EOR. Farmers in financial level 2 have less than two-thirds the money needed to apply to all cropland at EOR. Farmers in financial level 3 have enough money to apply to at least some cropland at EOR.

The paper FOT makes assumptions about the measuring units that the farmer can use to calibrate the visual and hand-feel perception of the correct rate. It is assumed that the farmer will plant as recommended. Assumptions are made about fertilizer costs and expected grain values on-farm at harvest. The paper FOT addresses the 4Rs of fertilizer use and recommends the right product, the right rate, the right time and the right method of application. It also informs the user on calibration of application.

Consider the paper FOT for South Sudan Savanna (Table 8.2). One of the three recommendations for the financial level 1 is “Rice lowland: Broadcast 28 kg urea (Gino for 11 m) at 0 WAT and 50 kg urea (Gino for 6 m) at panicle initiation, and 106 kg NPK (Gino for 2 m) at 0 WAT.” Therefore, the farmer will broadcast apply 28 kg/ha of urea and 106 kg/ha NPK 15-15-15 to lowland rice, including irrigated rice, at transplanting time and another 50 kg/ha urea at panicle initiation. When broadcasting, he/she will broadcast with a 3 m width. He/she should use a Gino brand tomato sauce can of 70 ml for calibration of his/her sense of application to achieve the correct rate. One Gino can is enough to broadcast to an area of 3 m wide and 11 m long for the transplant application of 28 kg/ha of urea. For the transplant application of 106 kg NPK, one Gino is sufficient to broadcast an area of 3 m wide and 2 m long. For the application at panicle initiation of 50 kg urea, one Gino is enough for an area 3 m wide and 6 m long.

A constraint of the paper FOTs is that it may need to be revised yearly if there are significant changes in fertilizer costs relative to grain values. This is to be done at the national level with redistribution such as publication in newspapers as well as with on-line access. The steps to paper FOT development and revision are described in Chapter 1.

Smallholder farmers typically farm small areas of land but numerous parcels of land that differ in crop history and management. The FOTs more or less work on a whole farm basis to optimize profit for the farm enterprise. The FOTs (Excel and paper versions) give optimized recommendations for fertilizer use within the farmer’s context and in situations of important agricultural land typical to an AEZ. However, optimization of fertilizer use needs to consider other practices that might affect nutrient availability on one or more of their land parcels (Table 8.3). Soil test results may indicate an adjustment in the fertilizer recommendation. Some practices, such as manure application, affect the optimal fertilizer use rate. For example, it is recommended that if farmyard manure is applied

Table 8.3: Fertilizer rate adjustments within an integrated soil fertility management framework

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT CONTEXT

FERTILIZER SUBSTITUTION AND SOIL TEST IMPLICATIONS

ISFM practice	Urea	DAP/TSP	KCl	NPK 17-17-17
	Fertilizer reduction, % or kg/ha			
Previous crop was a green manure crop (Sesbania and dolichos)	Incorporation at the end of the rainy season increase cereal grain and stover yields by 27% and 49%compared to cereal monoculture without organic amendment (Kouyaté, 2000).			
Farmyard manure per 1 t of dry material in the Sudan Savanna	11 kg	7 kg	13 kg	73 kg
Dairy or poultry manure, per 1 t dry material	53 kg	27 kg	27 kg	
Compost, per 1 t	38 kg	12 kg	14 kg	
Rotation	0% reduction in fertilizer rate but an average of 18 and 23% more cereal yield expected following cowpea compared with a cereal on loamy sand and loam respectively (Kouyaté et al., 2000).			
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 11 kg/ha, reduce urea by 9 kg/ha and no change in K compared with sole cereal fertilizer			
If soil P > 15 ppm by Bray 1	Apply no P			

in the Sudan Savanna, then urea, TSP/DAP, KCl, or NPK can be allocated elsewhere by 11, 7, 13 and 73 kg/ha per 1 t/ha manure applied (dry weight), respectively; this does not apply to the Sahel, however, as farmyard manure application commonly results in increased response to fertilizer.

8.6 Targeted crops and cropping systems by AEZ

Mali has four major AEZ for crop production. The OFRA project was implemented in areas of 450 to 1200 mm annual rainfall for the major staple cereals including maize, sorghum, millet and rice in the regions of Koulikoro (Samanko and Kolombada), Kayes (Bema), Sikasso (Bougouni, Kebila, Longorola and Finkolo) and Segou (Cinzana and Niono). Other crops were addressed using results of past research including data from neighbouring countries.

Crop nutrient response functions for N, P and K were developed (Tables 8.4a-c). The coefficients a, b and c of the response functions (column 3-5), the expected yield increase due to increments of nutrient application (column 6-9) and the EOR compared with the recommended rates are reported (column 10-11).

In the Sahel, rice and maize had more response to N compared with sorghum and pearl millet but all of the upland cereals had big responses to P (Table 8.4a). Rice and groundnut did not have economic responses to P. Only rice and cowpea had economic responses to K. EOR of N is less than half the recommended rate (REC) for maize and rice, but also less for sorghum and pearl millet. The EOR is sometimes more for P than the REC. The rice EOR for K was about 25% the REC.

In the North Sudan Savanna, maize and sorghum had greater response to N compared with rice and most of the grain yield increase occurred with 30 kg/ha applied (Table 8.4b). Responses to P were relatively small except for with pearl millet. Evidence of response to K was lacking. The N REC for rice was low compared with the rate of the Sahel and similar to the EOR for N. The EOR for N applied to rice was greater than for maize and sorghum because of the higher value for rice grain. The EOR of N were less than the REC for maize and sorghum. The EOR of P varied inconsistently with the REC.

In the South Sudan Savanna (Table 8.4c) upland rice, maize and sorghum have the best response

Table 8.4a: Sahel Zone in Mali (200-600mm). Response functions (col 3-5), expected yield increases (t/ha) for crop-nutrients (col 6-9), and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations by AEZ in Mali. P_2O_5 = P x 2.29; K_2O = K x 1.2

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			t/ha				kg/ha	
Pearl millet	N	0.742	0.223	0.930	0.198	0.022	0.003	0.000	21	32
Sorghum	N	1.098	0.273	0.970	0.164	0.066	0.026	0.011	20	32
Maize	N	1.275	0.687	0.951	0.535	0.118	0.026	0.006	31	84
Rice (irrigated)	N	4.461	0.564	0.942	0.470	0.078	0.013	0.002	48	120
					0-5	**5-10**	**10-15**	**15-20**		
Pearl millet	P	1.717	0.768	0.940	0.204	0.150	0.110	0.081	23	10
Sorghum	P	0.975	0.548	0.908	0.210	0.129	0.080	0.049	16	10
Groundnut	P	0.254	0.032	0.870	0.016	0.008	0.004	0.002	0	9
Cowpea	P	0.605	0.109	0.930	0.033	0.023	0.016	0.011	15	10
Maize	P	1.275	0.687	0.951	0.153	0.119	0.092	0.072	0	7
Rice (Irrigated)	P	5.190	0.189	0.919	0.065	0.043	0.028	0.018	14	20
Groundnut	K	1.093	0.104	0.800	0.070	0.023	0.008	0.002	0	0
Cowpea	K	0.477	0.063	0.650	0.056	0.006	0.001	0.000	8	0
Rice (irrigated)	K	6.036	0.223	0.750	0.170	0.040	0.010	0.002	12	50

†EOR was determined with grain values (in CFA) of 330 for rice, 80 for maize, 130 for sorghum, 135 for pearl millet, 600 for cowpea. Fertilizer use costs in CFA per 50 kg bag were: 13,500 for urea; 20,000 for DAP; 16,000 for TSP; 16,000 for KCl; and 13,500 for NPK 15-15-15.

Table 8.4b: North Sudan Savanna of Mali (600-1200 mm)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			t/ha				kg/ha	
Rice, lowland	N	2.483	0.429	0.974	0.234	0.106	0.048	0.022	67	60-80
Maize	N	2.290	1.619	0.960	1.143	0.336	0.099	0.029	54	84
Sorghum	N	4.068	1.534	0.860	1.517	0.016	0.000	0.000	26	32
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	3	7
Cowpea	P	1.095	0.075	0.700	0.062	0.010	0.002	0.000	0	10
Groundnut	P	1.320	0.141	0.855	0.077	0.035	0.016	0.007	6	9
Pearl millet	P	2.010	0.662	0.870	0.332	0.165	0.082	0.041	13	10

to N and the best increase with the 0-30 kg/ha N increment. Application of P to sorghum and upland rice and of K to upland rice resulted in good yield increases. Application of N, P and K resulted in small cowpea yield increases that were economical because of the high value given to cowpea grain.

The EORs were similar to the REC for lowland and upland rice but less for maize, sorghum and pearl millet. The EOR for P was low compared to the REC for all crops except for sorghum. The EOR for K were determined for upland and lowland rice, sorghum and cowpea while REC are lacking.

Table 8.4c: South Sudan Savanna of Mali (1000-1200mm)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Maize	N	3.000	1.760	0.970	1.054	0.423	0.170	0.068	65	84
Rice, upland	N	4.655	1.908	0.988	0.580	0.404	0.281	0.196	70	60-80
Sorghum	N	4.067	1.530	0.860	1.513	0.016	0.000	0.000	28	32
Rice, lowland	N	2.482	0.428	0.970	0.256	0.103	0.041	0.017	62	60-80
Cowpea	N	1.860	0.168	0.770	0.168	0.000	0.000	0.000	15	0
Pearl millet	N	1.111	0.110	0.930	0.098	0.011	0.001	0.000	8	32
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	2	7
Rice, upland	P	3.633	0.979	0.904	0.388	0.234	0.141	0.085	13	20
Sorghum	P	2.770	1.470	0.910	0.553	0.345	0.215	0.134	12	10
Cowpea	P	0.929	0.040	0.700	0.033	0.006	0.001	0.000	3	10
Pearl millet	P	1.520	0.129	0.900	0.053	0.031	0.018	0.011	2	10
Rice, upland	K	4.439	0.838	0.800	0.563	0.185	0.060	0.020	25	20
Sorghum	K	2.016	0.114	0.900	0.047	0.028	0.016	0.010	23	12
Rice, lowland	K	1.950	0.091	0.961	0.016	0.013	0.011	0.009	14	20
Cowpea	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	13	0

The EOR determined from field research results were more than 20% less or more than the REC for 61 and 27%, respectively, of 33 comparisons (Table 8.4a,b,c). This implies that farmers, overall, who apply fertilizer at the REC are losing profit potential due to over-application. One exception is for N applied to upland and lowland, including irrigated, rice where the EOR and REC were generally similar. However, farmers who are financially constrained in fertilizer use need to benefit from the typical curvilinear to plateau response of crops to applied nutrients and generally apply at less than EOR where yield gain for kg/ha of applied nutrient is high.

8.7 Conclusion

Fertilizer use profitability can be improved for all AEZ of Mali. Recommended rates for farmers who are not financially constrained in fertilizer use need to be adjusted to reflect EOR. Farmers who are financially constrained in fertilizer use need to have the capacity to choose the crop-nutrient-rate options that are most likely to maximize returns on their investment. Computer run and paper-based fertilizer optimization tools have been developed to enable determination of current EOR, depending on fertilizer costs and commodity values, and to determine the combination of crop-nutrient-rates for maximizing returns on investment. The fertilizer rate adjustment in an ISFM framework is important to optimizing fertilizer use to give credit to alternative nutrient supply practices, to apply additional fertilizer when justified (such as for intercropping) and to consider soil test values. If farmer profitability is the objective of fertilizer use optimization, it is essential that farmers have an adequate choice of single nutrient or two-nutrient compound fertilizers.

8.8 Acknowledgements

Our thanks go to all those who contributed to this chapter. We thank AGRA, CABI, University of Nebraska-Lincoln, the Mali Soil Health Consortium, and Institut d'Economie Rurale (the National Research Service) for their contributions and support.

8.9 References

AGRA (2013) Africa Agriculture Status Report. Focus on staple crops. AGRA. http://www.archive.agra.org/our-results/annual-reports

CNFA (2010) Répertoire des agro-dealers du Mali. 2000 adresse à travers tout le pays

Diarra A (1993) Utilisation des ressources naturelles et occupation de l'espace par les agriculteurs et les pasteurs en Zone aride au Mali, Cercle de Bourem (Région de Gao). Thèse de Doctorat, Université Paul Valery Montpellier III, France

Dixon J, Gulliver A and Gibbon D (2001) Systèmes d'exploitation agricole et pauvreté. Améliorer les moyens d'existence des agriculteurs dans un monde changeant. FAO, Banque Mondiale

Johnston AM and Bruulsema TW (2014) 4R nutrient stewardship for improved nutrient use efficiency. Proc Engin. 83:365–370

Koné M and Doumbia M (1997) Les difficultés pour maintenir la fertilité des sols en cultures paysannes. Collection Colloques Montpellier, CIRAD-CA

Kouyaté Z, Franzluebbers K, Juo ASR and Hossner LR (2000) Tillage, crop residue, legume rotation, and green manure effects on sorghum and millet yields in the semiarid tropics of Mali. Plant and Soil 225:141-151

Landais E and Lhoste PL (1993) Systèmes d'élevage et transfert de fertilisation dans la zone des savanes Africaines. Cahiers Agricultures 2:9-25

Mason SC, Ouattara K, Taonda SJB, Pale SB, Sohoro A and Kabore D (2014) Soil and cropping system research in semi-arid West Africa as related to the potential for conservation agriculture. Internat J Agricul Sustain doi: 10.1080/14735903.2014.945319

MEATEU (2000) Stratégie nationale en matière de diversité biologique, Tome 1, situation de diversité biologique au Mali. Ministère de l'Equipement de l'Aménagement du Territoire, de l'Environnement et de l'Urbanisme

Soumaré M (2004) Contribution à la prévision de l'aire de diffusion de variétés de sorgho au Mali. Couplage entre modèle de croissance des cultures et systèmes d'information géographique. Mémoire de DEA, Université Paris 10, INA-PG

Wane A (2009) Exploitation et gestion des ressources naturelles dans l'ile à Morphil. Etude de cas : l'arrondissement de cas-cas (département de Podor) Maitrise/Université CAD de Dakar/Géographie

9. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Malawi

Patson C Nalivata[1] patienalivata@yahoo.com, Moses W Munthali[2], Wilson I Makumba[3], Emmanuel Mbewe[1] and Hastings Manase[1]

[1]Lilongwe University of Agriculture and Natural Resources, Bunda Campus, P.O. Box 219, Lilongwe, Malawi
[2]Bvumbwe Agricultural Research Station, Box 5748, Limbe, Malawi
[3]Department of Agricultural Research Services, P.O. Box 30, Lilongwe, Malawi

9.1 Agricultural systems of Malawi

9.1.1 Agro-ecological zones (AEZ)

There are four AEZ in Malawi based on altitude: the highlands; the mid-elevation and upland plateau; lakeshore, middle and upper Shire Valley; and the lower Shire Valley (Figure 9.1). The sub-humid tropical agro-ecosystems of Malawi are characterised by a long dry season, with a unimodal rainfall pattern between November and April (Table 9.1) (MoAFS 2012).

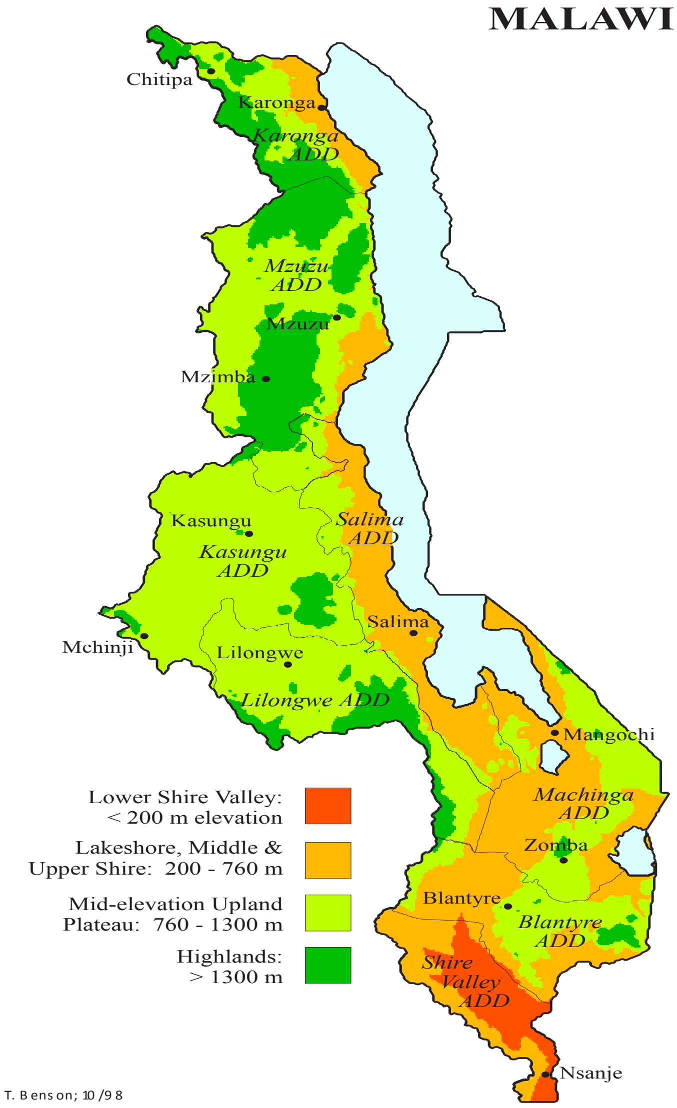


Figure 9.1: Agro-ecological zones of Malawi.

The highlands AEZ, lying between 1320 and 3000 m above sea level (masl), consist of isolated mountains with extensive highland plateaus found in Nyika, Viphya and Mulanje, while Dedza and Zomba are more isolated. The climate is sub-humid with 84% of the rainfall occurring during December to March. The minimum and maximum mean temperatures range is 9 to 16 and 19 to 25°C, respectively (Table 9.1). The predominant soils are the leached Latosols, Alfisols and Utilsols. The major crops include maize, pigeonpea, tea, coffee, bananas, pineapples, cassava, potatoes and many more.

The mid-elevation and upland plateau AEZ lies between 760 and 1300 masl. This zone consists of escarpments and plateaus running from Karonga in the north to Nsanje in the south. The plateaus have a flat to rolling topography with scattered rock inselbergs. The climate is semi-arid with monthly rainfall range of 1 to 221 mm; and minimum and maximum mean temperatures range of 8 to 17 and 24 to 30°C, respectively (Table 9.1). The escarpment soils are predominantly shallow latosols. Soils higher in the plateau catenas are deep well drained latosols while poorly drained sand and clay soils dominate in the valleys, locally called dambos. Other important soil groups include Ferrasols, Luvisols, Lixisols, Lithic and Leptosols. The major crops include maize, tobacco, cassava, rice and pulses.

The lakeshore, middle and upper Shire Valley AEZ lies between 200 and 760 masl. It is flat to gently undulating, with deep calcimorphic soils in the valleys and the shorelands of Lake Malawi. The Upper Shire River flows through a broad flat valley from the south of Lake Malawi. Mopanosols are found in some areas of the Shire River Valley. The climate is semi-arid. Monthly rainfall ranges from 0 to 339 mm and mean monthly minimum and maximum

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

Table 9.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZs of Malawi

	J	F	M	A	M	J	J	A	S	O	N	D
Highlands (Dedza 1632 m)												
Rainfall	289	234	180	67	11	4	4	1	4	12	74	231
Tmax	23	23	23	23	21	19	19	21	23	25	25	24
Tmin	16	15	15	14	12	10	9	11	13	15	16	16
Mid-elevation, upland plateau (Chitedze-Lilongwe)												
Rainfall	202	221	195	149	47	11	2	1	0	2	11	81
Tmax	27	27	27	27	27	26	24	24	26	28	30	30
Tmin	17	17	17	16	15	11	9	8	9	12	15	17
Lakeshore, middle and upper Shire (Salima)												
Rainfall	339	266	254	93	11	2	0	0	0	6	44	250
Tmax	29	29	30	29	28	26	26	28	31	33	32	30
Tmin	21	21	21	21	18	16	16	17	19	21	22	22
Lower Shire Valley (Makhanga)												
Rainfall	157	127	111	38	15	17	17	7	5	29	61	167
Tmax	33	33	33	31	30	28	28	30	34	36	36	34
Tmin	23	23	22	20	17	14	14	16	19	22	23	23

Source: http://www.malawi.climatemps.com

temperatures range from 16 to 22 and 26 to 33°C, respectively. Important food crops include maize, rice, cassava, sorghum and millet.

The lower Shire Valley AEZ is below 200 masl and extends from Kapachira Falls to Nsanje District. The climate is semi-arid with a monthly mean rainfall range of 5 to 167 mm and minimum and maximum mean monthly temperatures of 14 to 23 and 28 to 36°C, respectively. The soils of the marsh lands are hydromorphic. Medium to coarse textured alluvial and colluvial soils are most common to the east of the Shire River and vertisols are common to the west of Shire River to the escarpment. The common food crops are maize, sorghum, cassava and Irish potato.

9.1.2 Current soil fertility management in Malawi

Soil degradation and inherently low soil fertility contribute to the unsustainable low productivity of existing production systems and threaten long-term food insecurity in sub-Saharan Africa. In Malawi, agriculture is dominated by production of maize, the main staple crop, with 1.2 million hectares of production annually, occupying about 80% of cultivated land. Most production is by smallholder farmers with limited access and use of fertilizer, improved seed and other inputs due to high costs and low financial ability.

Low-cost good agricultural practices (GAP) for enhancing soil nutrient availability have been studied including crop residue management; agro-forestry; maize-legume rotations; area-specific maize fertilizer recommendations to improve nutrient use efficiency; conservation agriculture; climate smart practices; and use of compost. Integration of organic resources and N fixing legumes in rotations with fertilizer use has been well studied. However, adoption of such GAP is low and the perceived profit potential of fertilizer use in maize production is unattractive to many smallholders at current maize price to fertilizer cost ratios relative to other uses of available finance.

Traditional practices affecting soil fertility have variable effects on soil fertility and crop productivity. Shifting cultivation is no longer feasible for soil fertility restoration due to land use pressure. Ridging of the soil for cereal production across the field slope using hand hoes is very common for soil aeration, water conservation and easy root development. There is little incorporation of crop residues in Central and Northern Malawi as the crop residue is harvested by uprooting and used for fuel and livestock feed, or often burnt to ease land preparation. Animal manure is a common nutrient source in the north where cattle density is high compared with other AEZ. In parts of central Malawi, tobacco residues are used to enhance soil fertility. In the Central and Northern Regions, sole crop production prevails with rotation of maize with tobacco, groundnut, bean, soybean, velvet bean and other crops. Some farmers intercrop legumes with other legumes in what is known as 'doubled-up legume technology'.

In the Southern Region, intercropping cereals with legumes is traditional and up to 10 crops can be found in a field. Pigeonpea is often intercropped with maize. Crop residue is incorporated soon after harvesting to recycle nutrients. Relay cropping is practised to take advantage of the residual soil water, especially in the Thyolo Escarpment area. Some farmers in southern Malawi apply manure, homestead wastes and compost.

9.1.3 Fertilizer use and recommendations

Most of the soils in Malawi are highly weathered, low in organic matter (OM) with low pH and low availability of P, K, S, B and Zn; over 40% are Oxisols and Ultisols (Saka et al., 2006).

In early 1970s, 20:20:0 was recommended as a basal dressing followed by top dressing with sulphate of ammonia or calcium ammonium nitrate (CAN). Later, in the 1980s, the government introduced urea and DAP which were cheaper. Later DAP was replaced with 23-21-0+4S as a basal dressing fertilizer followed by top dressing with urea or CAN. However, recently, K is also becoming a more common deficiency, especially on soils that are continuously and intensively cultivated. Much

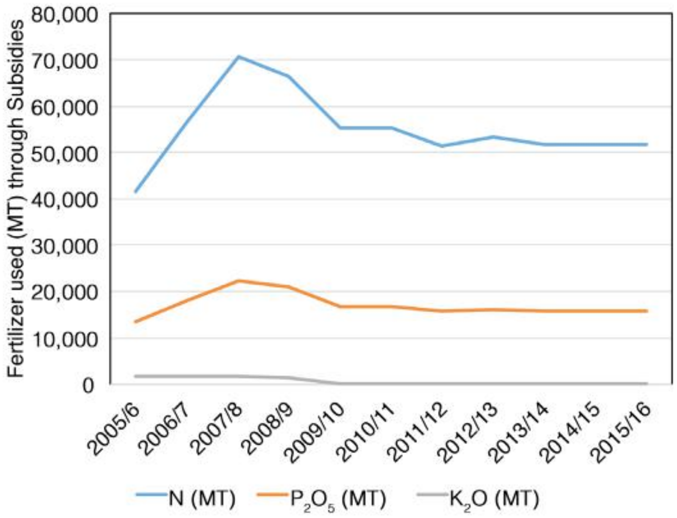


Figure 9.2: Fertilizer use components (NPK) of Fertilizer Input Subsidy Program (FISP) in Malawi from 2005 to 2016 (Source: NSO 2005; Nakhumwa, 2006; MoAFS 2012).

K is removed in crop harvest and soil K has been mined; some recent studies have shown crop yield response to applied K (Chilimba and Liwimbi 2008). Soil S deficiency is nearly as important as N deficiency in many places and 23-21-0+4S has proven appropriate for maize production but usage has been inadequate relative to the importance of S deficiency.

Overall, current fertilizer use in Malawi was estimated at 43 kg per arable hectare in 2015, up from 31 kg/ha in 2003. This rate of use is high compared with mean rates for many African countries; however, it is very low considering the intensity of land use.

The prevailing poverty of smallholder farmers prevents many from using fertilizer. Fertilizer use is constrained by the financial ability of farmers. The profit potential of fertilizer use needs to be increased such as by reducing fertilizer use costs through more efficient fertilizer supply with reduced transport costs, subsidizing fertilizer use, higher commodity prices and better access to low cost and accessible financing. All of these factors have been difficult to achieve. A government subsidy program has contributed

Table 9.2: Common fertilizer recommendations (kg/ha) for cereal production in Malawi although there is area specificity for maize recommendations

Crop	Maize	Millet	Sorghum	Rainfed rice	Irrigated rice
Nutrient type					
N	92 kg	46 kg	46 kg	83 kg	83 kg
P_2O_5	42 kg	42 kg	42 kg	25 kg	25 kg
S	8 kg	8 kg	8 kg	4.8 kg	4.8 kg

to increased fertilizer use and also seed of improved varieties, but primarily targeting fertilizer N (Figure 9.2). There has been a strong focus on fertilizer use for maize production with little attention to other, generally higher value, crops such as pulses.

There are many fertilizer recommendations made for different crops in the country based on the type of the crops grown and agro-ecological zones. The fertilizer recommendations are in three categories that include: 1) general recommendations mostly based on 23:21:0+4S plus N fertilizer (Table 9.2); 2) area specific recommendations; and 3) based on soil and plant tissue analysis. Even though fertilizer recommendations are made for different crops for optimum economic returns, less than 50% of smallholders in the country use any fertiliser and about 70% use less than 50 kg/ha. Mean maize yield is below 2.5 t/ha (MOAFS 2012). A fertilizer blend of 23-10-5+3S+1Zn is now marketed to respond to more frequent occurrence of K and Zn deficiencies. Liming use is recommended for amendment of acid soils.

Efficient fertilizer use requires well managed crops. Fertilizer use can complement organic nutrient sources from manure application and nitrogen fixation by green manure crops, agro-forestry and cereal-legume rotation and intercropping. The value of such integration of practices has been validated through research but there has been little adoption of such practices among smallholder farmers.

9.2 Soil diagnosis and diagnostic trials in Malawi

Mapping soil resources and better targeting of soil amendment practices is ongoing but challenged by the extreme variability in soil fertility conditions. Sixteen OFRA-Malawi trials were conducted on-station or on-farm between 2013/14 and 2014/15 seasons in the mid-altitude and lake shore AEZ of Malawi for different legumes and maize. Fertilizer treatments included a diagnostic nutrient package of Mg, S, Zn and B in addition to N, P, K (P, K for legumes) that was directly comparable to an N, P, K treatment.

The results were inconsistent across sites and years within AEZ (Figure 9.3). There was a mean yield increase of more than 10% with

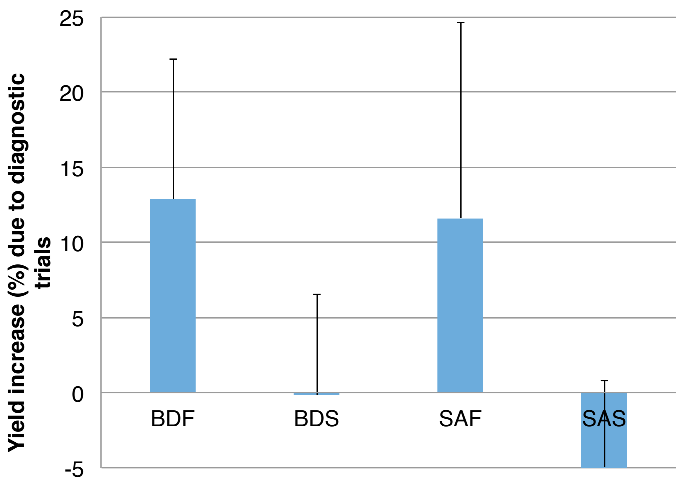


Figure 9.3: The percent yield increase due to application of a diagnostic treatment of N, P, K, Mg, S, Zn and B compared with N, P, and K averaged over maize, groundnut and soybean for 16 on-station or on-farm trials conducted during the 2013/14 and 2014/15 growing seasons. BDF = Bunda on-farm; BDS = Bunda on-station; SAF = Salima on-farm; SAS = Salima on-station. The bars represent standard errors of the mean.

the diagnostic treatment applied for on-farm trials but the mean effect was greater than the standard error of the mean only for the mid-altitude AEZ trials. There was no yield increase due to the diagnostic package of nutrients for on-station trials. The mean response to the diagnostic treatment was similar for all test crops which included cowpeas, soybean and maize. The results suggest more research is needed to better determine if the response was to Zn alone or at least partly due to Mg, S or B.

9.3 Optimizing fertilizer use in Malawi

Fertilizer use optimization in this chapter is considered to be maximization of farmer profit from fertilizer use. It assumes that farmers with adequate financial ability will want to maximize profit per hectare from fertilizer use while financially constrained farmers will want to maximize net returns on their limited investment in fertilizer use. The magnitude and nature of a crop response to an applied nutrient in a given AEZ is important to profitability for both the financially able and the financially constrained farmer. Also very important to the financially constrained farmer is the relative profit potential associated with specific nutrients applied to specific crops, that is, of the crop-nutrient choice.

Crop response to applied nutrients varies with the crop, the nutrient and site-season, and

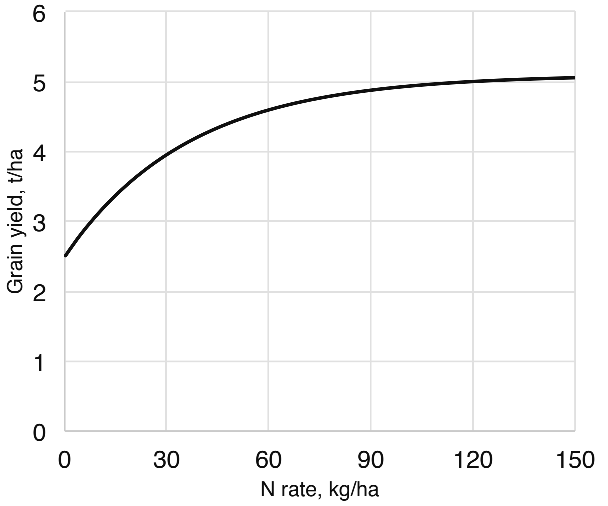


Figure 9.4: A curvilinear yield response maize to applied N for the Highland AEZ of Malawi (Y = 5.1 – 2.6 * 0.973N).

may include no or negative response, a linear response, a quadratic response with yield loss at higher rates of application, and others. However, the response considered over numerous site-seasons of results is typically a curvilinear to plateau as shown for maize response to N in the highland AEZ of Malawi (Figure 9.4) with yield on the vertical axis (y-axis) and rate of applied N on the horizontal axis (x-axis). With such a response, there is a steep yield increase with increasing N at low rates, a smaller rate of yield increase at higher N rates, until yield reaches

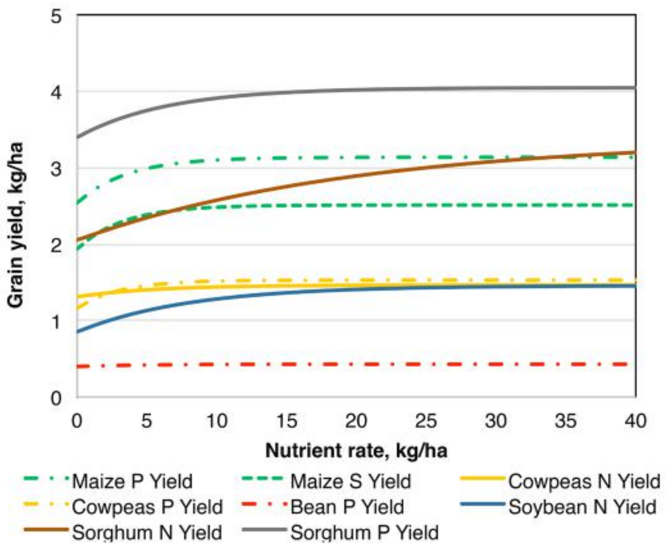


Figure 9.5: Yield nutrient functions for different crops for highlands in Malawi, >1300 masl.

a plateau with no more yield increase. Such responses can be mathematically represented by the asymptotic equation of: Yield (t/ha) = a – bc^r where a is yield at the plateau, b is the maximum gain in yield due to application of the nutrient of interest, c determines the shape of the curve, and r is the nutrient application rate. Such response curves are typical for most crops and nutrients in the highland AEZ (Fig. 9.5). The financially able farmer wants to apply a nutrient until the point where the value of the

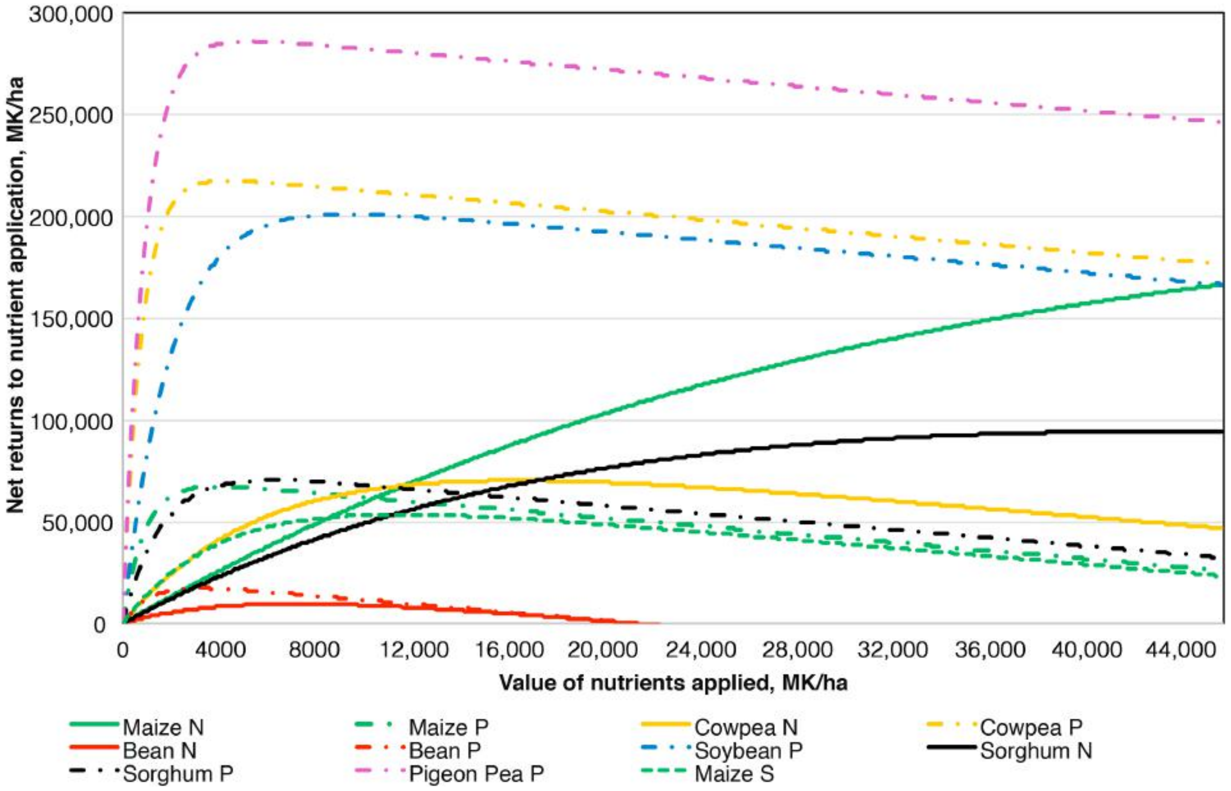


Figure 9.6: Net returns to investment in a crop-nutrient for Highlands AEZ in Malawi (>1300 masl). The assumed fertilizer use cost for 50 kg were: MK 23,000 for NPS and urea, and MK 25,000 for KCl and TSP. Commodity values (MK/kg) were: maize 120; cowpea 600; bean 350; soybean 350; sorghum 300 and pigeon pea 600.

yield increase equals the cost of an additional increment in nutrient rate. This is considered to be the economical optimal rate (EOR). The financially limited farmer, however, should strive to apply at a rate at which yield is still increasing and may choose to apply no more than 30 or 40 kg/ha N for the highland maize response of Figure 9.4, but not more than 5 kg/ha elemental nutrient for several of the crop-nutrient responses displayed in Figure 9.5 and no application of P to bean and N to cowpea.

Some nutrients applied to some crops have much more profit potential than other nutrients applied to the same or other crops (Figure 9.6). Financially constrained farmers need to consider this opportunity to achieve high profit from fertilizer use. The x-axis represents the amount of money invested in one nutrient applied to one crop. The y-axis shows the net returns to investment in application of a nutrient to a crop. Each curve represents the profit potential of a nutrient applied to a crop. The steeper the slope of the curve, the higher the net returns of the investment. As the amount invested increases, the slope decreases but if the response is still increasing, profit is increasing. Where curves reach a peak and the slope is flat, the point of maximum profit per hectare (EOR) is reached. When slopes decline, profit declines.

The financially constrained farmer wants first to take advantage of the crop-nutrient combinations that will give the most profit. The greatest profit potential on a small investment was with a small amount of P applied to legume crops, partly because of their high grain value, and especially for pigeonpea, compared with maize or sorghum. Also, a small amount of P applied to maize and sorghum was very profitable although these responses may only occur if some N is applied. Application of N to maize, sorghum and cowpea, and of S to maize, also have good profit potential although less with small investments compared to other options. Therefore, the financially constrained farmer needs to take advantage of the best profit opportunities according to their ability and, hopefully, use some of the increased profits to gradually become less financially constrained and eventually apply fertilizer to all cropland at rates to maximize profit per hectare.

Consideration of the nature of different crop nutrient response functions together with the farmer's land allocation, the expected value of the commodity, the fertilizer costs and the farmer's budget constraint is very complex. To deal with this complexity, easy to use fertilizer use optimization tools (FOTs) were developed using Excel Solver © (Frontline Systems Inc., Incline Village, NV, USA) which use complex mathematics of linear optimization to integrate the economic and agronomic information and give a solution (https://agronomy.unl.edu/OFRA).

Use of the Excel FOT requires that the add-in Solver is activated and macros are enabled; step-by-step instructions are given in the 'Help and Instructions' worksheet of the FOT (Figure 9.7). More detailed instructions are in Extension Materials and FOT Manual at the same website.

The data input screen is where the farmer needs to estimate how much land will be planted to each crop of interest, the farm-gate value per kg at harvest considering that some is for home consumption (the most valuable) and that the surplus will be marketed, and the cost of using different fertilizers (Figure 9.7). The farmer's available money for fertilizer use is also entered as the budget constraint.

The results are displayed as in Figure 9.8, including the amount of each fertilizer to apply to each crop, the expected average yield increases and net returns, and the total net returns to fertilizer use for the farm. In this example, the farmer has only NPS and urea as available fertilizers. The budget constraint of Malawi kwacha (MKW) 150,000 is not sufficient to apply fertilizer at EOR but gives recommendations of more than 25 kg/ha for urea and NPS applied to maize and NPS applied to cowpea and pigeonpea. The recommended rates of less than 25 kg/ha are too low for feasible application and it is suggested that these fertilizers or the money be allocated elsewhere such as to increase the fertilizer applied to cowpea and pigeonpea. The expected average total return to MKW 150,000 invested in fertilizer use is MKW 918,133. If, however, TSP were available for a cost of MKW 30,000 per 50 kg, the expected average total net return is MKW 1,1012,746 increasing the farmer's profit potential by over 10%. Restricted availability of fertilizer types requires farmers to buy and apply nutrients that give no or less return compared to other nutrient application options.

DARS

above 1300 M

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	July 6, 2016

Crop Selection and Prices

Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Maize	3	120
Cowpea	1	600
Bean	1	700
Soybean	1	350
Sorghum	1	120
Pigeon pea	1	600
Total	8	

Fertilizer Selection and Prices

Fertilizer Product	N	P2O5	K2O	S	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	25,000
TSP	0%	46%	0%	0%	0
NPS	23%	21%	0%	4%	25,000
	0%	0%	0%	0%	0
	%	%	%	0%	0

Budget Constraint

Amount available to invest in fertilizer	150000

Figure 9.7: The input screen of the FOT for the Highlands AEZ in Malawi (>1300 masl).

Fertilizer Optimization

	Application Rate - kg/Ha				
Crop	Urea	TSP	NPS	xx	
Maize	29	0	30	0	0
Cowpea	0	0	46	0	0
Bean	0	0	0	0	0
Soybean	0	0	7	0	0
Sorghum	22	0	0	0	0
Pigeon pea	0	0	47	0	0
	0	0	0	0	0
Total fertilizer needed	109	0	191	0	0

Expected Average Effects per Ha

Crop	Yield Increases	Net Returns
Maize	1,494	149,688
Cowpea	410	223,193
Bean	0	181
Soybean	47	12,966
Sorghum	519	51,579
Pigeon pea	341	181,150
	0	0

Total Expected Net Returns to Fertilizer

Total net returns to investment in fertilizer	918,133

Figure 9.8: The output screen of the FOT for the Highlands AEZ in Malawi (>1300 masl).

Table 9.3: Malawi Fertilizer Use Optimizer: paper version, Mid-elevation, upland and plateau (760-1300 m)

The below assumes:
Calibration measurement unit: a water bottle cap (CAP, 8 ml) for 5.6 g urea, 8 g of NPS.
Row spacing: maize, 75 cm; bean, soybean, cowpea all 50 cm; pigeonpea 75 cm.
Application point spacing: maize and cowpea, 25 cm; groundnut 20 cm; pigeonpea 75 cm.
Grain prices: per kg (MK): 120 maize; 350 bean; 120 rice; 300 sorghum; 600 pigeonpea; 600 cow pea; 700 groundnut; Fertilizer use costs per 50 kg bag (MK): 25,000 urea; 23,000 NPS.
Weeks after planting (WAP).

Level 1 financial ability.	
Maize	point apply 69 kg NPS, 8 WAP (1 CAP for 5.8 plants or 2.9 points)
Cowpea	point apply 55 kg NPS at planting (1 CAP for 7.9 plants or 4 points)
Bean	band apply 33 kg urea at planting (1 CAP for 2.2 m)
Soybean	band apply 66 kg NPS at planting (1 CAP for 1 m)
Pigeonpea	point apply 85 kg NPS at planting (1 CAP for 5.1 plants or 2.5 points)
Level 2 financial ability.	
Maize	137 kg NPS at 2 WAP (1 CAP for 3.1 plants and 1.5 points); point apply 45 kg urea, 8 WAP (1 CAP for 6.2 plants and 3.1 points)
Cowpea	point apply 72 kg NPS at planting (1 CAP for 6.5 plants and 3.2 points)
Bean	band apply 30 kg Urea at planting (1 CAP for 9.4 m) at planting
Soybean	band apply 90 kg NPS at planting (1 CAP for 0.7 m)
Pigeonpea	point apply 98 kg NPS at planting (1 CAP for 4.4 points)
Sorghum	52 kg NPS, 2 WAP (1 lid for 8.2 plants and 4.1 points); point apply 28 kg urea, 8 WAP (1 lid for 10 plants and 5 points)
Level 3 financial ability (maximize profit per acre).	
Maize	150 kg NPS at 2 WAP (1 CAP for 2.9 plants and 1.5 points); point apply 121 kg urea, 8 WAP (1 CAP for 2.4 points)
Cowpea	point apply 89 kg NPS at planting (1 CAP for 4.8 plants and 2.4 points)
Bean	band 71 kg NPS at planting (1 CAP for 1.5 m)
Soybean	point apply 142 kg NPS at planting (1 CAP for 0.4 m)
Pigeonpea	point apply 125 kg NPS at planting (1 CAP for 3.5 plants and 1.7 points)

A consequence of the very restricted fertilizer availability is that for the farmer to apply P to pigeonpea, cowpea, and soybean, three very profitable options in Figure 9.6, they also must pay for N and S in the compound fertilizer, even though there is no evidence of these crops having a response to these nutrients; therefore the benefits to fertilizer use for these crops is, in this example, much less than the potential indicated in Figure 9.6.

Farmers and their advisors often do not have ready access to a computer for use of the Excel Solver © FOT. A paper-based FOT has therefore been developed for each Excel Solver© FOT for the mid-elevation, upland and plateau AEZ (Table 9.3). The paper FOT is constructed for three financial levels: 1) for the farmer who is poor and has no more money than one-third the amount required to apply fertilizer to all cropland at EOR; 2) for the farmer with more money but has no more money than two-thirds the amount required to apply fertilizer to all cropland at EOR; and 3) for the farmer with enough money to apply fertilizer to at least some of the cropland at EOR.

The paper tool makes assumptions about: the calibration measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer; crop row and plant spacing; fertilizer use costs per 50 kg bag; and expected commodity values on-farm at harvest, considering the value both for home consumption and for market.

Table 9.4: Fertilizer use within an ISFM Framework: fertilizer substitution and soil test implications

ISFM practice	Urea or CAN	DAP or TSP	NPK 23-21-0+4S or 23:10:5+6S+1.0Zn
	Fertilizer reduction, % or kg/acre		
	N	P	K
Previous crop was a green legume manure (Mucuna, Crotalaria and Lablab) crop	100%	8 kg	28 kg †
Early incorporation of a green legume manure (Mucuna, Crotalaria and Lablab) crop	57 kg	3 kg	11 kg †
Use of agroforestry technologies (e.g. leaf prunings of Gliricidia, Leucaena, Sesbania, *Senna spectabilis*) applied, per 1 t of fresh material	10 kg	1 kg	6 kg††
Farmyard manure per 1 t of dry material	2 kg	1 kg	1 kg
Residual value of FYM applied for the previous crop, per 1 t	1 kg	0.4 kg	0.4 kg
Dairy or poultry manure, per 1 t dry material	24 kg	7 kg	14 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	5 kg	1.4 kg	3 kg
Compost, per 1 t/ha dry wt	20 kg	1 kg	20 kg
Doubled-up legume-technology (pigeonpea/groundnuts etc)	In the following year, reduce urea by 50 kg/ha †††		
Cereal-bean intercropping	Increase DAP/TSP by 18 kg/ha, but no change in N & K compared with sole cereal recommendations		
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 20 kg/ha, reduce urea by 30 kg/ha, and no change in K compared with sole cereal recommendations		
If Mehlich III P >18 ppm	Do not apply P		
If soil test K < 0.25 cmol/kg	Apply 20 kg KCl/ha		

†Saka et al. 2006
††Akinnifesi et al. 2006
†††Njira et al. 2012

The paper FOT tables address the 4Rs of fertilizer use advising on the right product, rate, time and method of application. It also advises on calibration, that is, the distance along the band or the number of points per measuring unit for the recommended fertilizer rate. A constraint of the paper FOTs is that these need to be revised, maybe annually, if significant changes occur in the costs of fertilizer use relative to the commodity values.

The paper FOT is easy to use (Table 9.3). Consider the recommendation for maize under Level 2 financial ability "Maize: 137 kg NPS at 2 WAP (1 CAP for 4.4 plants); point apply 45 kg urea, 8 WAP (1 CAP for 12.5 points)".

Therefore, 137 kg/ha of NPS is to be point applied at 2 weeks after planting. One 8 ml water bottle cap is sufficient for 4.4 plants. In addition, 45 kg/ha
urea is to be applied at eight weeks after planting. The farmer learns to apply this rate by applying one water bottle lid to 12.5 plants.

Another aspect of fertilizer use optimization is to adjust fertilizer rates according to other practices when these are applied to a parcel of land and to soil test values. After getting the results of the FOT, the farmer considers parcels of land where practices of Table 9.4 have been or will be applied. Some of the practices have fertilizer substitution value and fertilizer rates can be decreased. Intercropping calls for an increase in some fertilizer. Soil test P is considered with the assumption that most fields have sufficiently low soil test P that the probability of response is high but if soil test results indicate adequate P, then the P application should be withheld from that land parcel and applied elsewhere or the money reallocated. The soil test K assumes that generally soil K availability is adequate and the FOT recommendation is followed, but if soil test results find very low K availability, some application of KCl is advised.

9.4 Targeted crops and cropping systems by AEZ

For Malawi, maize, bean, pigeonpea, soybean, cowpea and sorghum were considered for the highlands and all of these crops except sorghum were considered for the other AEZ (Table 9.5a-c). The lakeshore and all of the Shire Valley were considered as one recommendation domain in the development of FOTs.

In this series of tables, column 1 and 2 give the crop and nutrient, columns 3-5 give a, b and c coefficients of the curvilinear to plateau response function, columns 6-9 give the yield increases asssociate with incremental changes in nutrient rate, column 10 and 11 give EOR determined from field research results and the recommended elemental nutrient application rates (REC).

In the highland AEZ, with the exception of bean, crops had good responses to applied N and P (Table 9.5a). Maize responded well to applied K and S. In the mid-elevation and upland plateau AEZ and in the lakeshore and the Shire River Valley AEZ, maize again responded well to N, P and S but not to K (Table 9.5b,c). Bean was more responsive to N than in the highlands.

Table 9.5a: Highlands >1300 masl - Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			**t/ha**				**kg/ha**	
Highlands (above 1300 m) AEZ										
Maize	N	5.100	2.600	0.973	1.456	0.641	0.282	0.124	81	69-92
Cowpea	N	1.465	0.154	0.835	0.153	0.001	0.000	0.000	16	0
Bean	N	0.429	0.031	0.798	0.031	0.000	0.000	0.000	7	23
Sorghum	N	3.377	1.326	0.951	1.032	0.229	0.051	0.01Y	43	58
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.137	0.600	0.756	0.452	0.112	0.028	0.007	8	3-18
Cowpea	P	1.529	0.371	0.720	0.299	0.058	0.011	0.002	11	20†
Bean	P	0.429	0.031	0.798	0.021	0.007	0.002	0.001	4	9
Soybean	P	1.457	0.607	0.883	0.281	0.151	0.081	0.043	20	9-18
Sorghum	P	4.047	0.651	0.856	0.352	0.162	0.074	0.034	11	9
Pigeonpea	P	2.538	0.487	0.758	0.365	0.091	0.023	0.006	15	20†
Maize	K	4.863	0.563	0.896	0.238	0.137	0.079	0.046	19	6-8
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	16	0
Soybean	K	0.837	0.019	0.908	0.007	0.004	0.003	0.002	0	0
Pigeonpea	K	2.535	0.127	0.666	0.110	0.014	0.002	0.000	10	0
Maize	S	2.510	0.577	0.738	0.451	0.099	0.022	0.005	12	4

†Kamanga et al. 2010. EOR was determined with the cost of using 50 kg NPS at MK 23,000, urea, KCl and TSP at MK 25,000. Commodity values (MK/kg) used were: maize 120; cowpea 600; bean 350; soybean 350; sorghum 300 and pigeonpea 900

Table 9.5b: Mid-elevation and upland plateau (760-1300 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Mid-elevation and upland plateau (760-1300m) AEZ										
Maize	N	4.906	2.572	0.982	1.081	0.627	0.363	0.211	78	69-92
Bean	N	0.838	0.293	0.862	0.290	0.003	0.000	0.000	21	23
Soybean	N	1.131	0.046	0.929	0.041	0.004	0.000	0.000	0	23-50
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.853	1.794	0.972	0.237	0.206	0.179	0.155	24	3-18
Cowpea	P	1.529	0.371	0.72	0.299	0.058	0.011	0.002	10	20†
Bean	P	0.884	0.058	0.869	0.029	0.014	0.007	0.004	4	9
Soybean	P	1.359	0.608	0.868	0.308	0.152	0.075	0.037	16	9-18
Pigeonpea	P	2.538	0.487	0.758	0.365	0.091	0.023	0.006	13	20†
Maize	K	4.084	0.097	0.9	0.040	0.023	0.014	0.008	2	6-8
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	16	0
Soybean	K	1.402	0.508	0.781	0.360	0.105	0.030	0.009	16	0
Pigeonpea	K	2.535	0.127	0.666	0.110	0.014	0.002	0.000	10	0
Maize	S	2.555	0.400	0.761	0.298	0.076	0.019	0.005	11	4

Table 9.5c: Lakeshore, middle and upper Shire (200-760 masl)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increases				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Lakeshore, Shire River valley (200-760 m) AEZ										
Maize	N	4.905	2.571	0.982	1.080	0.626	0.363	0.211	87	69-92
Bean	N	0.838	0.293	0.862	0.290	0.003	0.000	0.000	22	23
Soybean	N	1.131	0.046	0.929	0.041	0.004	0.000	0.000	0	23-50
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.853	1.794	0.972	0.237	0.206	0.179	0.155	30	3-18
Cowpea	P	1.529	0.371	0.720	0.299	0.058	0.011	0.002	10	20†
Bean	P	0.884	0.058	0.869	0.029	0.014	0.007	0.004	5	9
Soybean	P	1.359	0.608	0.868	0.308	0.152	0.075	0.037	17	9-18
Pigeonpea	P	2.538	0.487	0.758	0.365	0.091	0.023	0.006	14	20†
Maize	K	4.084	0.097	0.900	0.040	0.023	0.014	0.008	2	6-8
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	16	0
Soybean	K	1.402	0.508	0.781	0.360	0.105	0.030	0.009	16	0
Pigeonpea	K	2.535	0.127	0.666	0.110	0.014	0.002	0.000	10	0
Maize	S	2.555	0.400	0.761	0.298	0.076	0.019	0.005	11	4-10

All crops had profitable response to P and all except for bean had profitable responses to K.

In 28% of 42 comparisons of EOR with REC, the REC was an average of 60% less. In 38% of the comparisons, the REC was on average 96% higher than EOR. For K applied to soybean, pigeonpea and cowpea, and for N applied to cowpea in the highlands, EOR were determined while the RECs were for no K application to these crops.

9.5 Acknowledgements

The Malawi team is indebted to the following people and organizations for their support and guidance in putting together this work: cooperating farmers in Malawi (especially in Lilongwe, Dedza and Salima districts), LUANAR support staff, agriculture extension development coordinators (AEDCs), agriculture extension development officers (AEDOs), AGRA, CABI, UNL, Kayuki Kaizzi and Charles Wortmann.

9.6 References

Akinnifesi FK, Makumba W and Kwesiga FR (2006) Sustainable maize production using gliricidia/maize intercropping in southern Malawi. Expl Agric 42:1–17 doi:10.1017/S0014479706003814

Chilimba ADC and Liwimbi L (2008) Evaluation of nitrophosphate fertilizer for maize production in Malawi. Annual Report of the Soil and Agricultural Engineering Commodity Group. Department of Agricultural Research Annual Planning meeting held at Andrews Holiday Resort, Mangochi, 14 – 19th September 2008; pp. 63-75

Kamanga BCG, Whitbread A, Wall P, Waddington SR, Almekinders C and Giller KE (2010) Farmer evaluation of phosphorus fertilizer application to annual legumes in Chisepo, Central Malawi. Afric J Agric Res 5:668-680

MOAFS (2012) Guide to Agricultural Production and Natural Resources Management in Malawi. Ministry of Agriculture and Food Security, Department of Agricultural Extension Services, Lilongwe, Malawi

Nakhumwa TO (2006) Rapid evaluation of the 2005 fertilizer subsidy program in Malawi. Policy Paper No 10, CISANET, Lilongwe, Malawi

Njira KOW, Nalivata PC, Kanyama-Phiri GY and Lowole MW (2012) Biological nitrogen fixation in sole and doubled-up legume cropping systems on the sandy soils of Kasungu, Central Malawi. Journal of Soil Science & Environmental Management 3:224-230

NSO (National Statistical Office of Malawi) (2005) Integrated household survey 2004–2005. NSO, Zomba, Malawi

Saka AR, Mtukuso AP, Daudi AT, Banda MHP and Phiri IMG (2006) Agricultural technologies released by the Ministry of Agriculture and Food Security – 2000-2005 [crop varieties, crop and livestock production technologies, and agricultural processing and utilization technologies]. Department of Agricultural Research Services, Ministry of Agriculture and Food Security, Lilongwe, Malawi

10. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Mozambique

Ricardo Maria[1] ricardo_dejesus@hotmail.com, Janete Americano[1], Jossias Matusso[2] and Cláudio Gundana[3]

[1] Instituto de Investigação Agrária de Moçambique (IIAM), Av. Das FPLM No. 2698, Caixa Postal 3658, Maputo, Mozambique
[2]Agência de Desenvolvimento de Manica (ADEM), Rua 16 de Junho, nr 217, Chimoio, Mozambique
[3]Africa Fertilizer Agrobusiness Partnership (AFAP), P.O. Box 1218, Maputo, Mozambique

10.1 Introduction

Inadequate soil fertility is an important constraint to crop production in Mozambique. Soil pH is mostly moderate but high sand content and low soil organic matter commonly contribute to low nutrient availability and low available soil water holding capacity.

Most crop production is by smallholders who are poor and unable to invest much in the use of inputs. Their severe financial constraint requires that they obtain high rates of return on their small investments and the investment must have a low rate of risk. A farmer typically faces different choices in fertilizer use and needs to choose the crop-nutrient-rate combinations that are expected to be most profitable with a low risk. Such decisions need to be based on solid information derived from field research. The Instituto de Investigação Agrária de Moçambique (IIAM) therefore partnered with national agricultural research organizations of 12 other countries under the AGRA funded project Optimizing Fertilizer Recommendations in Africa (OFRA) with management support from CABI and technical and scientific support from the University of Nebraska-Lincoln. This partnership improved the field research derived information base needed for optimizing fertilizer use, applied the information to develop easy to use decision tools (FOTs) for three broad recommendation domains in Mozambique, and provided training to research and extension personnel for advising farmers on fertilizer use optimization.

10.2 Agricultural systems of Mozambique

Agriculture in Mozambique is practised mainly by smallholder farmers with less than 5 hectares of crop production. There are over 3 million smallholder family farms which is 99% of all farms accounting for 95% of the cultivated land. About 25% of 36 million hectares of arable land

Table 10.1: Characteristics of agro-ecological zones (AEZ) of Mozambique

AEZ	Location	Altitude m	Mean rainfall mm	Mean temperature °C	Dominant soils
R1	Maputo, south of Gaza	0-500	<800	>24	Arenosols, Nitisols
R2	Coastal region and southern Sabi River valley	0-500	<1000	>24	Arenosols, Fluvisols
R3	Central and northern Gaza and east of Inhambane	0-500	<800	>24	Arenosols, Lixisols
R4	Central medium altitude areas	200-1000	1000-1200	22-24	Ferralsols, Luvisols
R5	Sofala and Zambézia areas	0-500	1000-1400	>24	Arenosols, Fluvisols
R6	Zambezi Valley and south of Tete	0-500	400-600	>24	Fluvisols, Lixisols
R7	Zambézia, Nampula, Tete, Niassa and Cabo Delgado	0-500	<1200	<24	Lixisols, Leptosols, Arenosols
R8	Coastal zone of Zambézia, Niassa and Manica	0-500	800-1200	<24	Lixisols, Luvisols
R9	Northern Cabo Delgado	400-1000	>1000	<22	Arenosols
R10	High altitudes of Zambézia, Niassa and Manica	>800	>1000	<22	Arenosols

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

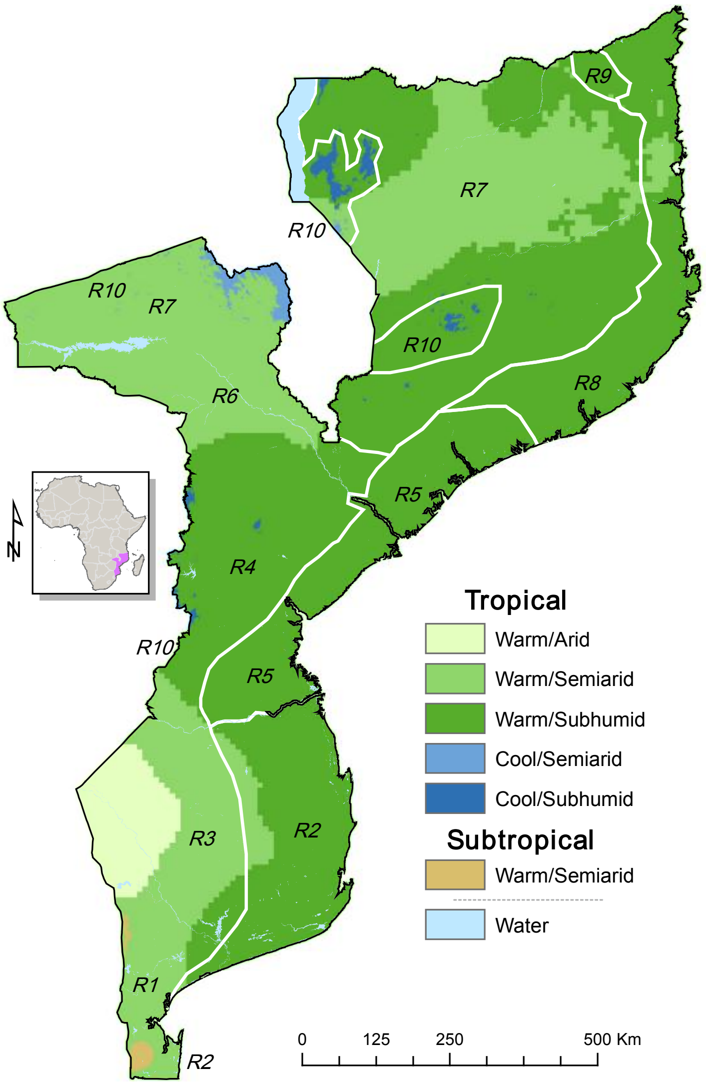


Figure 10.1: Agro-ecological zones of Mozambique overlain on climatic zonation of HarvestChoice.

is currently under cultivation. However, mean cereal yields, including maize, are below 0.7 t/ha due to low soil fertility, drought, pests and disease. Smallholder agriculture makes little use of inputs, mechanization and irrigation to enable both the expansion and intensification of production. Average fertilizer use for crop land is only about 2 kg/ha and most smallholders use no fertilizer. Maize, lowland rice, cassava and bean are the priority crops of smallholders.

10.2.1 Agro-ecological zones (AEZ)

Mozambique has diverse farming systems associated with ten agro-ecological zones (AEZs) (Figure 10.1; Table 10.1) of which annual rainfall and elevation are important determinants (Figure 10.2). The most productive soils are Fluvisols such as in the valleys of the Zambezi, Incomate and Limpopo rivers. Sandy Arenosols are the dominant soil type covering approximately 28% of the country. Lixisols and Luvisols are important in medium altitude

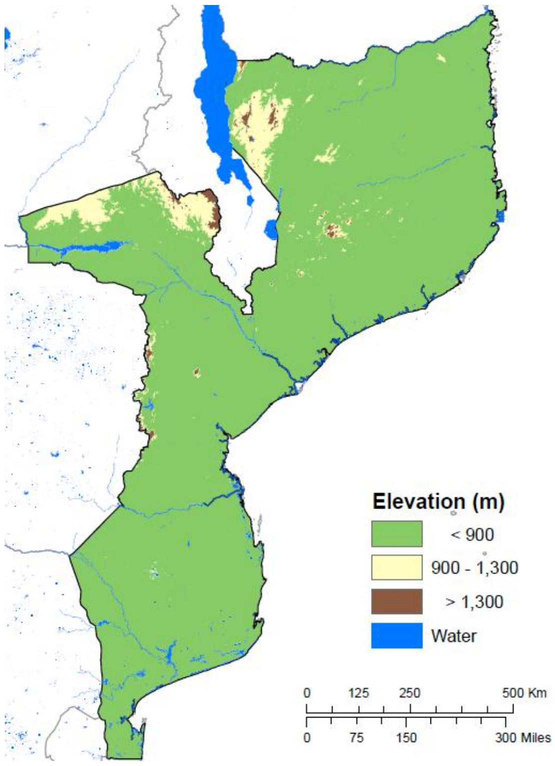


Figure 10.2: Elevations of Mozambique.

areas, and cover 23 and 5% of total land area, respectively. These soils are heavily weathered with sandy surface layers and an accumulation of clay in the subsurface layer. Ferralsols and Acrisols are common in high rainfall plateau areas and generally have low soil pH, low nutrient availability and high P sorption capacity due to high aluminium content. Leptosols, Acrisols and Ferralsols cover 9, 8 and 7% of the land area.

10.2.2 Soil fertility management in Mozambique

Shifting cultivation with no nutrient application is common in Mozambique. Manure is applied when available, mostly for vegetables and other high value crops, and especially in central and southern Mozambique where livestock production is significant. Expansion of crop production has resulted in less use of fallow periods and increased cultivation of marginal land that is often highly erodible. Significant deforestation has occurred. Burning of vegetative material after clearing fallow land and burning of crop residues is common. Soil nutrient depletion is relatively great with cassava and maize compared with other crops. Estimated nutrient depletion (kg/ha/yr) for all of Mozambique, including from erosion, is estimated at 34, 6 and 25 for N, P and K, respectively.

The Ministry of Agriculture and Food Security (MASA) and agriculture development organizations have initiated a voucher subsidy programme to enable increased fertilizer use. Efficient fertilizer use, however, has been constrained by inadequate soil information and fertilizer recommendations. Fertilizer availability is generally limited to N:P:K 12:24:12 and urea. Therefore, the application of some nutrients which result in little or no profit reduce the profit potential of fertilizer use.

Soil test results and nutrient-need prediction tools such as the Nutrient Management Support System (NuMaSS) (http://www.ctahr.hawaii.edu/sm-crsp/program_areas/AnnRepPY10/numass/AnnualReportNuMaSSUnivHawaii2006_2007a.pdf) and Phosphorus Decision Support System (PDSS) (http://www2.ctahr.hawaii.edu/tpss/research_extension/soliresearch/pdss.html) indicate widespread occurrence of N and

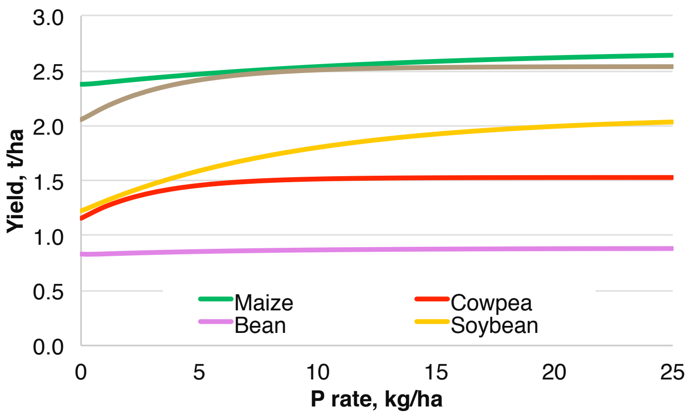


Figure 10.3: Examples of crop nutrient response curves determined from crop response functions for applied P in mid-altitude areas of Mozambique.

P deficiencies, as is common throughout sub-Saharan Africa. A critical level for soil exchangeable potassium (K) of 0.2 meq/100 g of soil or 80 ppm appears appropriate for Mozambique. Typical soil K levels in Mozambique range from 0.26 to 0.98 meq/100 g soil for Arenosols and Acrisols, respectively, with other soil types having intermediate levels.

10.2.3 Diagnosis of nutrient deficiencies

Trials were conducted for maize, sorghum and soybean in the Manica and Burwe areas under OFRA in 2014-15. The mean yield increases for maize and sorghum over 14 variety-site combinations were 81, 22 and 18% for applied N, P and S, respectively, and the mean yield increases for soybean over four sites were 38 and 16% for applied P and S. The trials included a diagnostic treatment of N+P+S+Mg+Zn+B which was comparable to an N+P+S treatment. No N was applied in the soybean trials. The diagnostic treatment was as likely to result in yield losses as gains and the average increase due to the diagnostic treatment was -8% of soybean and 1% for cereals, neither of which was significantly different from zero. The results support other diagnoses of N and P deficiencies but also S deficiency and indicate that application of other secondary and micro nutrients is not likely to be profitable.

10.3 Fertilizer use optimization in Mozambique

Normally farmers wish to maximize profit from fertilizer use. Farmers with adequate financial resources may strive to maximize profit per hectare resulting from fertilizer use. However, most farmers in Mozambique are very poor

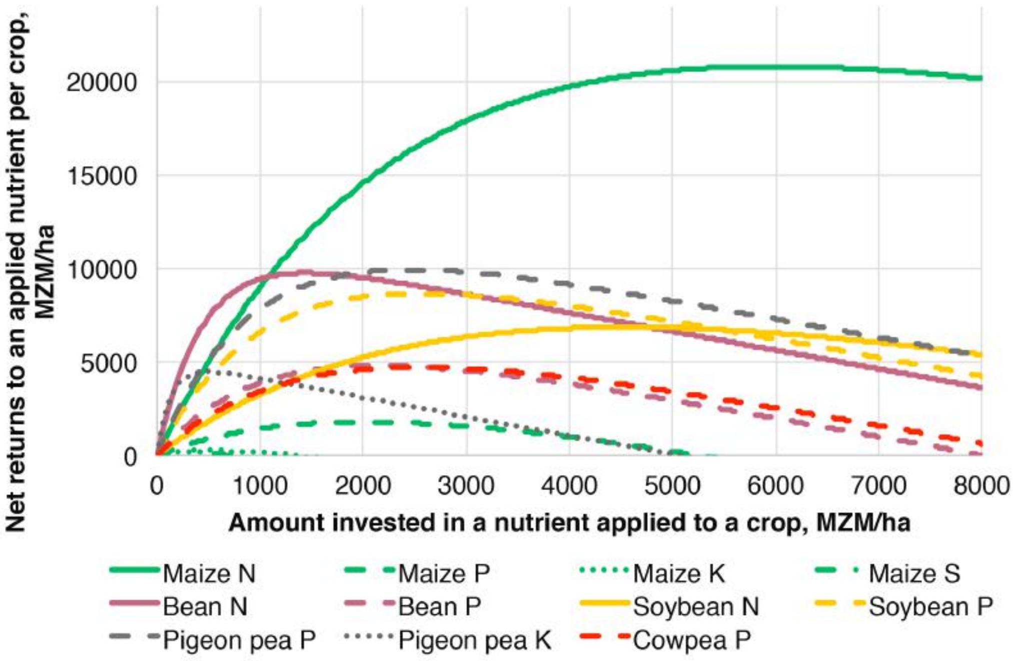


Figure 10.4: Net return to investment in the application of a nutrient to a crop in areas at <900 masl in Mozambique with the cost of using 50 kg urea, TSP, NPK 12-24-12, and NPS 12-24-0-6 being MZM 1500. Commodity values (MZM/kg) used were 15 for maize and sorghum; 30 for cowpea and soybean; 40 for bean and pigeonpea.

and have the financial resources to use little if any fertilizer. These poor farmers need to obtain very high net returns on their small investments in fertilizer use. Therefore, fertilizer use optimization in this chapter refers to maximizing profit from fertilizer use according to the farmer's agronomic and economic situation.

The nature of crop response to applied nutrients, over a large number of trials, is usually curvilinear to a plateau as illustrated most clearly by cowpea and pigeonpea response to P in mid-altitude areas of Mozambique (Figure 10.3). The soybean P response is relatively large and has not reached the yield plateau with 25 kg/ha of P applied. Maize and bean responses to P were small in this AEZ.

These responses are mathematically represented by the equation $Y = a - bc^r$ where Y is yield, a is yield at the plateau for application of that nutrient, b is the maximum yield increase due to application of the concerned nutrient, c is a determinant of the response curve, and r is the nutrient application rate. As P rates increase, the yield increase per additional kg of applied P decreases. In all cases, the yield increase per kg/ha of P applied is relatively great at lower compared with higher P rates. Greater net returns to Mozambique metical (MZM) invested in fertilizer use are expected with lower compared with higher P application rates.

Another consideration in optimizing fertilizer use for high profit is that the profit potential is greater for some nutrients applied to one or more crops compared with other crop-nutrient combinations. An example is given from areas of less than 900 masl (Figure 10.4). On the horizontal x-axis, the amount of money (MZM) invested in a nutrient applied to a crop is given. On the vertical y-axis, the net return to nutrient application is given. Each curve represents a crop-nutrient combination. Because the figure represents economics of fertilizer use, the fertilizer costs and crop values influence the magnitude and shape of response. Throughout this chapter, the current subsidized fertilizer cost of MZM 1500 per 50 kg bag was used irrespective of the actual cost. Grain prices used were MZM 15/kg for maize and sorghum, 30 for cowpea and soybean, and 40 for bean and pigeonpea. When the curves are steep, the net return for the amount invested is high. Several crop-nutrient curves are very steep initially offering potential for very high rates of return at low application rates including for N applied to maize and bean, P applied to soybean and pigeonpea, and K applied to pigeonpea. As application rates increase, slopes become less steep and some other options, such as N applied to soybean and P applied to cowpea and bean, become competitive options. Some of the curves reach a peak at low rates. The rate of application at the peak is the rate expected to give the most profit per hectare and is called the economically optimal rate (EOR) in this chapter. For example, K applied to pigeonpea has very high profit potential but the cost of application should not exceed about 200 MZM/ha.

Farmers who are not constrained financially in fertilizer use should apply to all crops at EOR to maximize profit per hectare due to fertilizer use. The large total profit potential is with N applied to maize, with an expected average return of about MZM 15,000 with 2000 invested or about 30 kg N applied, after which the rate of return is less until a peak with approximately 100 kg N applied. Using different commodity values relative to fertilizer costs will change the shape of the curves and Figure 10.3 may not apply well to a farmer who cannot access subsidized fertilizer.

Profit from fertilizer use therefore depends on the nature of the response of a crop to applied nutrient (Figures 10.3 and 10.4), the costs of fertilizer use and the on-farm value of the commodity considering both the expected market value for the surplus and value of that kept for home consumption. The farmer's choice of crops, the land allocated to each crop and the amount of money that the farmer has to invest in fertilizer use also need to be considered. Decisions for fertilizer use optimization for maximization of net returns are complex for farmers with several crops and financially constrained fertilizer use. Easy to use decision tools utilizing the complex mathematics of linear programming were developed for three recommendation domains of Mozambique.

10.4 Fertilizer optimization tools for Mozambique

The computer fertilizer optimization tools (FOTs) have been developed to integrate economic and agronomic information through linear programming using Excel Solver© (Frontline Systems Inc., Incline Village, NV, USA). These are available at http://agronomy.unl.edu/OFRA. To use a FOT, the add-in Solver needs to be activated and macros need to be enabled; this is addressed in the 'Help and Instructions' worksheet of the FOT and in more detail in an FOT user manual in Extension Training Materials at this website.

The data input screen (Figure 10.5) requires entry of the land area to be planted for each crop and the estimated on-farm value per kilogram of grain near harvest time. The example shows that the FOT does optimization across six crops. These FOTs do not address intercropping at this time. Each crop is allocated one hectare but the farmer is likely to allocate land differently for each crop; if the crop is not planted, enter 0 for land area. The cost of using different fertilizers is entered; the example shows the subsidized price of MZM of 1500, but the farmer should enter the real cost, with or without subsidy, and including transport and application costs. If a listed fertilizer is not available, enter 0 for the cost. Finally, the money available for fertilizer use is entered as the budget constraint; MZM 15,000 was entered in the example. The optimize button is left clicked to run the optimization.

The output includes: the amount of fertilizer to apply to each crop; the expected average yield increases and net returns to fertilizer use per hectare; and the total net returns to fertilizer use for the farm (Figure 10.6). Most of the recommended fertilizer is for maize which has an expected average maize yield increase of 1775 kg/ha. The expected mean net return to fertilizer use was estimated to be MZM 84,725 for a benefit:cost ratio of 5.6. In this example, TSP and KCl were assumed to be available. If fertilizer availability were limited to urea and NKP, the expected mean net return is MZM 70,896, 84% of the profit potential compared with availability of important single nutrient fertilizers.

Financially constrained fertilizer use optimization contributes to low risk associated with fertilizer use through diversification of investment. Rather than applying all fertilizer to a single crop at a recommended rate, fertilizer use optimization results in fertilizer being applied to two or more crops and over more land at lower rates. All crops in all fields are less likely to fail compared to a single well fertilized crop in, maybe, only one field.

For each Excel FOT, a companion paper FOT was developed to be used when a computer is not available. The paper FOT has three financial levels: level 1 for the poor farmer who has less than one-third of the amount needed to buy the fertilizer to apply to all the cropland at EOR; level 2 for the farmer who has less than

Elevation > <900 m

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	**August 18, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Ha)***	**Expected Grain Value/kg †**
Maize	1	20
Cowpea	1	30
Bean	1	40
Sorghum	1	20
Soybean	1	30
Pigeon Pea	1	40
Total	**6**	

Fertilizer Selection and Prices					
Fertilizer Product	**N**	**P2O5**	**K2O**	**S**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	1500
Triple super phosphate, TSP	0%	46%	0%	0%	1500
NPK	12%	24%	12%	0%	1500
Blank	0%	0%	0%	0%	0
Optional	23%	20%	0%	6%	1500

Budget Constraint	
Amount available to invest in fertilizer	15000

Figure 10.5: An image of the input screen for a fertilizer optimization tool.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**TSP**	**NPK**		**Optional**
Maize	117	4	0	0	48
Cowpea	0	38	0	0	0
Bean	33	36	0	0	0
Sorghum	19	36	0	0	0
Soybean	0	65	0	0	52
Pigeon Pea	0	51	0	0	0
	0	0	0	0	0
Total fertilizer needed	170	230	0	0	100

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
Maize	1,772	30,348
Cowpea	161	3,691
Bean	390	13,513
Sorghum	355	5,435
Soybean	866	22,476
Pigeon Pea	270	9,261
	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	84,724

Figure 10.6: An image of the output screen for a fertilizer optimization tool.

Table 10.2: Example of a paper fertilizer use optimizer tool

Mozambique Fertilizer Use Optimizer Tool: >1300 m elevation, May 2016

The below assumes:
Calibration measurement is with an Agua Vumba water bottle lid (CAP); contains 8 ml, 5.6 g urea, 8g NPK, 9.6 g NPS, and 10.4 g TSP.
Plant spacing: maize at 75 x 30 cm; cowpea, bean and soybean with 60 cm row spacing; pigeonpea with 75 cm row spacing.
Grain values per kg (MZM): 15 for maize and sorghum; 30 for cowpea and soybean; 40 for bean and pigeonpea.
50 kg of fertilizer use costs (MZM): 1500 for urea, TSP, NPK 12-24-12, and NPS 23-20-0-6.
Application rates are in kg/ha.

Level 1 financial ability.	
Maize	point apply 90 kg NPS (1 CAP for 5.7 plants) and 65 kg NPK (1 CAP for 5 plants) at planting; topdress 50 kg urea (1 CAP for 6.2 plants)
Sorghum	band apply 60 kg NPS (1 CAP for 2.1 m)
Soybean	band apply 38 kg TSP applied at planting (1 CAP for 3.9 m)
Level 2 financial ability.	
Maize	point apply 153 kg NPS (1 CAP for 3.3 plants) and 160 kg NPK (1 CAP for 6.2 plants) at planting; and topdress 50 kg urea (1 CAP for 4.4 plants)
Sorghum	band apply 25 kg urea (1 CAP for 3 m) and 49 kg of TSP at planting (1 CAP for 2.4 m); topdress 25 kg urea (1 CAP for 3 m)
Cowpea	band apply 36 kg TSP applied at planting (1 CAP for 4.1 m)
Soybean	band apply 77 kg TSP applied at planting (1 CAP for 1.9 m)
Level 3 financial ability (maximize profit per acre).	
Maize	point apply 200 kg NPS (1 CAP for 2.6 plants), 84 kg TSP (1 CAP for 5.6 plants) and 150 kg NPK (1 CAP for 6.2 plants); topdress 82 kg urea (1 CAP for 3.6 plants)
Sorghum	band apply 100 kg of NPK at planting (1 CAP for 1.1 m); topdress 50 kg urea (1 CAP for 1.5 m)
Bean	band apply 29 kg urea (1 CAP for 3.2 m) and 49 kg TSP at planting (1 CAP for 3 m)
Cowpea	band apply 56 kg TSP applied at planting (1 CAP for 2.6 m)
Soybean	band apply 129 kg TSP applied at planting (1 CAP for 1.1 m)

two-thirds of the money to apply fertilizer to all cropland at EOR; and level 3 is for the farmer with enough money to apply fertilizer to some cropland at EOR. Fertilizer use options within financial levels have similar profit potential. The paper FOT requires some assumptions: the volume of measuring units to be used by farmers in calibration; plant spacing for each crop; the fertilizer use costs per 50 kg bag; and the expected commodity values on farm at harvest, considering the value of both home consumption and for market.

The paper FOT advises on the 4Rs of fertilizer use including the right type, rate, time and method of application. It also advises on calibration to help the farmer to adjust his/her eyes and feel to the rate of application, that is a water bottle lid full of fertilizer is sufficient for so many metres of band application or so many plants.

In using the paper FOT for >1300 m (Table 10.2), first consider the farmer's financial ability for fertilizer use. If the farmer has little money, begin with financial level 1, which has options for only maize, sorghum and soybean as fertilizer use options for bean and cowpea were not profitable enough to fit into this category. For example, the level 1 recommendation for maize is: "point apply 90 kg NPS (1 CAP for 5.7 plants) and 65 kg NPK (1 CAP for 5 plants) at planting; topdress 50 kg urea (1 CAP for 6.2 plants)". Therefore, the farmer should use NPS, NPK and urea. The NPS and NPK should be applied at planting. One Agua Vumba brand 8 ml bottle cap of NPS is sufficient for 5.7 plants and one cap of NPK is sufficient for 5 plants. Urea should be topdress applied at 40 kg/ha which requires 1 cap for 6.2 plants.

10.5 Fertilizer use in an integrated nutrient management framework

Optimization of fertilizer requires good agronomic practices such as for variety selection, planting and control of weeds, insect pests and diseases. Some practices such as manure application or intercropping, and soil test results, may have implications for the optimal fertilizer rate. These are not considered in the FOTs which are for sole crop production and assume that soil N and P availability is sufficiently low for profitable response to nutrient application. Therefore, these factors are considered as a second step in the fertilizer use optimization decision process using a one-page decision guide (Table 10.3).

The use of green manure and the application of manure calls for adjustment of fertilizer rates. The fertilizer substitution value varies with the quality of manure. Poultry and dairy manure are expected to have greater fertilizer substitution value than farmyard manure which has had much exposure to the weather and is mixed with soil. Other practices with fertilizer substitution value include bringing material such as tree prunings into the field, rotations and intercropping. Soil test information should be considered. When soil test information is not available, soil test P should be considered low and fertilizer P applied according to the FOT recommendations. If soil test P by Mehlich 3 is above 18 ppm, do not apply fertilizer P to that field until soil test P is found to be below this level. If soil test K is found to be < 0.25 cmol/kg or <100 ppm, apply K even if not recommended by the FOT. As an example, “For each 1 t of fresh leguminous leafy tree prunings applied (e.g. gliricidia, leucaena, sesbania, senna)”, the urea, TSP or DAP, or NPK rate can be reduced from the FOT recommendation for the field by 10, 1 and 6 kg/ha, respectively. The prunings may be from alleys within the field, field boundary areas, or nearby treelots.

Table 10.3: Fertilizer use in an ISFM framework

Mozambique: Fertilizer rate adjustment for ISFM practices and soil test information

ISFM practice	**Urea**	**DAP or TSP**	**NPK 10-20-10+6S**
	Fertilizer reduction, % or kg/ha		
	N	**P**	**K**
Early incorporation of a green legume manure (mucuna, crotalaria and lablab)	57 kg	3 kg	11 kg
For each 1 t of fresh leguminous leafy tree prunings applied (e.g. gliricidia, leucaena, sesbania, senna)	10 kg	1 kg	6 kg
Farmyard manure per 1 t of dry material	2 kg	1 kg	1 kg
Residual value of FYM applied for the previous crop, per 1 t	1 kg	0.4 kg	0.4 kg
Dairy or poultry manure, per 1 t dry material	24 kg	7 kg	14 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	5 kg	1.4 kg	3 kg
Compost, per 1 t/ha dry wt	20 kg	1 kg	20 kg
Doubled-up legume-technology (pigeonpea)	In the second year of rotation a mean reduction of 50 kg urea		
Cereal-bean intercropping	Increase DAP/TSP by 18 kg/ha, but no change in N and K compared with sole cereal fertilizer		
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 20 kg/kg, reduce urea by 30 kg/ha, and no change in K compared with sole cereal fertilizer		
If Mehlich III P >18 ppm	Do not apply P		
If soil test K < 0.25 cmol/kg	Apply 20 kg/ha KCl		

10.6 Crops addressed by region for optimized fertilizer use

The crops and nutrients addressed by OFRA are given in column 1-2 of Tables 10.4a-c. The response coefficients a, b and c for the response equation $Y = a - bc^r$ are reported in column 3-5. The effects on changes in nutrient rates on yield increases are reported in column 6-9. The elemental nutrient application rates at EOR and as recommended (REC) are given in column 10-11. The information in this chapter does not apply to drier areas of Mozambique represented by light green in Figure 10.2 with the exception of valley soils. It is also not likely to apply to sandy soils unless these have been amended over the years through application of much organic material.

Land area at >1300 masl is small in Mozambique (Figure 10.2) and is in AEZ R10 (Figure 10.1). Results of field research indicate a mean response of maize to N and P of up to 2.6 and 1.6 t/ha, respectively, and corresponding sorghum yield increases. Mean maize responses to K and S were >0.5 t/ha (Table 10.4a). Available bean research results for this zone were few with low yields and low responses to applied nutrients. Mean soybean and cowpea response to P were 0.6 and 0.37, respectively, but mean response to K was less than 0.1 t/ha.

Most land in the 900 to 1300 masl range is also in AEZ R10.The mean response of maize to N and P was 1.79 and 0.32 t/ha, respectively (Table 10.4b). Bean is an important crop in this zone and mean response to applied N was 0.29 t/ha with an N EOR of 22. All crops had mean responses to P that were economical.

Most crop production in Mozambique occurs at <900 masl (Table 10.4c) and the recommendations best apply to AEZ R4, R5, R7, R8 and R9 (Figure 10.1). The mean response of maize to N and P was 1.94 and 0.37 t/ha, respectively. Bean and soybean had profitable responses to N and all crops had economic responses to P. Maize had profitable responses to K and S in all zones. Pigeonpea response to K was profitable in the <1300 masl areas.

Table 10.4a: High elevation >1300 m. Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information.

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			t/ha				kg/ha	
Maize	N	5.100	2.600	0.973	1.456	0.641	0.282	0.124	100	58
Bean	N	0.429	0.031	0.798	0.031	0.000	0.000	0.000	7	
Sorghum	N	4.07	0.730	0.964	0.487	0.162	0.054	0.018	49	70
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.90	1.600	0.972	0.212	0.184	0.159	0.138	40	11
Cowpea	P	1.5299	0.371	0.720	0.299	0.058	0.011	0.002	10	
Bean	P	0.429	0.031	0.798	0.021	0.007	0.002	0.001	3	
Soybean	P	1.457	0.607	0.883	0.281	0.151	0.081	0.043	22	
Sorghum	P	4.047	0.651	0.856	0.352	0.162	0.074	0.034	15	13
Maize	K	4.863	0.563	0.896	0.238	0.137	0.079	0.046	26	10
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	16	
Soybean	K	0.837	0.019	0.908	0.007	0.004	0.003	0.002	0	
Maize	S	2.510	0.577	0.738	0.451	0.099	0.022	0.005	14	

†EOR was determined with the cost of using 50 kg urea, TSP and NPK 12-24-12 MZM 1500. Commodity values (MZM/kg) used were: 15 for maize and sorghum; 30 for cowpea and soybean; 40 for bean and pigeonpea.

Table 10.4b: Mid-elevation (900-1300 masl)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Maize	N	2.85	1.794	0.972	1.029	0.439	0.187	0.080	86	58
Bean	N	0.84	0.293	0.862	0.290	0.003	0.000	0.000	22	
Soybean	N	1.13	0.046	0.929	0.041	0.004	0.000	0.000	0	
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.69	0.322	0.929	0.099	0.069	0.048	0.033	12	11
Cowpea	P	1.53	0.371	0.72	0.299	0.058	0.011	0.002	9	
Bean	P	0.88	0.058	0.869	0.029	0.014	0.007	0.004	10	
Soybean	P	2.09	0.867	0.895	0.369	0.212	0.122	0.070	6	
Pigeonpea	P	2.54	0.487	0.758	0.365	0.091	0.023	0.006	27	
Maize	K	4.08	0.097	0.900	0.040	0.02003	0.014	0.008	10	13
Pigeonpea	K	2.53	0.127	0.666	0.110	0.014	0.002	0.000	10	
Maize	S	2.55	0.400	0.761	0.298	0.0706	0.019	0.005	13	

Table 10.4c: Lower elevation, <900 m elevation.

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**Yield increase, t/ha**			**kg/ha**	
Maize	N	3.436	1.942	0.973	1.088	0.478	0.211	0.093	90	58
Bean	N	0.838	0.290	0.862	0.290	0.003	0.000	0.000	23	
Soybean	N	2.828	0.473	0.977	0.238	0.118	0.059	0.029	69	
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.967	0.368	0.917	0.129	0.084	0.054	0.035	14	11
Cowpea	P	1.880	0.288	0.898	0.120	0.070	0.041	0.024	17	
Bean	P	0.88	0.200	0.869	0.101	0.050	0.025	0.012	15	
Soybean	P	2.774	0.408	0.865	0.210	0.102	0.049	0.024	18	
Pigeonpea	P	2.64	0.332	0.849	0.185	0.082	0.036	0.016	17	
Maize	K	3.317	0.113	0.940	0.030	0.022	0.016	0.012	10	13
Pigeonpea	K	2.53	0.127	0.666	0.110	0.014	0.002	0.000	10	
Maize	S	3.014	0.047	0.750	0.036	0.009	0.002	0.000	5	

Fertilizer use recommendations (REC) have not been available for most crops. The EOR were determined using the current subsidized fertilizer prices. The N EOR was high and low compared with REC for maize and sorghum, respectively. The P EOR for maize was high or similar compared with REC. The EOR were determined for numerous crop-nutrient combinations for which REC are unavailable. The EOR would be less for farmers lacking access to subsidized fertilizer.

10.7 Acknowledgements

OFRA activities were funded by AGRA and implementation was managed by CABI. Several IIAM research teams contributed to OFRA activities in Mozambique and we are grateful to farmers who cooperated in field research. We are grateful for the scientific and technical support of Professor Charles Wortmann of the University of Nebraska-Lincoln and Dr KC Kaizzi of the National Agricultural Research Organization of Uganda.

11. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Niger

Maman Nouri[1] mamank.nouri@gmail.com, Maman Garba[1] and Charles S. Wortmann[2]

[1] Institut National de Recherche Agronomique du Niger (INRAN), BP 240 Maradi, Niger

[2] University of Nebraska-Lincoln, Department of Agronomy and Horticulture, Lincoln, NE 68583, USA

11.1 Agricultural systems of Niger

The crop and livestock sectors are the basis of Niger's economy. These sectors employ more than 80% of the population, generate 43% of GDP and contribute on average to 30% of export earnings of the country.

Most crop production is of staple crops such as pearl millet, sorghum, cowpea, groundnut and rice. Rainfed cash crops produced in favourable areas are groundnut, sesame, cotton and tiger nut, the latter gaining in importance with more fertilizer use than for other crops, particularly in Maradi region.

Land cultivated annually is increasing and competes with grazing. Livestock densities have declined in the Sahel but much livestock is brought from further north for dry-season grazing.

Crop production in Niger is challenged by climate-related risks, soil degradation and demographic pressure which contributes to an improper use of the natural resources and exacerbates food insecurity.

11.1.1 Agro-ecological zones (AEZ)

The AEZ of Niger include the Sahara desert zone in the north of the country; the sub-Saharan pastoral zone in the centre of the country; the Sahelian zone with agro-pastoral prevalence in the southern centre and the Sahelo-Sudan or North Sudan Savanna zone with better agriculture production conditions in the South-West (Figure 11.1). The latter two AEZ are the sedentary areas in contrast to the northern zones where primarily nomadic activities with livestock predominate.

The Sahara AEZ covers more than 65% of the country and has fewer than five inhabitants per km^2 (Figure 11.1). Agadez, which is in this zone, has a mean annual rainfall of 111 mm, 45% of which falls in August (Table 11.1). Monthly mean maximum and minimum temperatures range

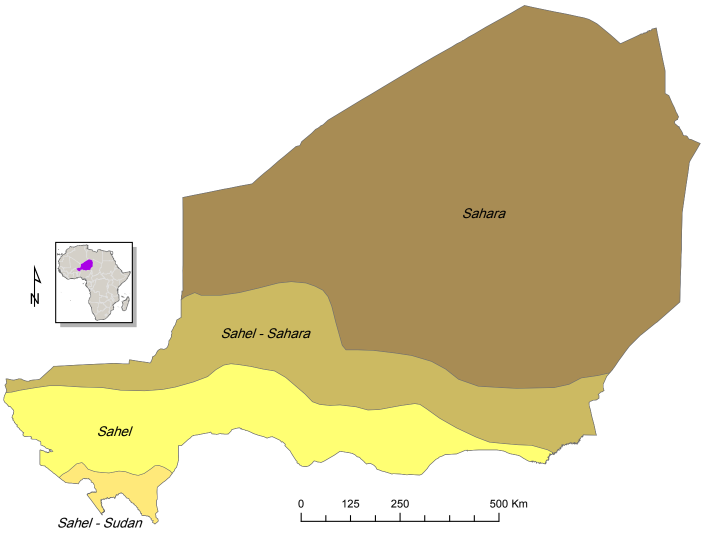


Figure 11.1: Agro-ecological zones (AEZ).

from 26 to 41°C and from 12 to 26°C, respectively. Agriculture activities are conducted in some depressions called oases with microclimates that permit production of high quality vegetables such as onion, garlic and potato.

The Sahelo-Sahara AEZ covers about 20% of Niger's area (Figure 11.1). It is mostly a pastoral and transhumance AEZ receiving about 350 mm of rainfall annually and is marginal for pearl millet and cowpea production. The mean annual rainfall for Tanout, which is in this zone, is 244 mm with 45% falling in August (Table 11.1). Monthly mean maximum and minimum temperatures range from 30 to 40°C and from 14 to 25°C, respectively.

The Sahel AEZ in Niger is semi-arid (Figure 11.1). Annual mean rainfall in Zinder, which is in this zone, is 411 mm with 85% falling from July to September (Table 11.1). Monthly mean maximum and minimum temperatures range from 28 to 42°C and from 12 to 29°C, respectively. The generally high sand content of upland soils combined with low rainfall makes frequent occurrence of drought a major constraint to crop production. The best adapted crops are pearl millet, groundnut,

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

Table 11.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Niger (2000-2014)

	J	F	M	A	M	J	J	A	S	O	N	D
Sahara AEZ: Agadez												
Rain	0.0	0.0	0.1	2.0	5.5	10.4	35.2	49.7	8.2	0.3	0.0	0.0
Tmax	27.9	31.1	35.0	39.2	41.3	41.3	39.1	37.9	38.9	37.1	32.4	29.0
Tmin	11.7	13.9	18.3	23.1	26.0	26.4	25.1	24.2	24.5	21.7	16.2	12.8
Sahelo-Sahara AEZ : Tanout												
Rain	0.0	0.0	0.0	0.0	3.0	22.0	83.0	99.0	35.2	2.0	0.0	0.0
Tmax	29.5	32.6	36.2	39.0	39.5	37.6	34.0	32.3	34.3	36.2	33.6	29.9
Tmin	13.7	15.7	19.9	23.1	24.6	24.0	22.0	20.9	21.2	20.8	25.5	21.9
Sahel AEZ : Zinder												
Rain	0.0	0.1	0.5	1.0	14.8	39.2	128.6	168.1	53.5	5.0	0.2	0.0
Tmax	29.3	32.5	36.3	39.7	40.6	38.1	34.9	32.7	35.5	37.1	33.7	33.5
Tmin	14.7	17.1	21.4	25.0	26.6	25.6	23.7	23.2	23.7	22.9	18.6	15.4
Sahel AEZ : Maradi												
Rain	30.2	33.6	37.0	40.0	39.7	37.0	33.2	31.7	33.8	36.8	33.9	31.1
Tmax	13.0	15.6	19.8	24.0	25.7	25.0	23.2	22.2	22.5	20.5	16.5	13.5
Tmin	0.0	0.0	0.3	4.1	18.9	63.5	149.0	175.1	74.9	6.6	0.0	0.0
Northern Sudan Savannah: Gaya												
Rain	0.0	1.4	2.6	16.2	70.7	125.0	177.6	225.6	160.1	17.1	0.1	0.1
Tmax	33.1	36.3	39.1	40.3	38.0	34.9	31.9	31.9	32.3	35.7	36.0	33.4
Tmin	18.6	21.6	25.1	27.1	26.3	24.3	22.8	22.4	22.4	22.8	20.5	18.7

sesame and cowpea. The valley soils have relatively more clay content and are suitable for sorghum, vegetables and even maize in low lying areas. Crop and livestock production are both important and transhumance is practised whereby much of the livestock is moved to drier areas during the crop production period and brought back to the arable lands following crop harvest. Manure from livestock is important for soil fertility management, but grazing and harvest of crop residues leave the land bare and exposed to erosion.

The Northern Sudan Savanna is a relatively small area in southwest Niger (Figure 11.1). Gaya, which is in this zone, has a mean annual rainfall of 800 mm (Table 11.1). Rainfall distribution is similar to the Sahel AEZ but with a longer season beginning in June. Monthly mean maximum and minimum temperatures range from 31 to 40°C and from 19 to 27°C, respectively. The soils have more clay and water holding capacity compared with the Sahel. The crops produced are pearl millet, sorghum, groundnut, cotton, maize, cassava and some rice in the Niger River valley and close to some seasonal streams.

11.1.2 Current soil fertility management

Agricultural soils of Niger, particularly upland soils, have a pH 4.5 to 6.0, just 0.1 to 0.7% soil organic matter, typically have Bray-1 P of 0.4 to 3.4 mg/kg of soil and have low N availability. Mean inorganic nutrient application is only about 1 kg/ha of cropland due to costs, low or untimely availability, lack of access to credit for inputs at a reasonable cost and marketing conditions (Kadi et al., 1990). Nutrient mining has been estimated to average 15, 2, and 11 kg/ha/yr of N, P and K, respectively.

The main traditional practice to restore or improve soil fertility was to fallow for 5 to 10 years following 3 to 5 years of cultivation, but due to high demand for cropland this is now rarely practised. Other traditional soil fertility management practices include application of organic resources such as manure, household waste and crop residues, and contracting herdsmen to keep livestock overnight in fields during the dry season to benefit from their excretion of urine and faeces. However, these practices are insufficient to meet crop-nutrient requirements as the organic materials are limited in quantity and generally of low nutrient content.

Most crop residue is removed from the field for other uses, such as animal feed, fuel and construction, with negative consequences including high soil temperature and increased evaporation, less trapping of relatively high fertility dust, seedling damage by blowing sand, reduced in-field nutrient cycling and less soil organic matter replenishment (Mason et al., 2015). Crop residue left in the field is subject to livestock grazing and removal by termites. Therefore, leaving residue in the field may be less valuable than anticipated.

Maintaining trees in crop fields, such as *Faidherbia albida*, is important to soil fertility management: crop performance under trees is often better than performance far from trees. Tillage can be advantageous to nutrient availability in that plant growth tends to be more vigorous with tillage compared with no tillage (Mason et al., 2015). Combining crop residue management, manure and/or compost application, and fertilizer application affords the greatest opportunity to increase yields, e.g. to apply 2 t/ha of poultry manure pre-planting followed by point application of 6 kg each of N, P_2O_5 and K_2O at tillering for pearl millet (Maman and Mason, 2013). Cereal yield is greater following a pulse compared with a cereal crop in rotation (Mason et al., 2015).

An important component of nutrient management is to control other constraints. This is true for the parasitic weed Striga, which can be reduced by late planting, reduced tillage, fertilizer application and intercropping cereals with legumes (Mason et al., 2015).

Alternating four-row strips of cereal and legume, followed by rotating crops on the strips the following year, is an improved intercrop system that takes better advantage of crop rotation effects compared with continuous intercropping. Other beneficial practices include application of alternative P sources such as rock phosphate (RP) and phospho-compost; fertilizer micro-dosing; and soil and water harvesting techniques such as zai and half-moon and stones bunds.

Current fertilizer use is about 3.7 kg/ha/yr for cultivated land but most fertilizer is applied to rice and high value rainfed crops like tiger nut. Fertilizer NPK blends (15-15-15 and 20-10-10) are more often used than urea and phosphate fertilizers. In Niger, fertilizer subsidies are an interim measure to enhance capacity for fertilizer use. Most of the fertilizers come from the agro-dealers of the Centrale d'Approvisionnement en Intrants et Matériels Agricoles (CAIMA), the national input supply organization, with less from the private sector. A uniform fertilizer price is applied throughout the country through adjustment and subsidy systems. More private sector supply of fertilizer is being encouraged.

Fertilizer recommendations are issued by the national research institute INRAN. The recommendations issued in 1981 and updated in 1992 were for sole crop pearl millet or sorghum with blanket application rates of 46 kg/ha N, 15 kg/ha P_2O_5 and 20 to 25 kg/ha K_2O when crop residues are returned, or 90 kg/ha N, 20 kg/ha P_2O_5, and 20 to 25 kg/ha K_2O with crop residue removal.

For groundnut and cowpea sole crop, the recommended rates were 22.5 kg/ha P_2O_5 . Fertilizer recommended for rice is 30-45 kg/ha of N, P_2O_5 and K_2O applied as NPK 15-15-15, plus 46 to 60 kg/ha N top-dressing applied as urea.

A modification of the recommendations for pearl millet and cowpea varies from 8 to 12 kg/ha of P applied as SSP and 46 kg/ha of N with early planting, but only 4 kg/ha of P for planting after July 15th.

Salou and Sido (2006) found 132-90-30 kg/ha to be economic for irrigated rice. Buerkert et al. (2001) suggested 30 kg/ha each of N, P_2O_5 and K_2O for pearl millet and 20 kg/ha P for cowpea. A starter N application of 15 kg/ha N is recommended for cowpea applied at 5-10 days after emergence.

Fertilizer micro-dosing is an approach to increase efficiency of fertilizer use through point application at 9 kg/ha each of N, P_2O_5 and K_2O at planting or after emergence. Alternative micro-dosing rates are about 4 and 9 kg/ha of N and

P_2O_5, respectively, for pearl millet and sorghum (Tabo et al., 2007; Saidou et al., 2014; Maman et al., 2015) and maize (MDA 2012).

The policy of fertilizer use in Niger is defined in the document 'Stratégie décentralisée et partenariale d'approvisionnement en intrants pour une agriculture durable (SIAD), Août 2006' with an objective to increase fertilizer use to an annual average application of 8 kg/ha/yr of nutrient elements.

CAIMA has regional and district input stores to facilitate farmers' access to fertilizer at low costs compared with open market prices. However, CAIMA often does not supply the most appropriate fertilizer types.

Extension workers and agro-input dealers are not well informed of good agronomic practices for fertilizer use and fail to advise farmers well. Good fertilizer use practices are summarized as the 4R Nutrient Stewardship approach, consisting of applying the right source of nutrients, at the right rate, at the right time for efficient uptake by the crop and in the right place to be accessible by plant roots. The 4Rs can result in increased crop yields and incomes, and prevent soil nutrient depletion.

11.2 Diagnosis of nutrient deficiencies in Niger

In Niger, P, followed by N, is generally considered to be the most limiting nutrient for crop production. In 30 recently conducted trials as part of the Optimizing Fertilizer Recommendations in Africa (OFRA) project, the average yield increases across all crops were 50, 29 and 16% with P, N and K application, respectively (Figure 11.2). These trials included a diagnostic treatment of N+P+ K+Mg+S+Zn+B that was compared with a treatment of the same N+P+K rates for non-legumes. A similar comparison was made for legumes with N omitted. The results determined if one or more of Mg, S, Zn and B are limiting yield once N, P and K are applied. There were mean increases in yield of 12 and 7% due to the diagnostic package for trials conducted on farmers' fields and on research stations, respectively (Figure 11.2a).

The average yield increases due to the secondary and micro nutrients were similar

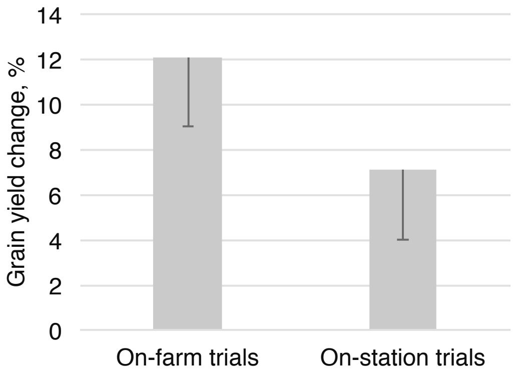


Figure 11.2a: Yield increase due to diagnostic treatment.

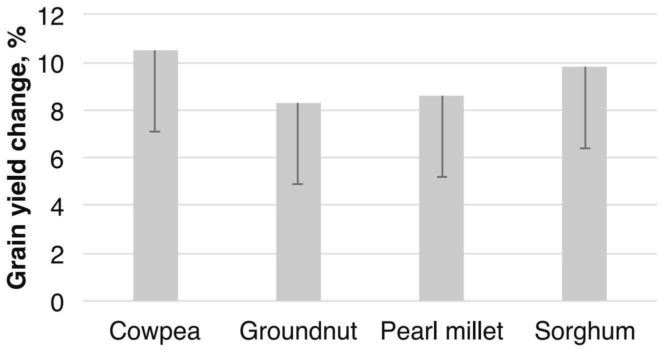


Figure 11.2b: Yield increase due to diagnostic treatment.

for cowpea, sorghum, groundnut and pearl millet (Figure 11.2b). Further investigation is needed to determine which of these four micro- and secondary nutrients are most commonly deficient in the Niger upland soils. Other nutrient deficiencies are likely to gain in importance as fallow is reduced and crop residue is removed from the fields.

11.3 Optimizing fertilizer use in Niger

Farmers want fertilizer use to be sufficiently profitable. Farmers with adequate finance strive to maximize net returns per hectare resulting from fertilizer use. For the finance constrained farmer, investment in fertilizer use competes with other livelihood needs. Therefore, investments in fertilizer must give high benefit to cost ratio with little risk. Fertilizer use optimization in this context refers to maximizing profit from fertilizer use: profit per hectare for farmers with adequate finance; and maximum benefit to cost ratio on the small investment in fertilizer by the financially constrained farmers.

Crop yield response to applied nutrients can be captured with a curvilinear to plateau yield response as shown for sorghum response (vertical axis or y-axis) to applied P (horizontal axis or x-axis) (Figure 11.3) with a steep yield

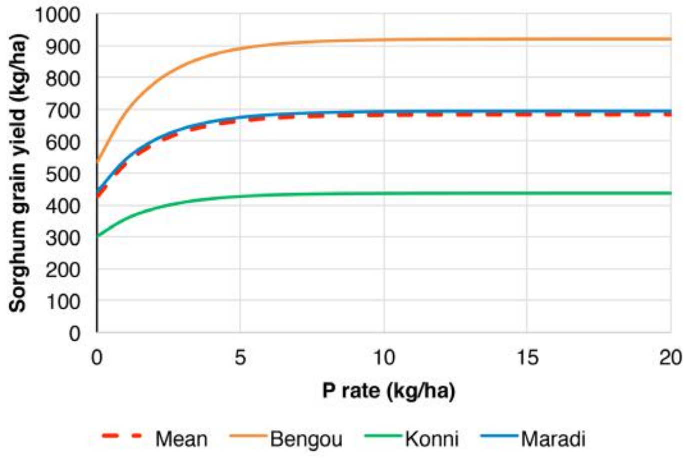


Figure 11.3: Sorghum sole crop with 2.5 t/ha manure P response.

increase with increasing P at low rates and a lesser rate of yield increase at higher P rates until yield reaches a plateau with no more yield increase.

This type of response is captured by the equation yield (kg ha-1) = $a - bc^r$, where a is near maximum yield for application of that nutrient, b is the gain in yield due to application of that nutrient, and c^r determines the shape of the curvilinear response where c is a curvature coefficient and r is the nutrient rate. This function tells us that the benefit relative to cost for P application is expected to be greater with low compared with high P rates. Such response curves are typical for most crops and nutrients.

Once crop-nutrient response functions have been determined for an AEZ, economics can be applied to fertilizer use to determine how crop-nutrient-rate choices affect potential profitability (Figure 11.4). The x-axis (horizontal axis) shows the amount of CFA franc per hectare (FCFA/ha) invested in a nutrient applied to a crop. The y-axis (vertical axis) shows the net returns resulting from a single nutrient applied to a crop. Therefore, each curve represents the profit potential of a nutrient applied to a crop. When the slope of the curve is steep, net returns to investment are very high. As the amount invested (the x-axis) increases the slope decreases but if still upward, profit is increasing. Where curves reach a peak and the slope is flat, the point of maximum profit per hectare is reached; the rate at the peak is considered the economically optimal rate (EOR). When slopes decline, profit is declining. The financially constrained farmer wants first to take advantage of the crop-nutrient combinations that will give the most profit.

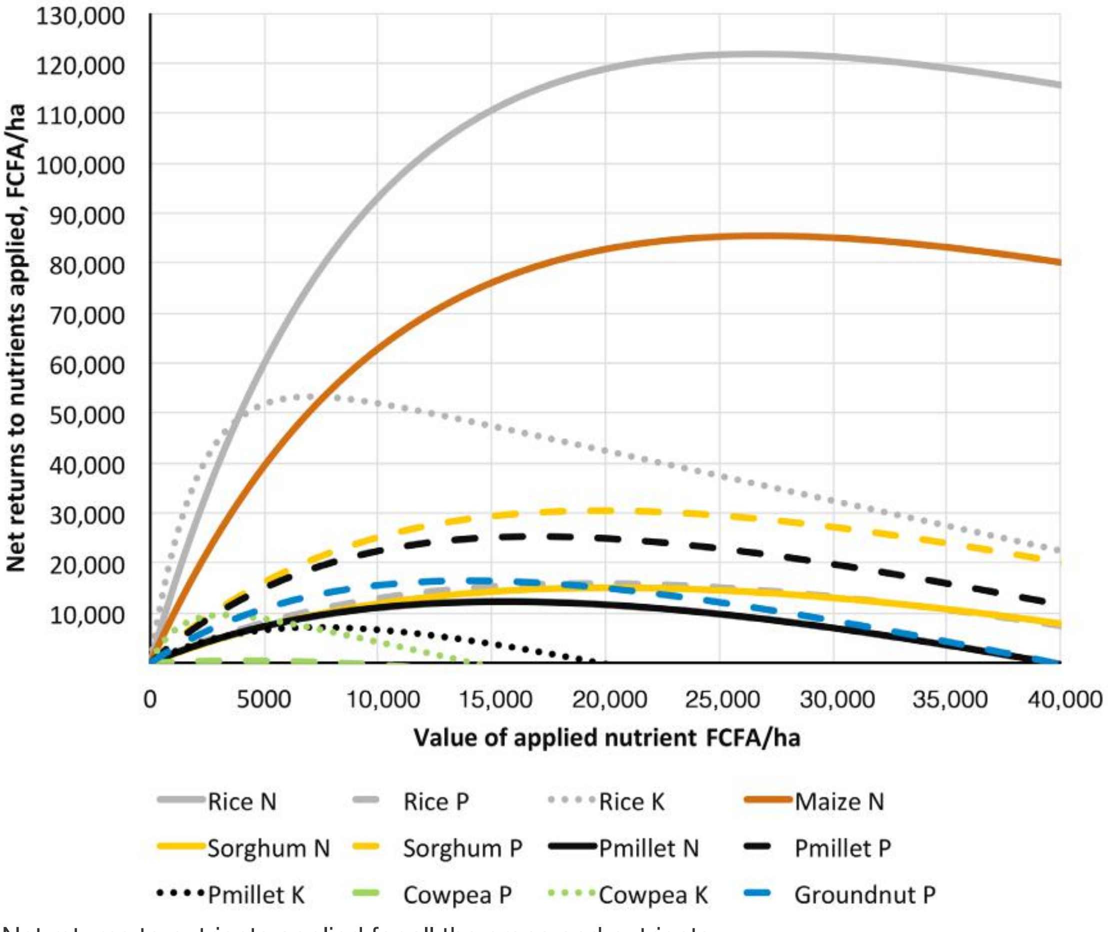


Figure 11.4: Net returns to nutrients applied for all the crops and nutrients.

The slopes are steepest for low rates of N and K applied to rice (Figure 11.4). For rice K, the EOR is reached with a low rate of application with little added profit potential for K application of more than 5000 FCFA/ha at which level the expected mean net profit is about FCFA 50,000. The net returns for investment in N applied to rice increase steadily up to 10,000 FCFA with a net return of about 90,000 FCFA. With more N applied, net return increases at a slower rate up to 20,000 FCFA with a peak in profit at about 25,000 FCFA with an expected mean net return of 125,000 FCFA.

Rice response to applied P is profitable but not nearly as profitable as for several other options. Maize N offers the third most profitable option with expected profit of about 75,000 with 15,000 FCFA invested and a profit peak at 85,000 FCFA with 20,000 FCFA investment. Below the maize N curve are several less profitable options such as with some P applied to sorghum and pearl millet with returns of net profit of about 20,000 with 10,000 FCFA invested. Further down are even less profitable options including P applied to rice and groundnut and N applied to pearl millet and sorghum. All K application options, with the exception of K applied to rice, have little profit potential and applications should be at a maximum of about 5,000 FCFA with a peak net return of about 10,000 FCFA.

11.4 Targeted crops and cropping systems by AEZ

Niger is a Sahelian country with agriculture activities concentrated in the Sahel AEZ and North Sudan Savanna AEZ. The OFRA project targeted pearl millet, sorghum, cowpea and groundnut in the Sahel and North Sudan Savanna uplands. Sorghum is mostly produced in the southern part of the Tahoua and Maradi regions. The major production areas for

Table 11.2a: Sahel AEZ. Response function coefficients (cols 3-5), expected yield increases (t/ha) for nutrient rate increases (cols 6-9), and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent recommendations (col. 10)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate			Effect of elemental nutrient rate change, kg/ha on yield increase in t/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Rice	N	4.461	0.564	0.942	0.470	0.078	0.013	0.002	47	92
Maize	N	1.275	0.687	0.951	0.535	0.118	0.026	0.006	48	46
Sorghum	N	1.346	0.325	0.972	0.186	0.079	0.034	0.014	30	46
P. millet	N	0.632	0.265	0.962	0.182	0.057	0.018	0.006	23	46
					0-5	**5-10**	**10-15**	**15-20**		
Rice	P	5.190	0.189	0.919	0.065	0.043	0.028	0.018	13	40
Maize	P	2.868	0.029	0.938	0.153	0.119	0.092	0.072	0	0
Sorghum	P	1.148	0.367	0.884	0.169	0.091	0.049	0.027	19	20
P. millet	P	1.191	0.330	0.868	0.167	0.082	0.041	0.020	26	9
Cowpea	P	0.605	0.109	0.930	0.033	0.023	0.016	0.011	0	20
Groundnut	P	0.708	0.225	0.865	0.116	0.056	0.027	0.013	0	
					0-5	**5-10**	**10-15**	**15-20**		
Rice	K	6.038	0.223	0.750	0.170	0.040	0.010	0.002	7	25
P. millet	K	1.259	0.128	0.905	0.050	0.031	0.019	0.011	0	25
Cowpea	K	0.477	0.063	0.650	0.056	0.006	0.001	0.000	5	
Groundnut	K	0.983	0.102	0.910	0.038	0.024	0.015	0.009	3	

† EOR was determined with the cost of using 50 kg in CFA: urea at 13,500; TSP at 18,000; DAP at 20,000; and 15-15-15 at 13,500. Commodity values (CFA/kg) used were: rice 280; maize 180; sorghum 170; cowpea 200; groundnut 180; and pearl millet 160. Nutrient applications for some crops are missing due to lack of evidence of response.

groundnut are in the southern part of Maradi, Dosso and Zinder regions. Maize is mostly produced in the southern part of Maradi and Dosso in valleys where soil has relatively more clay.

Crop responses to N, P and K were determined for important food crops in each AEZ using results of past and recent field research (Tables 11.2a,b). The first two columns are for crop and nutrient. Columns 3-5 have coefficients a, b, c for the curvilinear to plateau response function, $Y = a - bc^r$. The next four columns report the expected average yield increase with increased nutrient rates compared with the next lower rate, and the right most columns are for the optimized nutrient rate for maximizing profit per hectare due to fertilizer use (EOR) compared with the current or recently recommended rate (REC).

Any nutrient application in excess of the field research based EOR is expected to result in loss of profit. Any nutrient application at less than EOR means less than maximum potential net return to fertilizer use per hectare but lower rates are typically most profitable with financially constrained fertilizer use.

The greatest yield increases, the b value and for the first increment of applied nutrient, in the Sahel were with rice and maize response to N (Table 11.2a). Sorghum, pearl millet and maize had relatively large responses to P. Response to K was relatively small, but greatest with rice and least with cowpea.

RECs were generally higher than EOR but similar for maize N and P and for sorghum P, while EOR P was relatively high for pearl millet. The EOR for groundnut P and K applied to cowpea and groundnut were determined but there were no RECs for these crop-nutrient combinations.

In the North Sudan Savanna, the greatest yield increases were with N applied to maize and sorghum. Sorghum also responded well to P (Table 11.2b). Of the legume crops, groundnut response to P and cowpea responses to N and K were relatively large. The RECs were high compared with EOR except for N applied to maize.

Over all comparisons of both AEZ, the REC was more than EOR for 73% of the cases and the mean of recommended nutrient rate compared with EOR was 60% higher.

Table 11.2b: Northern Sudan Savanna

		Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate			Effect of elemental nutrient rate change, kg/ha on yield increase in t/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
			t/ha			**t/ha**			**kg/ha**	
Rice	N	2.882	0.614	0.976	0.318	0.153	0.074	0.036	85	92
Maize	N	2.727	1.740	0.978	0.847	0.435	0.223	0.114	92	46
Sorghum	N	4.068	1.534	0.860	1.517	0.016	0.000	0.000	29	46
P. millet	N	1.293	0.093	0.919	0.085	0.007	0.001	0.000	0	46
Cowpea	N	1.860	0.178	0.770	0.178	0.000	0.000	0.000	0	
					0-5	**5-10**	**10-15**	**15-20**		
Sorghum	P	2.435	1.103	0.894	0.474	0.270	0.154	0.088	20	40
P. millet	P	1.761	0.600	0.884	0.276	0.149	0.080	0.043	2	20
Cowpea	P	0.929	0.040	0.700	0.033	0.006	0.001	0.000	0	9
Groundnut	P	1.831	0.399	0.872	0.198	0.100	0.050	0.025	13	20
Rice	K	1.951	0.091	0.800	0.061	0.020	0.007	0.002	10	25
Sorghum	K	2.016	0.114	0.902	0.046	0.027	0.016	0.010	12	25
P. millet	K	1.583	0.044	0.899	0.018	0.011	0.006	0.004	0	25
Cowpea	K	0.938	0.280	0.908	0.107	0.066	0.041	0.025	23	
Groundnut	K	1.272	0.068	0.285	0.068	0.000	0.000	0.000	3	

Application of an N-P-K blended fertilizer could only be justified for sorghum in both AEZ and, at low rates, for rice in the Sahel. Otherwise, crops had economic response to only one or two of the three nutrients.

11.5 Fertilizer use optimization tools for Niger AEZ

When a farmer has several crops of interest and is financially constrained in fertilizer use, consideration of the various crop-nutrient response functions together with information about the farmer's financial ability and agronomic interests is very complex. Therefore fertilizer optimization tools (FOTs) were developed to adequately consider the farmer's financial and agronomic situation in determining optimal use of fertilizer (http://agronomy.unl.edu/OFRA).

Crop nutrient response functions (Tables 11.2a,b) are the backbone of the FOTs for the Sahel and Northern Sudan Savanna AEZ. The FOTs use linear programming (Chapter 1) with Excel Solver© (Frontline Systems Inc., Incline Village, NV, USA) to consider an indefinitely large number of fertilizer use scenarios and recommends the combination of nutrient rates for each crop to maximize the net returns on the farmer's investment in fertilizer use.

The FOTs use complex mathematics to integrate the agronomy of the responses to applied nutrients for the different crops of interest to farmers, but also the farmer's land allocation to different crops, the value of the grain, the costs of fertilizer use and the money available for fertilizer use. The FOTs and other decision tools are available at http://agronomy.unl.edu/OFRA.

The FOTs, although of complex mathematics, are easy to use. The Solver add-in and macros must be enabled for the Fertilizer Optimization spreadsheet to function appropriately; see the 'Help and Instructions' worksheet of the FOT. When enabled the Solver add-in appears under the Data tab on the Quick Access Toolbar.

In the input panel (Figure 11.5) the user enters the hectares to be planted and the expected value for each crop on-farm at harvest time considering both that which is likely to be marketed and that which is saved for home consumption, the cost of using 50 kg bags of available fertilizers, and the amount of money the farmer has to invest in fertilizer use. Then, the user clicks on the 'Optimize' cell to run the optimization calculations.

The output panel (Figure 11.5) displays the recommended fertilizer rate for each crop, the expected average yield increases and net returns to fertilizer application for each crop, and the expected total net return to investment in fertilizer.

Note that in this example 500,000 FCFA was made available for fertilizer use while a total of about 11 bags of fertilizer was needed valued at less than 200,000. The FOT only used the money needed to determine the EOR for all crops and nutrients. A more typical farmer may have only 50,000 available for fertilizer use, in which case the recommended rates would be much lower and some crops may not have a fertilizer recommendation.

Fertilizer costs and expected grain values are important for the results. Therefore, seasonal variation in fertilizer use costs and grain prices requires ready access to current information on fertilizer prices and grain markets to better determine the input costs and expected grain values for the season.

11.6 Paper fertilizer optimization tools

For each Excel Solver© FOT, there is a companion paper FOT to be used when a computer is not available (Table 11.3). The paper FOT is devised for three financial levels based on the total amount of money required to apply fertilizer at EOR for all the cropland: level 1 financial ability for the poor farmer who cannot invest more than one-third the total EOR amount; level 2 for the farmer with more money but has no more money than two-thirds of the total EOR amount; and level 3 for the farmer with enough money to apply fertilizer at EOR to at least some of the cropland and thereby at rates to maximize profit per hectare. The paper tool makes assumptions about the:

- measuring units to be used by farmers to calibrate their eyes and feel for applying the right rate of fertilizer
- crop row and plant spacing
- fertilizer use costs per 50-kg bag

Crop Selection and Prices		
Crop	**Area Planted (Ha)***	**Expected Grain Value/kg †**
Pearl millet	1	160
Sorghum	1	170
Groundnuts, unshelled	1	180
Cowpea	1	200
Maize	1	180
Rice	1	280
Total	**6**	

Fertilizer Selection and Prices (N)					
Fertilizer Product	**N**	**P2O5**	**K2O**	**xx**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	13500
Single super phosphate, SSP	0%	18%	0%	0%	18000
Diammonium phosphate, DAP	18%	46%	0%	0%	20000
Murate of potash, KCL	0%	0%	60%	0%	15000
NPK	15%	15%	15%	0%	13500

Budget Constraint	
Amount available to invest in fertilizer (N)	500,000

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**SSP**	**DAP**	**KCl**	**NPK**
Pearl millet	0	0	128	25	0
Sorghum	26	0	94	0	0
Groundnuts, unshelled	0	0	0	17	0
Cowpea	0	0	0	10	0
Maize	102	0	0	0	0
Rice	75	0	66	24	0
0	0	0	0	0	0
Total fertilizer needed	204	0	287	76	0

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
Pearl millet	882	82,772
Sorghum	618	60,655
Groundnuts, unshelled	89	10,793
Cowpea	56	8,127
Maize	622	84,413
Rice	872	190,288
0	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	436,998

Figure 11.5: FOT panel displaying the entries and the output for investing 500,000 FCFA in fertilizer.

- expected grain values on-farm at harvest, considering the value both for home consumption and for market.

The paper FOTs address the 4Rs of fertilizer use: the right product, rate, time and method of application. It also advises on calibration, e.g. the band length or number of planting hills per measuring unit.

For example, a level 1 maize grower from the Sahel is advised to apply urea at 48 kg/ha for

Table 11.3: Example of paper FOT

NIGER SAHEL AEZ

FERTILIZER USE OPTIMIZER:

Paper Version: February 2016

The below assumes:
Measurement for calibration is with a: Oriba bottle cap (Oriba) of 7 ml: holds about 4.9 g urea, and 7.7 g DAP, TSP or KCl.
Row spacing: 80 x 40 cm for maize and sorghum; 100 x 100 cm for pearl millet; 20 x 20 cm for rice; 80 x 50 cm for cowpea; and 40 x 20 cm for groundnut.
Grain prices per kg (FCFA): pearl millet 160; sorghum 170; maize 180; rice 280; groundnut unshelled 180; cowpea 200.
Fertilizer use costs per 50 kg bag (FCFA): urea 13,500; TSP 18,000; DAP 20,000; KCl 15,000; SSP 12,500 and NPK (15-15-15) 13,500.
Broadcast width: 2.0 m; DAS=Days After Sowing; DAT= Days After Transplanting.

Level 1 financial ability.	
Lowland rice	broadcast 56 kg/ha urea at panicle initiation (1 Oriba for 0.4 m)
Pearl millet	point apply and incorporate 30 kg/ha DAP 5-10 DAS (1 Oriba for 2.6 hills)
Sorghum	point apply and incorporate 24 kg/ha DAP 5-10 DAS (1 Oriba for 7.4 hills)
Maize	point apply and incorporate 20 kg/ha urea at 8-leaf stage (1 Oriba for 7.2 hills) and 28 kg/ha urea at tasselling (1 Oriba for 5.2 hills)
Level 2 financial ability.	
Lowland rice	broadcast 32 kg/ha DAP 3-7 DAT (1 Oriba for 1.2 m). Broadcast 68 kg/ha urea, (1 Oriba for 3.4 m) and 20 kg/ha KCl (1 Oriba for 2 m) at panicle initiation
Pearl millet	point apply and incorporate 82 kg/ha DAP 5-10 DAS (1 Oriba for 1 hills)
Sorghum	point apply and incorporate 63 kg/ha DAP 5-10 DAS (1 Oriba for 3.8 hills)
Maize	point apply and incorporate 30 kg/ha urea at 8-leaf stage (1 Oriba for 4.8 hills) and 47 kg/ha urea at tasselling (1 Oriba for 3 hills)
Cowpea	point apply 20 kg/ha DAP 5-10 DAS (1 Oriba for 9.6 hills)
Groundnut	band apply and incorporate 20 kg/ha TSP 5-10 DAS (1 Oriba for 9.6 m)
Level 3 financial ability (maximize profit per hectare).	
Lowland rice	broadcast 66 kg/ha DAP 3-7 DAT (1 Oriba for 0.6 m). Broadcast 75 kg/ha urea (1 Oriba for 0.3 m) and 24 kg/ha KCl, (1 Oriba for 1.6 m) at panicle initiation
Pearl millet	point apply and incorporate 128 kg DAP/ha 5-10 DAS (1 Oriba 0.7 point)
Sorghum	point apply and incorporate 94kg/ha DAP 5-10 DAS (1 Oriba for 2.6 hills); point apply 26 kg/ha urea at tillering stage (1 Oriba for 5.5 hills)
Maize	Point apply and incorporate 50 kg/ha urea at 8-leaf stage (1 for 2.9 hills) and 52 kg/ha urea at tasselling (1 for 2.8 hills)
Cowpea	point apply and incorporate 25 kg/ha DAP 5-10 DAS (1 Oriba for 9 hills)
Groundnut	band apply and incorporate 27 kg/ha TSP 5-10 DAS (1 Oriba for 9.8 m)

maize. The paper FOT recommends that the urea should be point applied twice to each planting hill and covered with soil. At the 8-leaf stage, 20 kg/ha urea should be applied; the farmer calibrates his/her application so that one Oriba brand lid is enough for 7.2 hills. The second application should be 28 kg/ha urea applied pre-tassel; the farmer calibrates application with one Oriba lid sufficient for 5.2 hills.

A constraint of the paper FOT is that it may need revision if grain prices and/or fertilizer costs are much changed. The procedure for paper FOT development and revision is given in Chapter 1.

Table 11.4: Fertilizer use in an ISFM Framework

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT FRAMEWORK

ISFM practice	Urea	SSP	KCl	NPK 15-15-15
	Fertilizer reduction, % or kg/ha			
Farmyard manure or compost applied	Both yield and response to fertilizer are expected to be increased; do not decrease fertilizer rates			
Dairy or poultry manure, per 1 t dry material*	25 kg	5 kg	17 kg	55 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	2 kg	2 kg	1 kg	3 kg
Previous crop was a green manure crop and plant material remained in the field	100%	70%	70%	70%
Rotation	0% reduction but more yield expected			
Cereal-cowpea or groundnut intercropping	Increase DAP/TSP by 7 kg/ha, but no change in N and K compared with sole cereal fertilizer			
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 11 kg/ha, reduce urea by 9 kg/ha, and no change in K compared with sole cereal fertilizer			
If Bray-1 >12 ppm	Apply no P			
If soil test K <40 ppm	Band apply 50 kg/ha NPK			

*The manure equivalent was calculated using the N, P and K composition of sheep and goat manure reported by Suzuki et al. 2014.

11.7 Adjusting fertilizer rates in consideration of other practices and soil test information

The Excel and paper versions of the FOTs give optimized recommendations for fertilizer use for within the farmer's context. However, these recommendations need to consider other practices that affect nutrient availability (Table 11.4). When soil test information is available, fertilizer rates may be adjusted. For example, the application of farmyard manure or compost at 2.5 t/ha is expected to result in increased yield but also increased response to fertilizer on upland soils. Therefore, fertilizer rate should not be reduced. However, application of high quality dairy or poultry manure justifies a fertilizer rate decrease and reallocation to another field. If Bray-1 P is above 12 ppm, recommended fertilizer P should not be applied to that field.

11.8 Acknowledgements

The authors gratefully acknowledge Alliance for a Green Revolution in Africa (AGRA) who provided the full financial support under Grant Number: 2014 SHP 03 for this work; CABI, Nairobi, Kenya and University of Nebraska-Lincoln, USA for scientific backstopping and Institut National de Recherche Agronomique du Niger (INRAN) for guidance and support.

11.9 References

Buerkert A, Moser M, Kumar AK, FuÈrst P and Becker K (2001) Variation in grain quality of pearl millet from Sahelian West Africa. Field Crops Res. 69:1-11

Kadi M, Lowenberg-Deboer J, Reddy KC and Abdoulaye B (1990) Sustainable millet cowpea technologies for semi-arid Niger. Indian J. Dryland Agric. Res. Develop. 4:95-98

Maman N and Mason SC (2013) Poultry manure and inorganic fertilizer to improve pearl millet in Niger. African J Plant Sci 7:162-169

Maman G, Logah V, Wildemeersch J, Mahaman S, Yadji G, Quansah C, Bonsu M, Cornelis W and Abaidoo RC (2015) Improvement in physical quality of a Saharan Arenosol and implications on millet yield. Archive Agron Soil Sci. doi 10.1080/03650340.2015.1104414

Mason SC, Maman N, and Palé S (2015) Pearl millet production practices in semi-arid West Africa: a review. Expl Agric 1-21 doi:10.1017/S0014479714000441

Ministère du Développement Agricole (MDA) (2012) Catalogue National des Espèces et Variétés Végétales (CNEV). Ministère du Développement Agricole, Niamey, Niger

Saidou AK, Mahaman S, Garba M, Ibrahima OI, Lauoli S, Gandah M and Karimou AJM (2014) Effets de l'enrobage des graines et de la micro dose d'engrais sur des variétés du mil en zones semi-arides du Niger. Rapport final projet AGRA microdose (2009-007 SHP), publié le 15/06/2014 dans le bulletin RECA http://www.reca-niger.org/

Salou M and Sido AY (2006) Etude sur le diagnostic de la fertilité des sols et de la qualité des engrais utilisés sur les périmètres rizicoles irriguées dans la vallée du fleuve Niger. Institut National de la Recherche Agronomique du Niger (INRAN)

Suzuki K, Matsunaga R, Hayashi K, Matsumoto N, Tabo R, Tobita S and Okada K (2014) Effects of traditional soil management practices on the nutrient status in Sahelian sandy soils of Niger, West Africa. Geoderma 223-225:1–8

Tabo R, Bationo A, Gerard B, Ndjeunga J, Marchal D, Amadou B, Annou MG, Sogodogo D, Taonda JBS and Hassane O (2007) Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa, pp. 201-208. In Bationo A, Waswa B, Kihira J and Kimetu J (Eds) Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities. Springer, Netherlands.

12. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Nigeria

Tarfa Bitrus Dawi[1] btarfa@gmail.com, Amapu Ishaku Yoila[1], Daudu Christogonus Kayode[2], Arunah Uthman Lucky[3], Isah Abdulazeez Shero[3], Yakubu Adamu Alhaji[2], Nafiu Abdu[1], Adeogun Tinuke Tawa[1], Bakodo Pwanogoshin Raymond[1], Ugbaje Enemona Marinus[1], Dauda Haratu[3] and Ugbabe Omadachi Ogbodo[4]

[1]Department of Soil Science, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria
[2]National Agricultural Extension Research and Liaison Services, Ahmadu Bello University, Zaria, Nigeria
[3]Department of Agronomy, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria
[4]Department of Agric Economic and Rural Sociology, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria

12.1 Introduction

Increasing agricultural productivity in Nigeria requires greater adoption of good agricultural practices (GAP) including efficient use of fertilizers. While all farmers can profit from fertilizer use, only those with adequate finance may strive to maximize net returns per hectare resulting from fertilizer use. In this chapter, these rates are referred to as economically optimal rates (EOR). Others need to maximize return on their limited investment. For example, by increasing the use and correct application of fertilizer, poor farmers surveyed in Nigeria were able to improve their yields by approximately 30–55%. In turn, they benefited by making an additional 30–40% profit through greater commodity sales (PrOpCom 2011).

Most of Nigeria's farmers use traditional low input-low output farming methods that have been in use for generations. Even when knowledgeable of improved GAP, many have not been able to apply their knowledge appropriately due to poor access to agricultural inputs such as improved varieties and fertilizer. Investment in fertilizer use has an opportunity cost vis-à-vis other uses of financial resources for meeting immediate needs. Deliberate efforts must be made in ensuring that fertilizer investments give high returns with little risk. This necessitates employment of ingenious techniques for optimizing fertilizer use. Fertilizer use optimization in this chapter refers to maximizing profit from fertilizer use, including profit per hectare for farmers with adequate finance and profit on the small investment in fertilizer use by the financially constrained farmers.

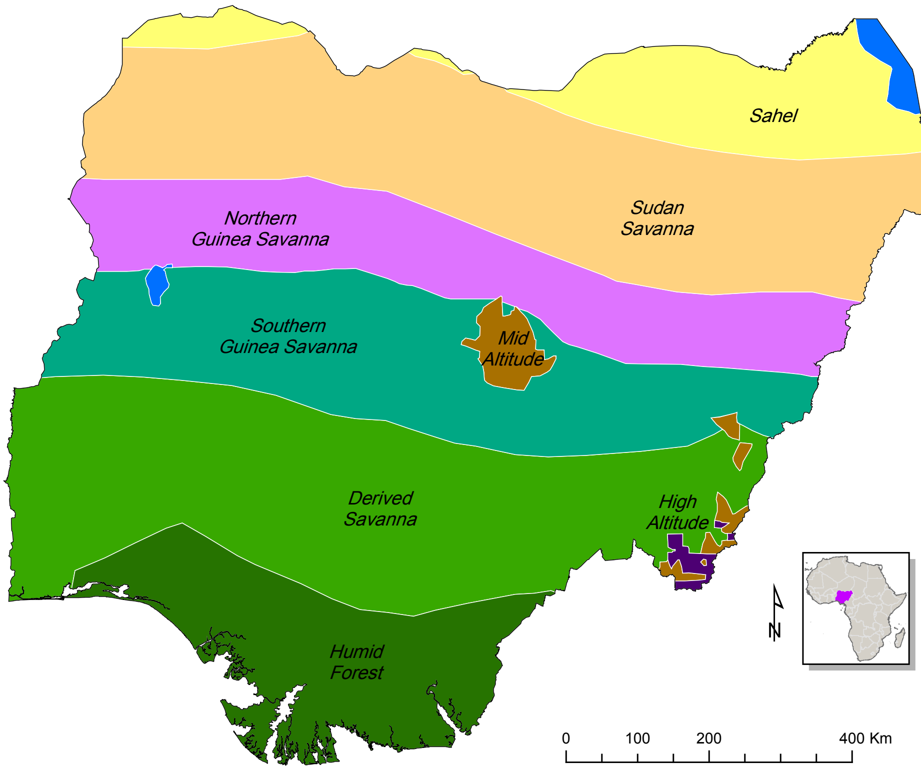


Figure 12.1: Agro-ecological zones of Nigeria.

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

The combined application of organic materials, especially farmyard manure (FYM), and fertilizer has long been advocated based on research results which established that combined application gave significantly higher yields than either the inorganic or FYM alone. It is recommended that FYM be applied once every two to three years of continuous cropping and then supplemented with fertilizer. However, FYM is inadequate for such application to all cropland and is often of low quality because very little attempt is paid to its storage and handling.

12.2 Agricultural systems of Nigeria

Nigeria's large climatic range is encompassed by the tropical humid forest in the south and the savanna in the north. The derived savanna is a transition zone between the rainforest and savanna biomes caused by forest clearance. The agro-ecological zone (AEZ) delineations in Figure 12.1 are the product of climatic and soil characteristics. The diverse agro-ecological environment of Nigeria makes it feasible to support the growth of several arable and tree crops of tropical and sub-tropical origin.

Rainfall increases northward from 3000 mm close to the equator to 500 mm in northeast Nigeria. The distribution generally is unimodal in areas above 9° N and bimodal between latitudes 4 and 9° N. The rainfall distribution is often erratic. A duration-of-dry-season gradient occurs with a range of three to eight months from the high rainfall areas in the south to the driest areas in the north. The country generally enjoys a high insolation and uniformly high

Table 12.1: Mean monthly rainfall (mm), maximum and minimum temperature (MJ m^2; °C; Tmax; Tmin) for representative locations of AEZ of Nigeria

	J	F	M	A	M	J	J	A	S	O	N	D
Sahel, Gashua (12°52′15″N11°02′53″E, 339 masl)												
Rainfall	1	0	0	8	67	31	101	119	60	6	1	0
Tmax	28	31	35	39	42	42	40	38	39	38	33	29
Tmin	13	15	19	23	27	29	27	26	26	23	18	14
Sudan, Kano (12°00′00″N 08°31′00″E, 484 masl)												
Rainfall	0	1.2	9.6	3	21	57	99	171	60	9	6	0
Tmax	30	33	37	38	37	34	31	31	31	31	31	31
Tmin	13	15	19	24	24	23	22	21	21	19	16	13
Northern Guinea, Samaru (11°06′40″N07°43′21″E, 644 masl)												
Rainfall	0	0	0	0	27	48	123	81	33	21	15	0
Tmax	33	35	36	34	30	28	28	28	28	30	32	32
Tmin	18	22	24	25	24	23	23	22	22	23	22	18
Southern Guinea, Zungeru (09°48′46″N 06°09′20″E, 117 masl)												
Rainfall	6	3	0	0	63	39	60	198	33	6	0	0
Tmax	35	37	37	36	33	31	29	29	30	32	34	35
Tmin	20	23	25	25	24	22	22	22	22	22	19	19
Mid High Altitude, Jos (09°55′00″N 08°54′00″E, 1295 masl)												
Rainfall	0	0	0	6.48	48	66	96	96	72	21	0	1.8
Tmax	28	30	32	31	29	27	25	24	27	29	29	28
Tmin	14	16	18	19	18	18	17	17	17	17	16	14
Derived Savanna, Ilorin (08°30′00″N 04°32′59″E, 310 masl)												
Rainfall	6	6	18	0	63	72	0	21	63	60	3	3
Tmax	34	36	36	34	33	31	29	28	29	31	33	34
Tmin	19	21	23	23	22	22	21	21	21	21	21	18

temperatures throughout the year (Table 12.1). Solar radiation varies from about 1250-1650 megajoule/cm^2/day (MJ/cm^2/d) close to the equator to about 1650- 2100 MJ/cm^2/d above 10^o N. A detailed description of the Nigerian agro-ecological zones is contained in Ojanuga (2006).

Most arable crop production is concentrated in the savanna AEZ (the focus of this chapter). The savanna lies between 8 and 19^o N, running in approximately east-west bands across the country. The savanna covers about 700,000 of the total area of 923,768 square kilometers (two thirds of the land area) of Nigeria and is subdivided into the Sahel, Sudan, Northern and Southern Guinea, Derived Savannas and Mid-high Altitude AEZ.

In general, soils in Nigeria have formed from the residues of deeply weathered, complex base rocks and alluvial materials derived from these under humid to dry tropical conditions (Table 12.2). Most soils are highly leached resulting in medium to high acidity, moderate to low cation exchange capacity and base saturation, and low organic matter content. The concentration of available levels of nitrogen (N), phosphorus (P) and potassium (K) are correspondingly low. Soil nutrient replenishment from organic and mineral sources is a prerequisite for continuous cultivation of such soils particularly under intensive production.

Many soils are susceptible to erosion due to their relatively low nutrient status and organic matter content, and fragile structure. Soil degradation and attendant depressed yields due to nutrient mining and inadequate soil and water conservation practices has already reached severe proportions in parts of the country. By removing the protective cover of natural vegetation and surface litter, conventional tillage practices lead to soil structure deterioration, loss of nutrients and erosion. Features of the AEZ are summarized in Tables 12.1 and 12.2.

Table 12.2: Description of the major AEZ in Nigeria

AEZ	Annual rainfall (mm)	Annual temperature (°C)	Days of growing period	Pristine vegetation (trees and grasses)	Main crop	Dominant FAO soil group
Humid Forest	2000–3000	25–27	270–360	Forest	Cocoa Oil palm	Ferralsols Acrisols
Derived Guinea Savanna	1500–2000	26–28	211–270	Forest	Oil palm Yam Maize	Ferralsols Luvisols Arenosols Nitosols
Southern Guinea Savanna	1200–1500	26–29	181–210	Savanna (*Dainella olivera Andropogon tectorum, Imperata cylindrica*)	Yam Maize, Sorghum Soybean Sesame	Luvisol Ferralsols Lithosols
Northern Guinea Savanna	900–1200	27–29	151–180	Savanna (*Dainella olivera Andropogon tectorum, Imperata cylindrica*)	Maize Sorghum Soybean Cotton	Luvisols Vertisols Lithosols Ferralsols
Sudan Savanna	500–900	25–30	91–150	Savanna (*Combretum, Acacia, Terminalia Andropogon gayanus*)	Millet Sorghum Groundnut	Lixisols Luvisols Regosols
Sahel Savanna	250–500	21–32	≤90	Grassland (*Acacia, Commiphora Cenchrus* spp)	Millet Sorghum	Aridisols Regosols
Mid-High Altitude	1100–1500	20–23	160–200	Savanna (*Isoberlinia* spp *Hyparrhenia, Andropogon*)	Maize Potato Vegetable	Luvisols Lithosols Ferralsols

Adapted and modified from Akpa et al. (2016)

12.3 Traditional practices affecting soil fertility

As in most parts of tropical Africa, the traditional method of maintaining soil fertility and productivity in Nigeria has been the bush-fallow system whereby arable land is allowed to revert to fallow after 3-4 years of continuous cultivation. The growing human population and other socio-economic pressures on available land have made this practice difficult to sustain. Attempts to improve soil fertility by planting legumes and grass fallows have not been popular and are inadequate for higher-yielding and nutrient-demanding crops and production systems.

The use of manures, particularly where there were large numbers of animals, replaced the fallow system and brought into eminence the agricultural value of FYM, poultry droppings, household refuse and other organic materials. The first recorded indication of the potential values of inorganic fertilizers in Nigeria was in 1937 when it was shown that response of cereal crops to small applications of FYM was matched by the use of single super-phosphate (SSP) containing equivalent quantities of phosphate. The need to apply fertilizer to depleted soils to resuscitate plant productivity heralded fertilizer use experimentation on the response of crops to applied nutrients such as N, P and K.

The recognition of the benefits of FYM by the late 1940s led to government encouragement of penning of cattle on the farm and mixed crop-livestock farming. The supply of FYM was not sufficient to meet farmers' demand as agriculture intensified, coupled with the introduction of higher-yielding and more nutrient-demanding crops. Other issues militating against the effective use of FYM included transportation problems due to bulk and labour costs.

Other practices that affect soil fertility such as crop rotation, green manuring, direct application of phosphate rock and agro-forestry have been promoted by agricultural extension personnel but the uptake and adoption of such practices has been too low to have much impact on production. It is recognized that fertilizer use needs to complement other management practices.

Effective fertilizer use requires good crop management. For example, unimproved local crop varieties of low-yield potential are less responsive to the use of fertilizer compared with improved varieties. Similarly, arrangement of plants and plant population affect yields. The farmer who carelessly plants late using unimproved crop varieties should not expect much benefit from the use of fertilizers, particularly if these are incorrectly applied.

Use of the wrong fertilizers, rates, placement and timing lead to inefficient fertilizer use and problems have developed. For example, the continuous application of sulphate of ammonium result in soil acidification and its use was stopped in 1969. There is the need for more education of farmers on manure management and use, and proper fertilizer use, including the 4Rs of fertilizer use, that is, applying the right fertilizer types at the right rate and time with the right placement.

12.4 Fertilizer use and recommendations

Widespread adoption of fertilizer began in the late 1970s with the proliferation of Agricultural Development Projects, but overall levels of fertilizer use have been too low to compensate for soil nutrient removal. The current national average NPK use hovers at 18 kg/ha of arable land (World Bank 2016).

The current fertilizer recommendations in Nigeria are reported in a manual titled 'Fertilizer Use and Management Practices for Crops in Nigeria', compiled by the National Fertilizer Use Committee and produced by the Federal Fertilizer Department of the Federal Ministry of Agriculture and Rural Development (2011).

Fertilizer recommendations for sole crops emanate almost exclusively from extensive laboratory and/or field trials over time and space. Such trials result in average recommendations for a crop within an area that normally have the approval of extension agencies. Where an approved fertilizer practice is considered inadequate or where no formal recommendation is available, the Fertilizer Use Committee suggests practices on the basis of existing information, including individual or common knowledge and experience. Current recommendations are largely 'blanket' or 'generic' in nature; its perils and the need for site-specific recommendations have been elucidated in a study on nutrient rationalization in Nigerian compound fertilizers by Adeoye (2006).

Fertilizer availability to farmers has been heavily subsidized, to as much as 95% of the real cost, since the late 1970s. The pattern of total fertilizer consumption in Nigeria is largely determined by the flow of federal and state government subsidies and the almost annual changes in procurement and distribution rules. For example, under the Federal Market Stabilization Program (FMSP), Liverpool-Tasie and Takeshima (2013) documented that the Federal Government of Nigeria (FGN) procures fertilizer for sale to states at a subsidy of 25%. State governments typically institute additional subsidies on fertilizer. Under this arrangement, companies make bids to the FGN to import and distribute subsidized fertilizer. Several states also procure fertilizer outside of the FMSP for sale to their farmers. Nevertheless, only an estimated 30 percent of subsidized fertilizer reaches small farmers at the subsidized price.

There is also remarkable variation in the subsidy rates state governments provide on the already federally subsidized fertilizer, ranging from 0 to 50%. In a typical state, there is federally subsidized fertilizer, federally plus state subsidized fertilizer and (in principle) unsubsidized fertilizer procured through private channels. However, the subsidy programmes have been plagued by pervasive problems of late delivery of fertilizer and delivery of inappropriate quantities and types of fertilizer. Political manipulation has also resulted in diversion of subsidized fertilizer from the intended beneficiaries.

Even though the subsidy programmes absorbed large proportions of the national budget, the impact of the programmes on agricultural productivity has been mixed at best. Arbitrage opportunities and incentives to adulterate and mislabel the source of fertilizer also abound.

Farmer access to fertilizer varies widely across states. Vigorous campaigns by the Fertilizer Producers and Suppliers Association of Nigeria (FEPSAN) and some international NGOs aimed at liberalization of fertilizer supply with smart subsidization, such as with the voucher system, are being pursued.

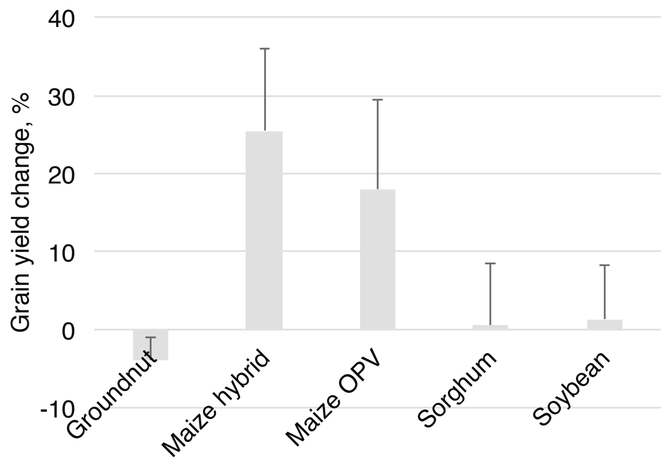


Figure 12.2: Relative yield increase due to application of Zn, S, B and Mg in the Nigerian Guinea Savanna.

12.5 Diagnostic results for the Northern Guinea Savanna AEZ

In 2014-15, 139 on-farm and 39 on-station fertilizer use trials were conducted for several crops in the Northern Guinea Savanna, which included a diagnostic treatment consisting of N+P+K+Mg+S+Zn+B compared with an N+P+K treatment (Figure 12.2).

Hybrid and open pollinated maize yields were increased by an average of 25 and 15%, respectively, by the diagnostic treatment compared with N+P+K. Mean yields of groundnut, sorghum and soybean were not much affected and the diagnostic package had a negative effect on groundnut in some trials. Therefore, one or more of four secondary and micronutrients in the diagnostic package are important to maize. There is ample evidence of maize response to Zn (Table 12.5b,c,e,f). More research is needed to determine if deficiency of Mg, S or B contributed to the maize response to the diagnostic treatment. There was a large

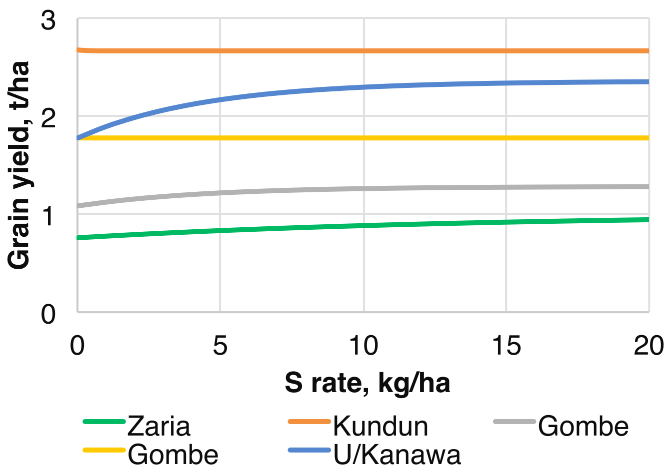


Figure 12.3: Response of soybean to sulphur in Nigerian Northern Guinea Savanna agro-ecological zone.

soybean response to S in the 2014-15 trials at Kaduna but little or no effect at other locations (Figure 12.3).

12.6 Optimizing fertilizer use in the savanna biome of Nigeria

Low commercial fertilizer use by farmers in Nigeria constrains their productivity. Many of the farmers are resource poor and do not have the financial ability to procure the required amount of fertilizers to maximize returns in fertilizer investment over all of their cropland. The unstable commodity prices and the high cost of fertilizers do not guarantee profit. Farmers have to choose between competing needs in deciding on fertilizer procurement. The profit to be made from fertilizer investment should therefore guide fertilizer use decisions.

Profit-oriented farmers without financial constraints (well resourced) invest in fertilizer use to maximize profits per hectare by applying at EOR over all cropland, while farmers with limited finances invest in fertilizer use to obtain high benefit to cost ratio while keeping risk low.

Maximizing net return requires understanding crop response to applied nutrients. The crop yield responses to applied nutrients were captured in curvilinear to plateau yield response functions as shown in Figure 12.4 for maize response (vertical axis or y-axis) to applied N (horizontal axis or x-axis) in the Mid-altitude zone. Maize grain yield response to increasing N rates in the Nigerian Mid-altitude AEZ has a steep response at low N rates and a reduced rate of increase at higher N rates until the yield plateau is reached, after which further increase in N rate has little or no effect to increase yield. There was increasing yield with N rates up to the 100 kg/ha rate beyond which maize grain yield

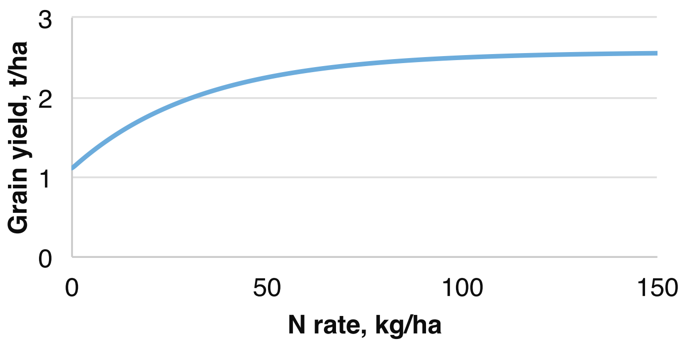


Figure 12.4: Maize response to nitrogen application in the Nigerian Mid-altitude AEZ.

tends to be constant. The maximum expected yield, on average, was 2.57 t/ha.

This type of response to applied nutrients is captured by the equation Yield (kg/ha) = $a - bc^r$, where a is near maximum yield for application of that nutrient, b is the maximum yield increase due to applied nutrient, and c^r determines the shape of the curvilinear response. The c is the curvature coefficient and r is nutrient rate. This function tells us that the benefit relative to cost for N application is expected to be greater with low N levels compared with high N rates.

Profit potential also varies with different nutrients applied to the same or different crops as shown in Figure 12.5 for the Nigerian Mid-altitude AEZ. Each curve represents the profit potential of a nutrient applied to a crop. Where the curve of the graph is steep, the net returns to investments are very high and where the curve flattens, the point of maximum profit per hectare is reached. When the graph slope starts declining, the profit is declining.

The results show that it is more economical to invest in N and K applied to cassava than in fertilizers for other crops. Application of low rates of N to sorghum and K to upland rice also have good profit potential. Other crop-nutrient options that have profit potential include the application of a very low rate of Zn for groundnut.

The resource-poor farmer needs to take advantage of the most profitable options first and gradually build financial capacity in order to take advantage of the less profitable choices. Poor farmers will benefit according to their financial ability by operating within the steep slope of the curves where there are high returns from investment, while well-resourced farmers will attempt to apply at EOR to maximize profit per hectare.

The results suggest the need to consider the various crop nutrient response functions in light of their other agronomic choices, the current economics of fertilizer use and their financial ability. Therefore, easy to use decision tools called fertilizer optimization tools (FOT), which use complex mathematics of linear optimization to consider reiteratively the numerous crop nutrient functions in light of the farmer's agronomic and economic situation, are needed to provide recommendations that maximize

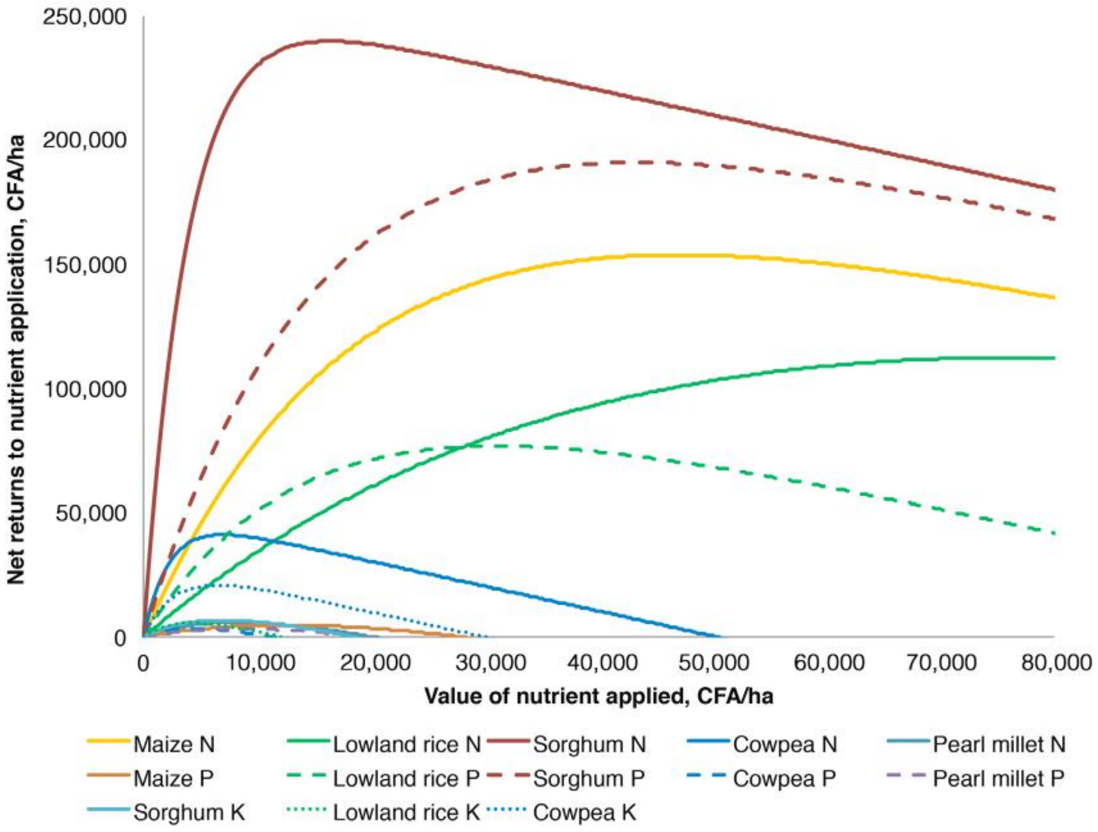


Figure 12.5: Net returns to investment in nutrients in the Mid-altitude AEZ of Nigeria

returns on investment. It also brings to the fore the need for farmers' education on the type of fertilizer they need to procure and use on different crops to maximize profit. Choices of single nutrient and double nutrient compound fertilizers are necessary for optimizing profit.

12.7 Fertilizer optimization tools for Nigerian AEZ

12.7.1 The Excel Fertilizer Optimization Tool

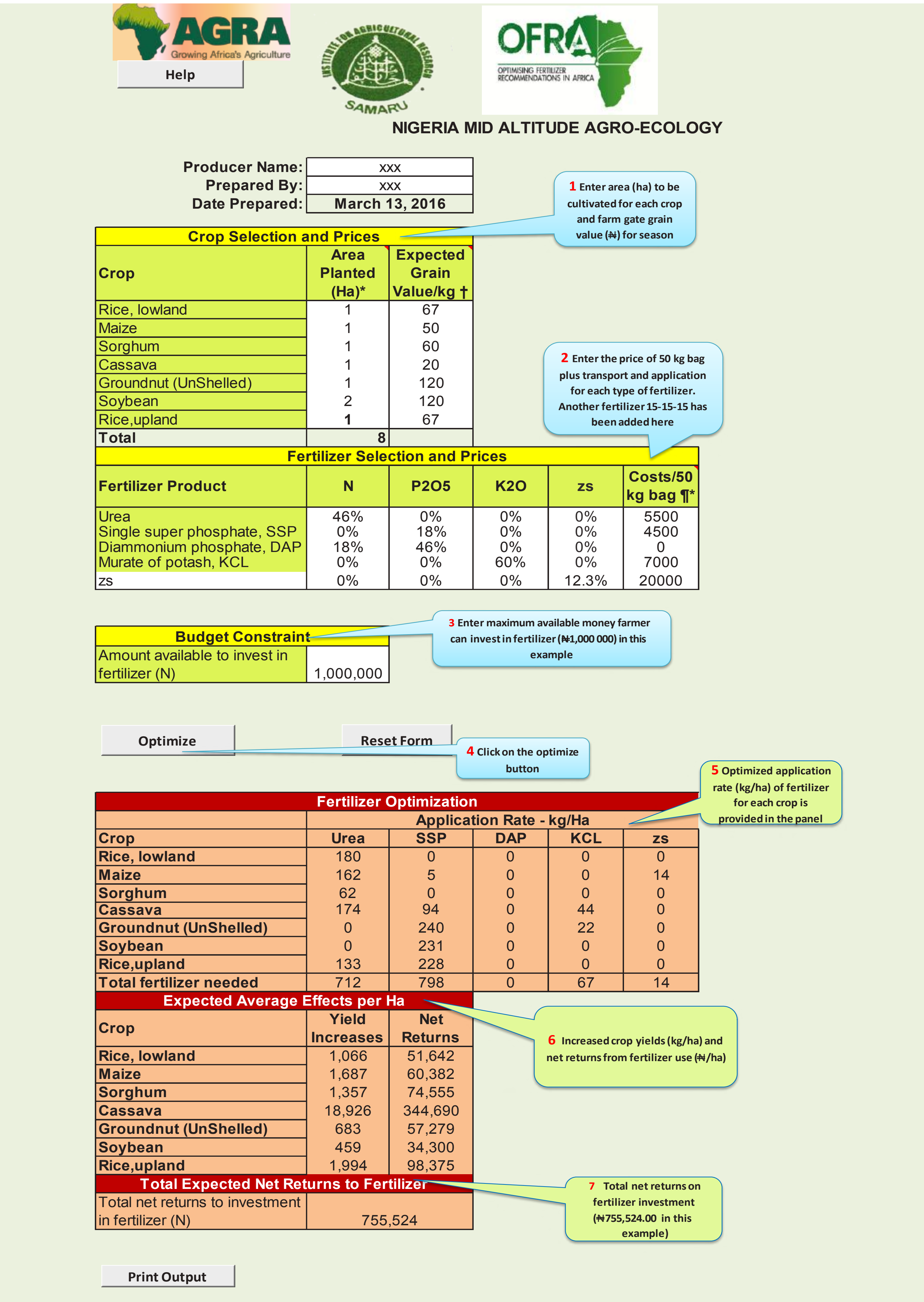
The Excel Fertilizer Optimization Tool (FOT) was first developed by Jansen et al (2013). It has been adapted to 67 country-AEZ of Africa including the six savanna AEZ of Nigeria. The FOTs are public goods that can be accessed by individuals at https://agronomy.unl.edu/OFRA. Educational institutions are encouraged to access the tool for use in their curriculum.

The FOTs are Excel Solver© (Frontline Systems Inc.) tools (Figure 12.6). To use the FOT, the Solver add-in of Excel needs to be engaged and macros need to be enabled; see the 'Help and Instructions' worksheet of the Excel FOT. More detailed instructions are in Extension Materials and the FOT Manual, also available at https://agronomy.unl.edu/OFRA. When Solver is enabled, it is indicated in the upper right of the Quick Access Toolbar under the Data tab.

The FOT is used to optimize investment in fertilizer use for the crops that the farmer chooses to cultivate in that season. It accounts for agronomic efficiency and economic returns from money invested in fertilizer use. The tool provides recommendations based on fertilizer cost, crop grown and resource level of the farmer, as well as the expected values of the various crops to be produced. It provides the best crop-nutrient-rate combinations to maximize returns on fertilizer investment for that farmer's situation.

The FOT has information input and output sections. The input section is a panel to enter: (1) area (ha) to be cultivated and expected value of each crop at harvest, (2) cost of buying and applying 50 kg bags of available fertilizers and (3) amount of money available for the farmer to invest in fertilizer use (Figure 12.6). When steps 1, 2 and 3 are completed, the user clicks on the 'Optimize' (4) button to run the optimization calculations.

The output panel (Figure 12.6) provides results of the optimization calculations. It displays: (5) recommended fertilizer rates for each selected crop, (6) expected average yield increases and



NIGERIA MID ALTITUDE AGRO-ECOLOGY

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	March 13, 2016

Crop Selection and Prices		
Crop	Area Planted (Ha)*	Expected Grain Value/kg †
Rice, lowland	1	67
Maize	1	50
Sorghum	1	60
Cassava	1	20
Groundnut (UnShelled)	1	120
Soybean	2	120
Rice,upland	1	67
Total	8	

Fertilizer Selection and Prices					
Fertilizer Product	N	P2O5	K2O	zs	Costs/50 kg bag ¶*
Urea	46%	0%	0%	0%	5500
Single super phosphate, SSP	0%	18%	0%	0%	4500
Diammonium phosphate, DAP	18%	46%	0%	0%	0
Murate of potash, KCL	0%	0%	60%	0%	7000
zs	0%	0%	0%	12.3%	20000

Budget Constraint	
Amount available to invest in fertilizer (N)	1,000,000

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	Urea	SSP	DAP	KCL	zs
Rice, lowland	180	0	0	0	0
Maize	162	5	0	0	14
Sorghum	62	0	0	0	0
Cassava	174	94	0	44	0
Groundnut (UnShelled)	0	240	0	22	0
Soybean	0	231	0	0	0
Rice,upland	133	228	0	0	0
Total fertilizer needed	712	798	0	67	14

Expected Average Effects per Ha		
Crop	Yield Increases	Net Returns
Rice, lowland	1,066	51,642
Maize	1,687	60,382
Sorghum	1,357	74,555
Cassava	18,926	344,690
Groundnut (UnShelled)	683	57,279
Soybean	459	34,300
Rice,upland	1,994	98,375

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer (N)	755,524

Figure 12.6: Fertilizer optimization tool.

Table 12.3: Paper FOT for the Nigerian Mid-altitude

NIGERIA MID-ALTITUDE AEZ

Fertilizer Use Optimizer

The below assumes:

Calibration measurement is with: a FARO water bottle lid (FARO) that holds about 6.3 g urea, 10 g SSP and KCl, 9 g NPK 15:15:15, 11 g NPK 20:10:10, and 14 g $ZnSO_4$; and with a GINO tomato can (GINO) of 70 ml to hold 49 urea, 77 g SSP and KCl; 165 g ZnSO4, 70 g NPK 15:15:15, and 84 g NPK 20:10:10.

Planting: Maize, sorghum and pulses are planted at 75 cm x 25 cm; pearl millet 1 x 1 m; cassava 1 x 1 m.

Crop values: Naira/kg 50 maize; 60 sorghum; 67 rice; 56 pearl millet; 120 unshelled groundnut; 165 cowpea, 120 soybean and 20 cassava.

Fertilizer use costs for Naira for 50 kg: 5500 Urea; 4500 SSP; 7000 MOP; 6000 for NPK 15-15-15 and 20-10-10; and 2000/kg for $ZnSO_4$.

Broadcast width: 2.5 m: WAP = weeks after planting, WAT = weeks after transplanting. Application rate is in kg/ha.

Level 1 financial ability.	
Cassava	Point apply 100 kg of NPK 15-15-15 (1 FARO for 0.5 plant) at 4 WAP also point apply 100 kg of urea (1 FARO for 0.5 plant) at 8 WAP planting
Maize	Point apply 48 kg urea (1 FARO for 6.5 plants) at 3 WAP
Groundnut	Mix 50kg of NPK 15:15:15 and 25 kg of SSP and point apply (1 FARO for 7 plants) at 2 WAP
Lowland rice	Broadcast 53 kg urea at 1 WAT (1 GINO for 1 m)
Upland rice	Mix 87 kg of SSP with 6 kg urea and broadcast at 3 WAP (1 GINO for 3 m)
Sorghum	Point apply 37 kg urea (1 FARO for 8.5 plants) at 3 WAP
Soybean	Point apply 23 kg SSP (1 FARO for 23 plants) at 2 WAP
Level 2 financial ability.	
Cassava	Mix 150 kg of NPK 15-15-15 and 100 kg of urea and point apply at 8 WAP planting (1 Gino for 2.5 plants)
Maize	Point apply 50 kg urea (1 FARO for 6.5 point) at 2 WAP. Apply 50 kg urea at 6 WAP (1 FARO for 6.5 plants)
Cowpea	Point apply 125 kg SSP at 3 WAP (1 FARO for 4 plants)
Groundnut	Mix 50 kg of NPK 15:15:15, 100 kg of SSP and point apply (1 FARO for 3.5 plants) at 2 WAP
Lowland rice	Broadcast 54 kg urea at 1 WAT (1 GINO for 3.5 m) and broadcast 54 kg urea at 5 WAT (1 Gino for 3.5 m)
Upland rice	Mix 1006 kg of NPK 15:15:15 with 50 kg SSP and broadcast (1 GINO for 2 m) at 2 WAP and broadcast 28 kg urea at 6 WAP (1 GINO for 6.5 m)
Sorghum	Point apply 48 kg of Urea (1 FARO for 6.5 plants) at 3 WAP
Soybean	Point apply 112 kg SSP (1 FARO for 4.5 plants) at 2 WAP
Level 3 financial ability (maximize profit per acre).	
Cassava	Mix 100 kg of NPK 15-15-15 and 87 kg of urea and point apply at 8 WAP (1 Gino for 3 plants)
Maize	Point apply 233 kg NPK 15:15:15 mixed with 7.5 kg $ZnSO_4$ (1 FARO for 2 plants) at 3 WAP. Point apply 75 kg urea at 6 WAP (1 FARO for 4 plants)
Cowpea	Point apply 125 kg SSP at 3 WAP planting (1 FARO for 4 plants)
Groundnut	Mix 100 kg NPK with 155 kg SSP and point apply (1 FARO for 2 plants) at 2 WAP
Lowland rice	Broadcast 90 kg urea at 1 WAT (1 Gino for 2 m) and broadcast 90 kg urea at 5 WAT (1 Gino for 2 m)
Upland rice	Broadcast 228 kg of SSP at land preparation (1 Gino for 1.5 m) and broadcast 50 kg urea at 3 WAP (1 Gino for 3.5 m) and 100 kg urea (1 Gino per 2 m) at 6 WAP
Sorghum	Point apply 62 kg of urea (1 FARO for 5 plants) at 3 WAP
Soybean	Point apply 231 kg SSP (1 FARO for 2.5 plants) at 2 WAP

net returns per hectare resulting from fertilizer use for each crop and (7) expected total net return on fertilizer investment.

The FOT recommendations are intended for the current season because both fertilizer costs and commodity prices vary seasonally. Good prediction of commodity values improves the optimization for a current season.

Once the optimal fertilizer rates are known, the farmer needs to know how to apply the fertilizer at the right rate. Therefore, the Nigerian OFRA project developed a calibration tool to guide application for the correct rates. The calibration tool is a reminder that optimization of fertilizer use does not include haphazard application. The Excel calibration tool offers options of measuring units of different volumes that are common in Nigerian rural communities. The type of fertilizer needs to be selected as fertilizers differ in specific gravity. Method of application and plant spacing are information provided. Depending on the amount and type of fertilizer that will be applied, the tool provides the application solution.

The Nigeria calibration tool used Faro brand water bottle caps (FARO-9ml), Gino brand tomato cans (GINO-70ml), and Peak Milk brand tins (PEAK-180ml). These measuring units were selected because of their availability in rural communities. The calibration units were designed to provide the farmer with visual estimates of fertilizer to be applied for a broadcast area, metres of band, or number of plants in the stand. After the farmer has ‘calibrated’ her eye and feel for the rate, the farmer proceeds with the actual fertilizer application free-hand.

12.7.2 Paper fertilizer optimization tools

The Excel FOT is useful for scientists, fertilizer retailers, extension staff and others with good computer access. However, paper versions of FOTs were developed for use by farmers and their advisors when a computer is not available (Table 12.3).

Table 12.4: Fertilizer use in an ISFM Framework

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT FRAMEWORK

ISFM practice	Urea	SSP	KCl	NPK 15-15-15
	Fertilizer reduction, % or kg/ha			
Farmyard manure or compost applied	Both yield and response to fertilizer are expected to be increased; therefore fertilizer rates should not be decreased			
Cattle manure 1 t dry material	12kg	59 kg	20 kg	35 kg
Poultry manure 1 t dry material	19kg	106kg	12kg	28
Horse 1 t dry material	12kg	24kg	8.6kg	19kg
Swine 1 t dry material	16kg	80kg	31kg	12kg
Sheep and goats 1 t dry material	12kg	75kg	8kg	24
Residual value of dairy and poultry manure applied for the previous crops per 1 t dry material	6kg	23kg	2kg	12
Compost	16kg	7kg	30kg	121kg
Cereals harvest waste	0% reduction of fertilizers. Use as soil cover for soil water conservation and erosion control.			
Cereal-cowpea or groundnut intercropping	Apply sole crop recommended rates of NPK to cereals only			
Cereal-cowpea or groundnut strip cropping	Apply sole crop recommended rates of NPK to strips of legumes and cereals separately			
Cereal-other legume (effective in N fixation) rotation with return of residues	Reduce urea by 11kg/ha and apply recommended rates sole crop rates of P and K fertilizer			
If Bray-1 >15 ppm	Apply no P			
If soil test K >0.17 cmol/kg (>68 ppm)	Apply no K			

Farmers' financial resource base determines how much fertilizer use they can afford. Farmers without financial constraints to procurement of fertilizers target the potential yield of the crop and can invest large amounts of money to attain optimum yield. Nigerian farmers commonly procure fertilizer blends that do not give maximum return on investment due to lack of knowledge or access to more cost-effective fertilizer choices. The paper FOTs consider three financial ability levels:

- Financial level 1 is the most constrained. This farmer has no more than one-third of the money needed to apply fertilizer at EOR to all cropland.
- Financial level 2, moderately constrained. This farmer has no more than two-thirds of the money needed to apply fertilizer at EOR to all cropland.
- Financial level 3, the least constrained. These rates are the EOR that on average will maximize profit per hectare.

Considering that urea, SSP and NPK 15:15:15 are the most common fertilizers in the Nigerian market, use of the paper FOT in this chapter is based on the use of these fertilizers, either alone or in combination to provide the optimized fertilizer rate for the AEZ. As fertilizer supply becomes more liberalized, more fertilizers will be added.

For a financially constrained farmer in level 1 who wants to produce cassava in the Nigerian Mid-altitude, he/she should procure 200 kg of NPK 15:15:15 and point apply 100 kg/ha (1 FARO per 0.5 plant at 4 weeks after planting (WAP)) and repeat the same at 8 WAP. For his/her maize crop, 48 kg/ha urea (1 FARO for 6.5 plants) should be applied at 3 WAP. For his/her groundnut plot the farmer

Table 12.5a: Sahel savanna, response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations by AEZ in Nigeria. $P_2O_5 = P \times 2.29$; $K_2O = K \times 1.2$. Some functions have zero response because of lack of response or lack of information

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
			t/ha			**Yield increase, t/ha**			**kg/ha**	
Pearl millet	N	0.742	0.223	0.930	0.198	0.022	0.003	0.000	18	60
Sorghum	N	1.098	0.273	0.970	0.164	0.066	0.026	0.011	24	64
Maize	N	1.275	0.687	0.951	0.535	0.118	0.026	0.006	39	120
Rice, lowland	N	4.461	0.564	0.942	0.470	0.078	0.013	0.002	38	100
					0-5	**5-10**	**10-15**	**15-20**		
Pearl millet	P	1.717	0.768	0.940	0.204	0.150	0.110	0.081	14	13
Sorghum	P	0.975	0.548	0.908	0.210	0.129	0.080	0.049	11	14
Groundnut	P	0.254	0.032	0.870	0.016	0.008	0.004	0.002	0	24
Cowpea	P	0.605	0.109	0.930	0.033	0.023	0.016	0.011	2	17
Maize	P	1.275	0.687	0.951	0.153	0.119	0.092	0.072	0	26
Rice, lowland	P	5.190	0.189	0.919	0.065	0.043	0.028	0.018	0	22
Groundnut	K	1.093	0.104	0.800	0.070	0.023	0.008	0.002	10	21
Cowpea	K	0.477	0.063	0.650	0.056	0.006	0.001	0.000	6	17
Rice, lowland	K	6.036	0.223	0.750	0.170	0.040	0.010	0.002	9	33

† EOR was determined with the cost of using 50 kg urea and SSP at N 5,500 and 4,500, respectively. Commodity values (N /kg) used were: cassava 20; rice 67; maize 50; sorghum 60; cowpea 165; groundnut 120; soybean 120; and pearl millet 60.

‡Source: OFRA-Nigeria 2015 country recommendation

Table 12.5b: Sudan Savanna

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**Yield increase, t/ha**				**kg/ha**	
Maize	N	3.000	1.760	0.970	1.054	0.423	0.170	0.068	70	120
Sorghum	N	4.067	1.530	0.860	1.513	0.016	0.000	0.000	27	64
Rice, lowland	N	2.482	0.428	0.970	0.256	0.103	0.041	0.017	43	100
Cowpea	N	1.860	0.168	0.770	0.168	0.000	0.000	0.000	12	20
Pearl millet	N	1.111	0.110	0.930	0.098	0.011	0.001	0.000	9	60
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.868	0.295	0.928	0.092	0.063	0.044	0.030	0	26
Groundnut	P	1.485	0.399	0.845	0.227	0.098	0.042	0.018	12	17
Sorghum	P	2.770	1.470	0.910	0.553	0.345	0.215	0.134	16	14
Cowpea	P	0.929	0.040	0.700	0.033	0.006	0.001	0.000	2	17
Soybean	P	1.319	0.141	0.855	0.077	0.035	0.016	0.007	5	26
Pearl millet	P	1.520	0.129	0.900	0.053	0.031	0.018	0.011	0	13
Groundnut	K	1.260	0.075	0.800	0.050	0.017	0.005	0.002	9	25
Sorghum	K	2.016	0.114	0.900	0.047	0.028	0.016	0.010	9	25
Rice, lowland	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	0	33
Cowpea	K	0.871	0.100	0.800	0.067	0.022	0.007	0.002	12	20
					0-1	**1-2**	**2-3**	**3-4**		
Maize	Zn	3.590	0.560	0.250	0.420	0.105	0.026	0.007	1.8	0.62
Groundnut	Zn	1.614	0.348	0.397	0.210	0.083	0.033	0.013	0.7	NA
Sorghum	Zn	4.300	0.100	0.500	0.050	0.025	0.013	0.006	0.4	NA
Soybean	Zn	1.614	0.348	0.397	0.210	0.083	0.033	0.013	2.7	NA

should mix 50 kg/ha of NPK 15:15:15 with 100 kg/ha SSP and point apply (1 FARO for 7 plants) at 2 WAP. For lowland rice, the farmer should broadcast 53 kg urea/ha at 1 week after transplanting (WAT) (1 GINO for 1 m length and 2.5m width).

12.7.3 Fertilizer use in an integrated soil fertility management context

Organic residues such as livestock manure, compost, cereal–legume rotation and intercropping with legumes can contribute to soil nutrient availability. Their contributions should be considered and some of the recommended fertilizer can be allocated elsewhere. The fertilizer nutrient substitution values of practices are provided in terms of adjustment to fertilizer rates in Table 12.4. For example, the level 1 farmer in the paper FOT needs to apply 37 kg/ha of urea for his sorghum. If he has already applied 1 t/ha of cattle manure, which has a urea equivalent of 12 kg/ha, he needs to apply only 25 kg/ha of urea and the remaining fertilizer or saved money can be used elsewhere.

12.8 Targeted crops by AEZ

During 2014-15, results of past research were compiled and analysed, and additional field research was conducted to improve the information for fertilizer use decisions in the savanna AEZ of Nigeria (Table 12.5a-f). The food crops addressed were cassava, maize, sorghum, pearl millet, lowland and upland rice, groundnut and soybean.

Current recommendations (REC) guiding fertilizer use in Nigeria were developed over 30 years ago, are outdated and do not reflect current soil, crop and weather situations.

Table 12.5c: North Guinea Savanna

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
			t/ha			**Yield increase, t/ha**			**kg/ha**	
Soybean	N	0.963	0.357	0.762	0.357	0.000	0.000	0.000	0	20
Maize LP <3t	N	2.493	1.601	0.972	0.918	0.392	0.167	0.071	79	120
Maize HP >3t	N	3.513	1.808	0.981	0.791	0.445	0.250	0.141	103	150
Rice, lowland	N	2.729	0.214	0.963	0.145	0.047	0.015	0.005	59	100
Rice, upland	N	3.058	0.738	0.968	0.460	0.173	0.065	0.025	58	80
Sorghum	N	4.154	1.338	0.906	1.269	0.066	0.003	0.000	35	64
					0-5	**5-10**	**10-15**	**15-20**		
Soybean	P	0.961	0.052	0.600	0.048	0.004	0.000	0.000	2	17
Groundnut	P	1.589	0.362	0.760	0.270	0.069	0.017	0.004	9	24
Maize LP <3t	P	2.678	1.653	0.980	0.159	0.144	0.130	0.117	18	26
Maize HP >3t	P	3.541	1.799	0.978	0.189	0.169	0.152	0.136	25	33
Rice, lowland	P	3.058	0.738	0.969	0.108	0.092	0.078	0.067	10	26
Rice, upland	P	3.165	0.770	0.908	0.295	0.182	0.112	0.069	15	17
Sorghum	P	1.721	0.576	0.980	0.055	0.050	0.045	0.041	0	14
Soybean	K	0.821	0.134	0.800	0.090	0.030	0.010	0.003	11	17
Groundnut	K	1.776	0.102	0.630	0.092	0.009	0.001	0.000	6	21
Rice, lowland	K	1.951	0.091	0.810	0.059	0.021	0.007	0.003	7	33
Rice, upland	K	2.500	0.300	0.945	0.074	0.056	0.042	0.032	25	30
					0-1	**1-2**	**2-3**	**3-4**		
Soybean	Zn	1.776	0.195	0.229	0.195	0.000	0.000	0.000	0.7	NA
Maize	Zn	3.729	0.679	0.300	0.677	0.002	0.000	0.000	1.0	0.62

These recommendations were formulated from results of soil samples collected from non-geo-referenced sites and, therefore, do not account for the indigenous potential supply of soils, climatic potential of the various AEZ, economic considerations and fertilizer availability.

In Table 12.5, a synthesis of much research information is presented by crop and nutrient (cols1-2), and the response coefficients are presented in cols 3-5 for the curvilinear to plateau response function represented by the equation $Y = a - bc^r$ where Y = yield, a = yield at the plateau of response to the given nutrient, b = yield increase at plateau in response to the nutrient, c is a curvature coefficient and r is the rate of nutrient application. The yield increases associated with changes in nutrient rates are presented in cols 6-9. The EOR is the nutrient rate required to maximize profit per hectare from fertilizer use and the RECs are given in cols 10-11.

In the Sahel Savanna, response of upland crops was greater to applied P compared with N, while lowland rice was more responsive to N. Cowpea and groundnut were not found to be responsive to N but had modest response to applied P and K.

The field research based EOR were consistently less and generally less than half REC. Therefore, even for cases of no financial constraint on the amount of fertilizer use, the REC are well above the most profitable rates and therefore a profit opportunity is lost in applying according to REC. For farmers with financial constraints to fertilizer use, the most profitable rates will be less than the EOR as determined through use of FOTs. These results suggest that most of the RECs for primary fertilizer elements did not consider economic benefits.

Table 12.5d: South Guinea Savanna

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**Yield increase, t/ha**				**kg/ha**	
Maize	N	3.130	1.680	0.980	0.955	0.484	0.245	0.124	97	100
Rice, lowland	N	3.100	0.750	0.950	0.588	0.341	0.198	0.115	46	100
Rice, upland	N	2.500	0.300	0.955	1.508	0.002	0.000	0.000	29	80
Sorghum	N	1.720	0.570	0.980	0.864	0.471	0.257	0.140	50	64
Soybean	N	3.160	0.340	0.880	0.333	0.007	0.000	0.000	0	30
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.160	0.340	0.880	0.161	0.085	0.045	0.024	5	26
Rice, lowland	P	3.100	0.000	0.000	0.000	0.000	0.000	0.000	0	17
Rice, upland	P	3.160	0.770	0.970	0.109	0.093	0.080	0.069	10	17
Groundnut, unshelled	P	1.580	0.360	0.760	0.269	0.068	0.017	0.004	9	24
Cowpea	P	1.060	0.185	0.890	0.082	0.046	0.025	0.014	26	17
Sorghum	P	2.190	0.800	0.890	0.353	0.197	0.110	0.062	14	14
Soybean	P	2.010	0.680	0.930	0.207	0.144	0.100	0.070	23	26
Rice, lowland	K	1.950	0.090	0.810	0.059	0.020	0.007	0.002	7	50
Rice, upland	K	4.430	0.840	0.800	0.565	0.185	0.061	0.020	17	33
Groundnut, unshelled	K	1.770	0.100	0.750	0.076	0.018	0.004	0.001	9	21
Cowpea	K	0.820	0.130	0.800	0.087	0.029	0.009	0.003	13	17

In the South Sudan Savanna, maize, sorghum and rice had large responses to applied N and P, and rice responded well to just 1 kg/ha Zn (Table 12.5b). Response of cowpea, groundnut and pearl millet were less but generally economical for all nutrients. The EOR were on average less than half REC although the EOR for sorghum P and the maize Zn EOR was more than recommended. Zinc EORs were determined for groundnut, sorghum and soybean but RECs are not available.

In the Northern Guinea Savanna, all cereals and soybean had a large yield increase with just 30 kg/ha N applied but EOR were generally greater (Table 12.5c). Most crops responded well to 5 kg/ha or more of P applied. Responses to K were small but often economical at low rates. Soybean and maize yield increased with 1 kg/ha Zn applied. The EOR were mostly less than half REC but the differential was less compared with the Sahel. The REC and EOR were similar for upland rice P.

Cereal yield increase with N application in the Southern Guinea Savanna varied from 0.34 t/ha for sorghum to 1.7 t/ha for maize (Table 12.5d). With respect to P, yield increases varied from zero for lowland rice to 0.8 t/ha for sorghum. Yield increases with K application varied from 0.1 t/ha for lowland rice to 0.8 t/ha for upland rice. The EOR for maize N and sorghum P were similar to REC. The EOR for cowpea P was more than REC. All other EOR were less, and mostly less than half, of REC.

Cereal and cassava yield increases with applied N were large in the Mid-altitude AEZ (Table 12.5e). The legumes and upland rice responded well to P and cassava and upland rice responded well to K. Maize had an economic response to 1 kg/ha of Zn. All field research derived EOR were less than REC except for Zn applied to maize.

In the Derived Savanna, cereals responded well to N and P with the exception of lowland rice response to P (Table 12.5f). Rice responded well to K. Maize, sorghum, groundnut and soybean

Table 12.5e: Mid-altitude Zone

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC‡
		t/ha			Yield increase, t/ha				kg/ha	
Rice, lowland	N	3.792	1.202	0.974	0.657	0.298	0.135	0.061	83	100
Maize	N	2.567	1.456	0.971	0.854	0.353	0.146	0.060	75	120
Sorghum	N	4.354	1.387	0.875	1.362	0.025	0.000	0.000	29	64
Cassava	N	44.800	11.935	0.967	7.574	2.768	1.011	0.370	80	90
Rice, upland	N	3.012	0.680	0.974	0.371	0.168	0.076	0.035	61	80
					0-5	5-10	10-15	15-20		
Rice, lowland	P	3.378	0.000	0.000	0.000	0.000	0.000	0.000	0	22
Maize	P	2.559	0.161	0.860	0.085	0.040	0.019	0.009	0	26
Sorghum	P	1.451	0.149	0.906	0.058	0.036	0.022	0.013	0	14
Cassava	P	28.790	1.527	0.770	1.114	0.301	0.082	0.022	7	9
Groundnut	P	1.875	0.659	0.900	0.270	0.159	0.094	0.056	19	24
Soybean	P	2.107	0.560	0.910	0.211	0.131	0.082	0.051	18	26
Rice, upland	P	3.166	0.770	0.910	0.290	0.181	0.113	0.070	18	17
Sorghum	K	0.869	0.024	0.9	0.010	0.006	0.003	0.002	0	25
Cassava	K	34.000	6.566	0.813	4.234	1.504	0.534	0.190	22	63
Groundnut	K	1.926	0.125	0.8	0.084	0.028	0.009	0.003	11	21
Rice, upland	K	4.439	0.838	0.806	0.553	0.188	0.064	0.022	0	33
					0-1	1-2	2-3	3-4		
Maize	Zn	4.019	0.795	0.310	0.549	0.170	0.053	0.016	1.5	0.62
Sorghum	Zn	4.923	0.252	0.280	0.182	0.051	0.014	0.004	0	na
Groundnut	Zn	1.060	0.080	0.300	0.056	0.017	0.015	0.013	0	na

had economic responses to Zn. The field research derived EORs for upland rice N and P were similar to REC. All other EORs were less than REC except for the Zn EOR of maize which was more than REC.

Overall, RECs were on average 114% greater than the EOR determined from field research results but there were four cases where the REC was low relative to EOR (Table 12.5a-f). Applications at REC generally result in loss of much of the profit potential of fertilizer use. Finance-constrained farmers should apply fertilizer nutrients at less than EOR to take advantage of the greater profit potential associated with relatively large yield increases per kg of nutrient applied at low rates.

12.9 Acknowledgements

The authors appreciate the support of the personnel of Institute for Agricultural Research, Ahmadu Bello University, Zaria, Nigeria, funding support from the Alliance for a Green Revolution in Africa, OFRA management support from CABI, technical support of the University of Nebraska-Lincoln, and data and literature contributions of the Nigerian Soil Health Consortium.

12.10 References

Adeoye GO (2006) Nutrient Rationalization in Nigerian Compound Fertilizers (NPK) with Special Focus on Phosphorus and Potassium Utilization. USAID MARKETS

Akpa IC, Odeh IOA, Bishop TFA, Hartemink AE and Amapu IY (2016) Total soil organic carbon and carbon sequestration potential in Nigeria. Geoderma 271:202–215

Federal Ministry of Agriculture and Rural Development (2011) Fertilizer Use and Management Practices for Crops in Nigeria. Bobma Publishers, Ibadan

Table 12.5f: Derived Savanna Transitional Zone

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Yield increases due to incremental increases in elemental nutrient rate				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**Yield increase, t/ha**				**kg/ha**	
Maize HP>3t	N	3.787	1.936	0.978	0.955	0.484	0.245	0.124	98	150
Maize LP<3t	N	2.526	1.399	0.982	0.588	0.341	0.198	0.115	92	120
Sorghum	N	4.170	1.510	0.800	1.508	0.002	0.000	0.000	20	32
Rice, upland	N	4.650	1.900	0.980	0.864	0.471	0.257	0.140	80	80
Rice, lowland	N	3.104	0.746	0.953	0.570	0.135	0.032	0.007	48	100
Soybean	N	1.800	0.000	0.000	0.000	0.000	0.000	0.000	0	NA
					0-5	**5-10**	**10-15**	**15-20**		
Maize HP>3t	P	2.820	0.310	0.520	0.424	0.188	0.084	0.037	10	33
Maize LP<3t	P	0.910	0.240	0.780	0.171	0.049	0.014	0.004	0	26
Sorghum	P	1.938	0.547	0.901	0.222	0.132	0.078	0.047	11	7
Rice, upland	P	1.830	0.420	0.910	0.158	0.099	0.061	0.038	0	17
Rice, lowland	P	3.210	0.150	0.700	0.125	0.021	0.004	0.001	0	22
Groundnut	P	4.430	0.830	0.800	0.270	0.069	0.017	0.004	9	23
Soybean	P	1.740	0.110	0.880	0.153	0.098	0.063	0.040	16	26
Maize HP>3t	K	3.759	0.036	0.550	0.035	0.002	0.000	0.000	2	62
Maize LP<3t	K	2.565	0.419	0.855	0.227	0.104	0.047	0.022	16	50
Rice, upland	K	4.430	0.830	0.800	0.558	0.183	0.060	0.020	0	25
Rice, lowland	K	4.43	0.830	0.800	0.558	0.183	0.060	0.020	17	25
Sorghum	K	1.570	0.000	0.001	0.000	0.000	0.000	0.000	4	25
Groundnut	K	1.740	0.110	0.880	0.052	0.027	0.014	0.008	14	21
Soybean	K	1.840	0.000	0.001	0.000	0.000	0.000	0.000	0	NA
					0-1	**1-2**	**2-3**	**3-4**		
Maize	Zn	4.010	0.790	0.310	0.545	0.169	0.052	0.016	2.3	0.62
Sorghum	Zn	4.920	0.250	0.280	0.180	0.050	0.014	0.004	1.4	na
Groundnut	Zn	1.060	0.080	0.300	0.056	0.017	0.005	0.002	1.1	na
Soybean	Zn	1.774	0.194	0.270	0.142	0.038	0.010	0.003	1.7	na

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

Liverpool-Tasie, LSO and Takeshima H (2013) Moving forward with fertilizer in Nigeria: Fertilizer promotion strategies within a complex fertilizer subsector. Agricultural Economics. doi: 10.1111/agec.12075

Ojanuga AG (2006) Agroecological Zones of Nigeria Manual. In: Berding F and Chude VO (eds) National Special Programme for Food Security (NSPFS) and FAO

ProOpCom (2011) Promoting Pro-Poor Opportunities in Commodity and Service Markets. Making Fertilizer Markets Work for the Poor in Nigeria. A PrOpCom case study. Green Ink Ltd (www.greenink.co.uk)

World Bank (2016) World Development Indicators: Fertilizer Consumption. http://data.worldbank.org/indicator/AG.CON.FERT.ZS

13. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Rwanda

Athanase R Cyamweshi[1] rusacyamweshi@gmail.com, John Kayumba[1] and Nsharwasi L Nabahungu[2]

[1]Rwanda Agriculture Board, PO Box 5016, Kigali, Rwanda

[2]International Institute of Tropical Agriculture (IITA), Bukavu, DR Congo

13.1 Agricultural systems of Rwanda

An agro-ecological zone is a land resource mapping unit, defined in terms of climate, landform and soils, and/or land cover, and having a specific range of potentials and constraints for land use (FAO 1996). An agro-ecological zones (AEZ) map is an essential tool for agricultural planning. There are three regional classification schemes of AEZ commonly used in Rwanda. These were defined based on differences in soils, altitude and rainfall, and as such also show marked differences in cropping patterns, farm size, livestock ownership and other important household and regional characteristics. The most used in Rwanda is that of Clay and Dejaegher (1987), who defined five AEZ with emphasis on agronomic and socio-economic homogeneity within AEZ among farmers and their farming systems (Figure 13.1).

The Northwest AEZ includes parts of Western and Northern Provinces and has both temperate highlands (>1800 m above sea level (masl)) that are dominated by fertile volcanic soils and the well-watered lowlands of Lake Kivu. Temperature varies little by month but is affected by altitude with mean minimum and maximum annual temperatures of 14 and 20°C at Gisenyi, respectively, and 2°C less at Musanze. Rainfall is bimodal with mean annual totals of 1170 and 1320 mm at Gisenyi and Musanze, respectively. Major cash crops are coffee, Irish potato and pyrethrum. Major food crops are maize, sweet

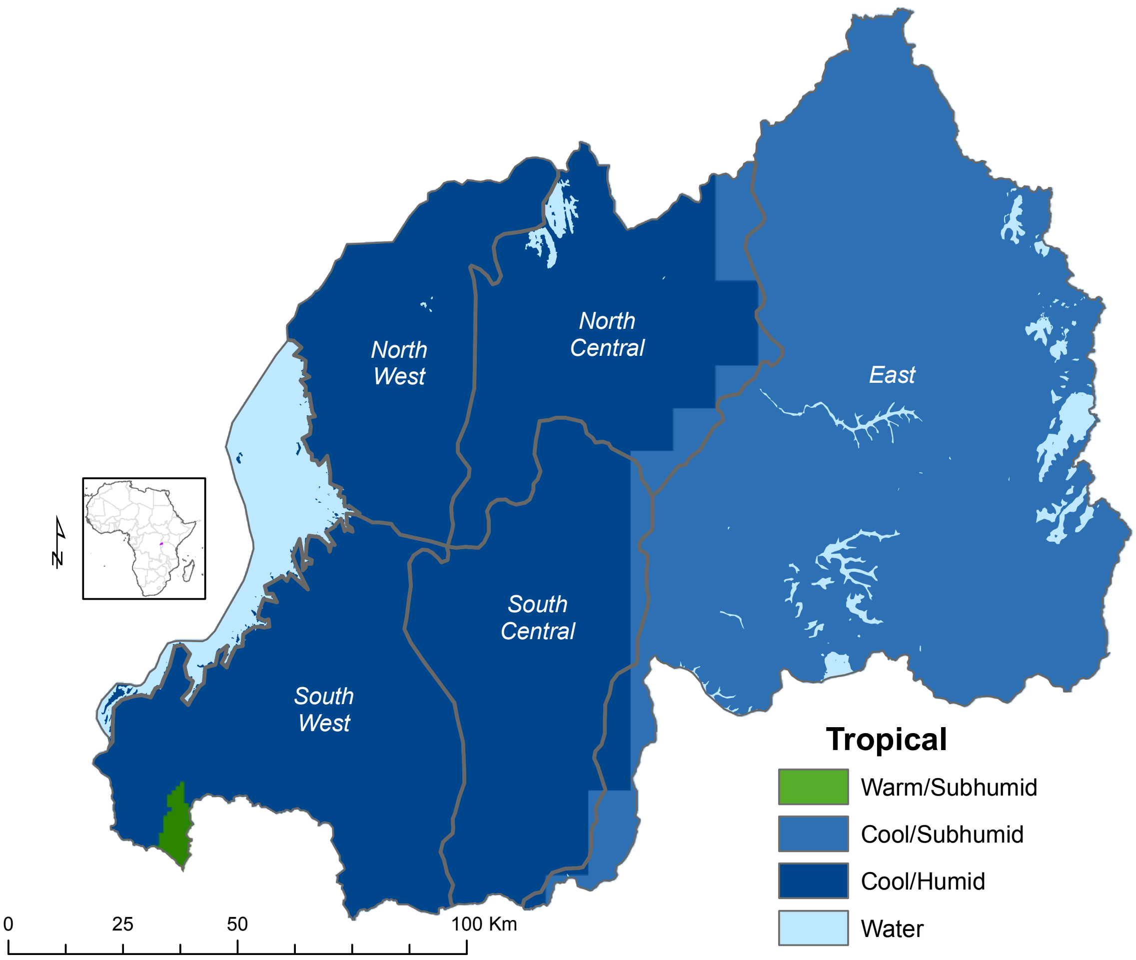


Figure 13.1: Agro-ecological zones of Rwanda.

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

Table 13.1: Rwanda farming systems

Farming system	Principal livelihoods
Cereal, root/legumes intercropping	Maize, sorghum, cassava, legumes
Banana mixed crops	Banana, common bean, maize, fodder for livestock
Cereal/root crop-legumes rotation	Maize, sorghum, potato, cassava, legumes
Sole cropping	Banana, coffee, cassava, tea, sweet potato, maize, bean, soybean, cassava, wheat and rice in marshland
Pastoral	Cattle in Eastern Rwanda
Tree crop integration	Maize, bean, Irish potato, agroforestry species (*Alnus acuminata, Calliandra callothyrsus*, etc.), green manure incorporated

potato, wheat and bean. The zone is very densely populated with 4,197,609 inhabitants (NISR, 2014).

The Southwest AEZ includes Nyamagabe District in Southern Province and the districts of Karongi, Nyamasheke and Rusizi in Western province. It is mostly high altitude with steep slopes and high rainfall, with concomitant soil erosion and soil acidity problems. A substantial but diminishing part of the Southwest AEZ is covered by the natural, protected Nyungwe Forest. Major cash crops are tea and coffee. The major food crops are bean, sweet potato, taro and cassava. Soils have a high proportion of clay, are often degraded and range from poorly to moderately suitable for agriculture. Acid soil prevails on the steep slopes of the Congo-Nile Divide and soils are fertile on the coast of Lake Kivu.

The North Central AEZ covers parts of Ruhengeri, Byumba and Kigali. It has high mountains, steep slopes and soils are susceptible to erosion. Major cash crops are bananas and coffee, with some highland areas specializing in potato and wheat. Food staples include sweet potato, bean and maize. Agro-climatically, it is quite similar to the South-Central zone.

The South Central AEZ comprises the districts from Kamonyi to Huye and part of Nyamagabe in Southern Province. The soils are acidic and require lime application. Major cash crops are banana and coffee, while the staples are bean, sweet potato, cassava, sorghum and rice in the wetlands.

The Eastern AEZ corresponds to current Eastern Province and is characterized by gentle slopes and relatively low altitude. Rainfall is less than in other AEZ. Because it is drier, livestock are important. The main staple crops are banana, sorghum, bean and cassava with coffee as an export crop.

13.2 Soil fertility management in Rwanda

Soils of Rwanda have a high clay content. Suitability classification for agriculture ranges from poor to moderate. Farming is principally by smallholders. The government supported Crop Intensification Program is based on consolidation of farmland use and facilitation of inputs access, including improved seeds and fertilizers by farmers at subsidized costs. This has resulted in increased fertilizer use from 4 to 32 kg/ha from 2007 to 2015 (NISR 2014).

Recommended rates of fertilizers (RECs) include: 41 kg N and 46 kg P_2O_5/ha for maize and wheat; 18 kg N and 46 kg P_2O_5/ha for bean and soybean; 50 kg/ha DAP for cassava; and 80 kg N, 34kg P_2O_5 and 34 kg K_2O/ha for rice. However more specific fertilizer use guidelines are needed.

The 4Rs of nutrient stewardship including the right product, rate, method and time of application needs to be applied for more fertilizer use efficiency. The ‘right’ combination of these factors needs to be location and cropping system specific.

Amendment of soil acidity and aluminium (Al) toxicity is essential for crop response to fertilizers with some soils. Deficiencies of nutrients other than macro nutrients can also limit response to N-P fertilizer. Lime application and planting of green manure crops are proven good agronomic practices although not much adopted. Minjingu rock phosphate from northern Tanzania is especially reactive on acid soils with some liming effect.

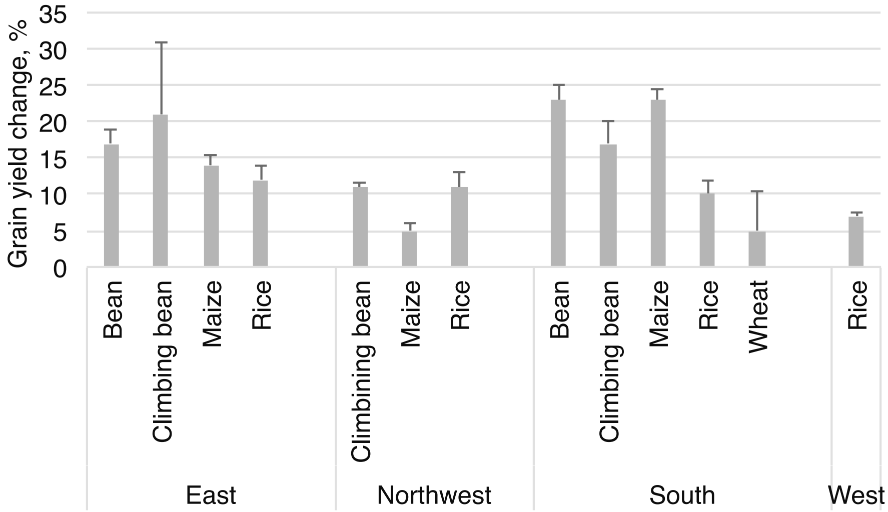


Figure 13.2: Yield change due to secondary and micronutrient application.

Nitrogen-fixing legumes are important in cropping systems; most are food crops but some farmers maintain leguminous trees. Land use and management by smallholders is very site specific in Rwanda with much crop production as diverse mixtures that vary with soil type, topographical position and distance from the household compound. The most common farming systems are summarized in Table 13.1.

13.3 Diagnosis of nutrient deficiencies in Rwanda

About 47% of soils in Rwanda are acidic, often with a pH below 5.2 and with high exchangeable Al (Beenart 1999). Plant growth and production on these soils are not only limited by low pH but also by increasing depletion of N, P, Ca and Mg, low cation exchange capacity and Al toxicity. Soil organic carbon is often low. In the volcanic highlands, crop production is highly constrained by P deficiency with high P sorption capacities (Cyamweshi et al., 2013). Research on the status of secondary and micronutrient availability is still in early stages in Rwanda.

Nutrient response trials were conducted in five AEZ during 2013-15, mostly on farmers' fields. The mean yield increases range from: 50% for bean to 94% for rice in response to applied N; 18% for rice to 59% for bean in response to applied P; and 18% for rice and 25% for bean in response to applied K. The mean responses of maize and wheat were within the same range.

These trials also included a diagnostic treatment of N+P+K+Mg+S+Zn+B that was compared to N+P+K alone. The crops were maize, rice, wheat, bush bean and climbing bean. There was a yield increase due to the diagnostic treatment of 12 to 21% in the East, 5 to 23% in the South, 5 to 11% in the Northwest and 7% in the West (Figure 13.2). This reveals that at least one of S, Mg, B and Zn are yield limiting in these AEZ.

In 2015, four levels of a secondary and micronutrient package were included in the wheat and rice trials. The mean yield increase was 10% with 5, 15, 1.25, 0.25 and 0.5 kg/ha of Mg, S, Zn, B and Cu, respectively, applied in addition to N, P and K. Doubling these rates of secondary and micronutrients increased yield by another 1%. Therefore, substantial yield increase can be achieved with low rates of application for these nutrients although the responses to N, P and K are much greater. More research is

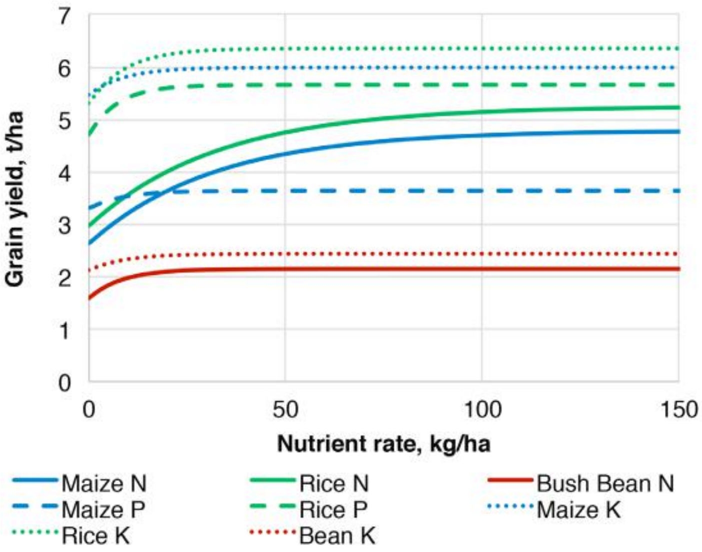


Figure 13.3: Crop response to nutrient application in Eastern AEZ.

needed to determine which of these secondary and micronutrients are most limiting.

13.4 Optimizing fertilizer use in Rwanda

Optimization of fertilizer use in this chapter refers to maximizing net return to application of nutrients as a means to improved production, food security and financial growth as well as improved profits from fertilizer application. Farming is a business and fertilizer use is one component of that business.

Fertilizer use can only be efficient and very profitable if crops are well managed; this implies investment in good quality seed of adapted varieties and control of weeds, diseases and insects as well as supplying or adding soil nutrients. Smallholder farmers, however, typically have severe financial constraints and investment in fertilizer use competes with other uses of available finance. Therefore, for the farmer with adequate access to finance, optimization of fertilizer use may mean applying fertilizer nutrients at rates to maximize profit per hectare from fertilizer which in this chapter is referred to as the economically optimal rate (EOR). For the financially constrained, however, optimization of fertilizer use is applying according to the crop-nutrient-rate combinations that will give the highest return on their limited investment.

Crop response to applied nutrients varies in magnitude and nature. The response can be negative, no response, or positive. Results from numerous trials indicated that the shape of the response is commonly curvilinear until a yield plateau is reached.

Figure 13.3 illustrates curvilinear to plateau responses of maize, rice and bush bean to applied N, P or K in eastern Rwanda with nutrient rate on the x-axis and yield on the y-axis. The magnitude of the response can be great as with N applied to maize and rice or small such as for P applied to bean. The shape of the responses differ with some being abrupt and with the yield increase occurring at low nutrient rates, such as with 10 kg/ha P applied to rice and 10 kg/ha N applied to bean. Other shapes have a more gradual curvature as with maize and rice response to N. In all cases, the yield increase per kg/ha of nutrient applied is greater at low rates as compared with higher rates of application until yield reaches a plateau beyond which increased rates of nutrient application will not result in increased yield. At some point before yield reaches the plateau, the value of yield increase per unit of applied nutrient is less than the added cost. The rate where added value equals added cost is the EOR. Therefore,

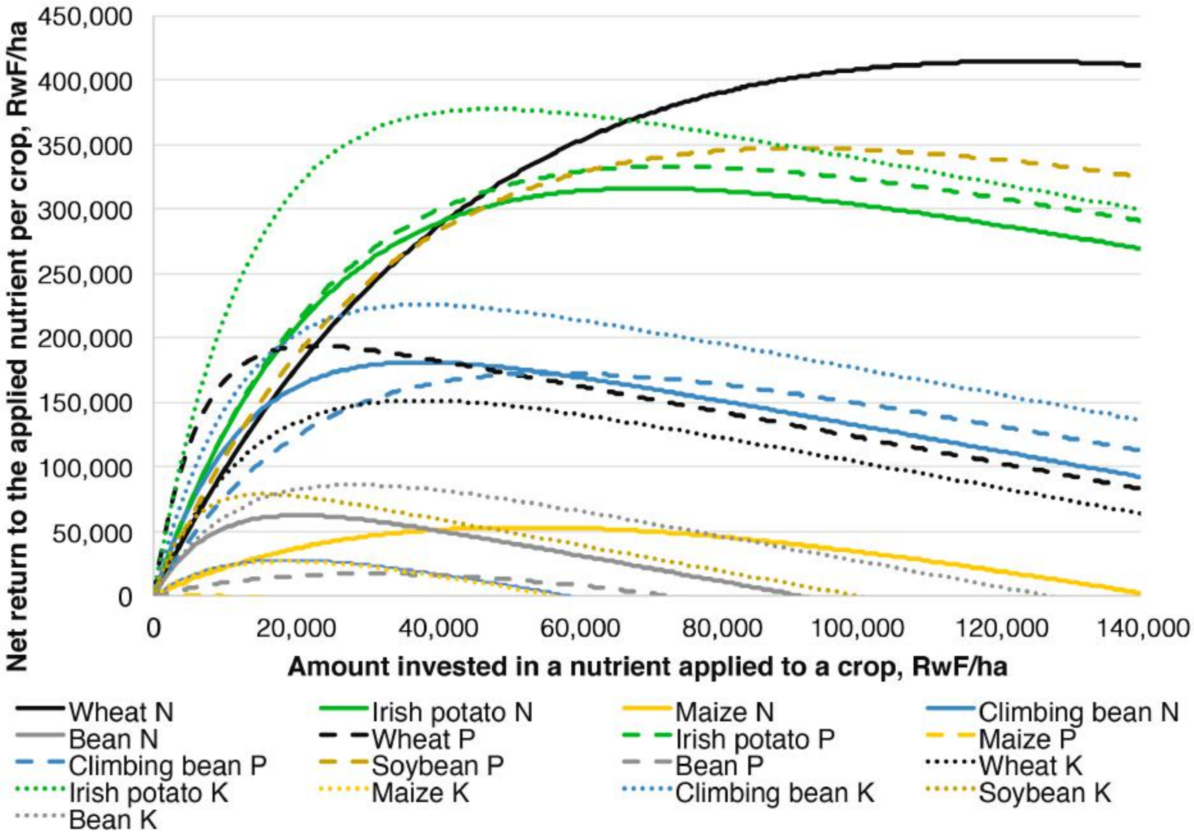


Figure 13.4: Net return to investment in the application of a nutrient to a crop in the Northwest AEZ.

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	**September 5, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Are)***	**Expected Grain Value/kg †**
Banana > 0.4 t/Are	10	200
Maize	35	110
Sorghum	10	130
Lowland rice, paddy	0	400
Beans	15	400
Soybeans	10	400
Sweet potato	10	150
Total	**90**	

Fertilizer Selection and Prices					
Fertilizer Product	**N**	**P2O5**	**K2O**	**xx**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	30,000
Triple super phosphate, TSP	0%	46%	0%	0%	40,000
Diammonium phosphate, DAP	18%	46%	0%	0%	40,000
Murate of potash, KCL	0%	0%	60%	0%	34,000
NPK	17%	17%	17%	0%	40,000

Budget Constraint	
Amount available to invest in fertilizer	50000

Figure 13.5: The input screen of the fertilizer optimization tool for Eastern Rwanda.

Fertilizer Optimization					
	Application Rate - kg/Are				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**NPK**
Banana > 0.4 t/Are	0.78	0.00	0.00	1.00	0.00
Maize	0.38	0.00	0.11	0.10	0.00
Sorghum	0.42	0.00	0.06	0.00	0.00
Lowland rice, paddy	0.00	0.00	0.00	0.00	0.00
Beans	0.13	0.00	0.45	0.25	0.00
Soybeans	0.00	0.00	0.96	0.19	0.00
Sweet potato	0.65	0.00	0.00	0.00	0.00
Total fertilizer needed	34	0	21	19	0

Expected Average Effects per Are		
Crop	**Yield Increases**	**Net Returns**
Banana > 0.4 t/Are	90	16,918
Maize	11	848
Sorghum	13	1,367
Lowland rice, paddy	0	0
Beans	11	3,612
Soybeans	14	7,516
Sweet potato	28	3,777

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	379,622

Figure 13.6: Output screen for the fertilizer optimization tool of Eastern Rwanda.

the farmer whose ability to use fertilizer is limited by financial constraints can expect to get more yield increase for a small investment by applying at a low rate to more land compared with applying at a higher rate to less land.

Application of a nutrient to a crop has different profit potential compared with other nutrients applied to the same or other crops (Figure 13.4). The net returns (RwF/ha; y-axis) resulting from investment in a nutrient applied to a crop (x-axis) are shown with each curve representing the economic response to a single nutrient applied to a crop. When the curves have a steep slope, as with N applied to high potential banana or N applied to climbing bean, the potential mean returns on investment are very high. As more nutrient is applied, the slopes decrease and other crop-nutrient combinations become equally or more competitive. The peak of the curves represent the EOR; application of nutrient beyond EOR results in a decline in profit from fertilizer use due to other factors. Therefore, the financially constrained farmer needs to take advantage of the most profitable options if he/she produces these crops. In the northwest AEZ, low rates of K applied to Irish potato and P applied to wheat have high profit potential followed by low application rates of K for climbing bean and N and P for Irish potato. Application of N for climbing bean and wheat and P for soybean also has high profit potential. Other options have less profit potential. It is hoped that the high profits from optimizing fertilizer use will result in increased financial ability so that eventually fertilizer use can be EOR for all cropland.

Consideration of available information for optimizing fertilizer use by choosing the crop-nutrient-rate combinations that are expected to result in the most profit for a farmer's situation is very complex. The agronomic response of each crop to each nutrient needs to be considered but also the farmer's choice of crops, land allocation, expected commodity values, fertilizer use costs and the farmer's financial ability. Therefore, fertilizer use optimization tools (FOTs) have been developed for each AEZ in Microsoft Excel Solver© (Frontline Systems Inc., Incline Village, NV, USA). The FOTs are easy to use but involve complex mathematics of linear optimization to generate crop-nutrient-rate combinations expected to optimize returns on investment (Jansen et al., 2013).

13.5 Fertilizer use optimization tools for AEZ of Rwanda

For Rwanda, FOT have been developed for the East, Northwest and South Central AEZ. The FOT for the East AEZ is used for illustration. The FOT for the East considers banana, maize, sorghum, rice, bush bean, soybean and sweet potato (Figure 13.5). Data input for the FOT include the farmer's choice of crops and land allocation to these crops, the expected on-farm value per kg of these crops at harvest time (considers the value of the kept harvest for home consumption and the surplus to be marketed), the choice of available fertilizers, the cost of a 50-kg bag for each fertilizer and the farmer's budget constraint to fertilizer use. In this example, the farmer has 90 are of upland cropland and opts to grow all crops except for lowland rice. The budget constraint is RwF 40,000. After completing data input, a left-click on the 'Optimize' cell runs the linear optimization.

The FOT provides the fertilizer recommendations for each crop, expected average effect per acre on yield and net returns to fertilizer use for each crop, and the average expected total net return on investment (Fig. 13.6). Very low rates of application, such as the 0.13 kg/are of urea for bean, may not be feasible and that fertilizer or money might be allocated elsewhere. Consideration of the net returns per crop may prompt the farmer to change the land allocation, e.g. the net returns to fertilizer use on soybean are high compared to that for maize and sorghum and the farmer might try allocating more land to soybean and less to maize or sorghum to increase expected average total net returns to fertilizer use. As it is, the expected average returns to fertilizer use for this example are RwF 7.6 for each RwF 1 invested.

Very often, farmers and their advisors do not have ready access to a computer. Therefore, a paper FOT has been developed for each Excel FOT (Table 13.2). The paper FOTs are constructed with 3 levels of financial ability. Level 1 financial ability is for the poor farmer who has no more money than one-third the amount required to apply fertilizer to all crop land at EOR. Level 2 financial ability farmers have less than two-thirds the amount required to apply fertilizer to all cropland at EOR, while level 3 financial ability is for farmers with enough

Table 13.2: The paper version of the Fertilizer Use Optimizer for Eastern Rwanda

RWANDA (EASTERN) FERTILIZER USE OPTIMIZER: paper version

The below assumes:
Measurement is with a Inyange water bottle cap of 8.4 ml that holds about 5.9 g urea and 9.2 g of DAP, KCl and TSP, or with Inyange bottle cut at 2 cm (89 ml) to hold 62 g urea and 98 g of DAP, KCl and TSP.
It is assumed maize and sorghum are planted with 75 cm row spacing (30 cm plant spacing) and the legumes (bean, soybean, groundnuts) are planted with 50 cm row spacing. Sweet potato 80 x 30 cm. Banana 300 x 300 cm.
Fertilizer costs per 50 kg bags are: FRW 30,000 for urea; 40,000 each for TSP and DAP; 34,000 for KCl.
Commodity values per kg are: 110 for maize; 450 wheat; 400 each for sorghum, rice, bean, and soybean; sweet potato 150; and 120 banana.
Broadcast will be done at 1.5m width. Application rates are in kg/are. WAP = weeks after planting.

Level 1 financial ability.	
Banana	Apply in a circle around the plant 0.62 kg/are urea (1 2-cm bottle per 1.1 plant) and 0.62 kg/are KCl (a 2-cm bottle for 1.8 plants)
Lowland rice	Broadcast at planting 0.4 kg/are DAP (CAP for 1.6 m) and 0.45 kg/are KCl (CAP per 1.4 m); sidedress with 0.82 kg/are urea (CAP for 0.5 m) at panicle initiation
Soybean	Band at planting 0.4 kg/are DAP (CAP for 5 m)
Sweet potato	Point apply 0.42 kg/are urea at 6 WAP (CAP for 6 plants)
Level 2 financial ability.	
Banana	Apply in a circle around the plant 0.82 kg/are urea (1 2-cm bottle per 0.8 plant) and 1.0 kg/are KCl (a 2-cm bottle per 1.1 plants)
Maize	Point apply 0.5 kg/are urea at 6 WAP (CAP for 5.3 plants)
Sorghum	Point apply 0.45 kg/are urea 6 WAP (CAP for 6.3 plants)
Lowland rice	Broadcast at planting 0.62 kg/are urea, (CAP per 0.6 m); and 0.95 kg/are DAP (CAP per 0.7 m) and 0.7 kg/are KCl (CAP per 1.5 m); sidedress with 0.77 kg/are urea (CAP for 0.5 m) at panicle initiation
Bean	Band at planting 0.5 kg/are DAP (CAP for 3.7 m) and 0.52 kg/are KCl (CAP for 3.6 m)
Soybean	Band at planting time 0.82 kg/are DAP (CAP for 2.5 m)
Sweet potato	Point apply 0.7 kg/are urea at planting and 0.7 kg/are urea at 6 WAP (CAP for 3.8 plants each time)
Level 3 financial ability (maximize profit per acre).	
Banana	Apply in a circle around the plant 1 kg/are urea (2-cm bottle per 0.7 plant) and 1 kg/are KCl (a 2-cm bottle per 1.1 plants)
Maize	Point apply 0.6 kg/are DAP (CAP for 7 plants) and 0.35 kg/are KCl at planting (CAP for 11 plants). Point apply 1.22 kg/are urea 6 WAP (CAP for 2.2 plants)
Sorghum	Point apply 0.4 kg/are DAP at planting and 0.57 kg/are urea 6 WAP (CAP for 3.9 plants)
Lowland rice	Broadcast at planting 35 kg urea (CAP per 0.5 m); and 58 kg/are DAP (CAP per 0.4 m) and 0.92 kg/are KCl (CAP per 0.7 m); sidedress with 42 kg/are urea (CAP for 0.4 m) at panicle initiation
Bean	Band at planting 30 kg/are DAP (CAP for 2.6 m) and 0.42 kg/ha KCl (CAP for 4.4 m)
Soybean	Band at planting time 1.22 kg/are DAP (CAP for 1.7 m)
Sweet potato	Point apply 0.92 kg/are urea at planting and 0.92 kg/are urea at 6 WAP (CAP for 2.8 plants)

money to exceed level 2 recommendations and apply fertilizer to at least some of their cropland at EOR.

The paper FOTs are developed with some assumptions including: calibration measuring units to be used by farmers to adjust their eye and feel for the correct rate of application; row and plant spacing; commodity values; fertilizer use costs; and broadcasting width. The paper FOTs go beyond the Excel FOTs and include instructions for all 4 Rs of nutrient stewardship including the right product, rate, method and

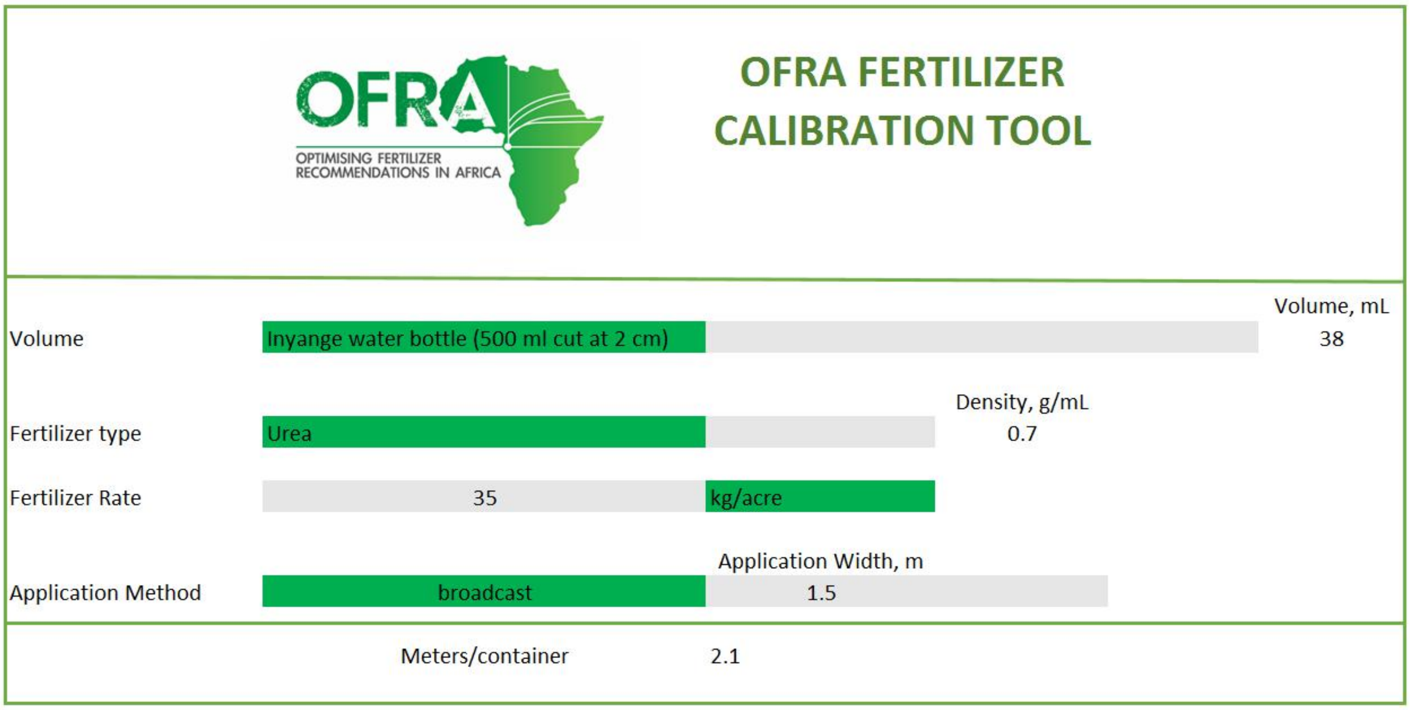


Figure 13.7: The OFRA Fertilizer Calibration Tool.

Table 13.3: Nutrient substitution and soil test implications for adapting fertilizer use rates

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT CONTEXT

ISFM practice	Urea	SSP	KCl	NPK 15-15-15
	Fertilizer reduction, % or kg/ha			
Previous crop was a green manure crop	100%	70%	70%	70%
Fresh vegetative material (e.g. prunings of Lantana or tithonia) applied, per 1 t of fresh material	10 kg	5 kg	5 kg	20 kg
Farmyard manure per 1 t of dry material	12 kg	7 kg	5 kg	20 kg
Residual value of FYM applied for the previous crop, per 1 t	5 kg	2 kg	2 kg	7 kg
Dairy or poultry manure, per 1 t dry material	20 kg	10 kg	12 kg	35 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	5 kg	5 kg	2 kg	7 kg
Compost, per 1 t	20 kg	7 kg	7 kg	35 kg
Residual value of compost applied for the previous crop, per 1 t	7 kg	5 kg	2 kg	12 kg
Rotation	0% reduction but more yield expected			
Cereal-bean intercropping	Increase DAP/TSP by 15 kg/ha, but no change in N and K compared with sole cereal fertilizer			
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 25 kg/ha, reduce urea by 20 kg/ha, and no change in K compared with sole cereal fertilizer			
If Mehlich III P > 15 ppm	Apply no P			
If soil test K < 100 ppm	Band apply 40 kg/ha KCl			

time of application. It also includes guidelines for farmer calibration of fertilizer application to achieve the correct rate.

The paper FOTs are easy to use and are intended for use by farmers themselves and their advisors. The farmer's budget constraint is first considered and the financial ability level is determined. Each level has several fertilizer use options, each of similar profit potential.

Consider the lowland rice recommendation under level 2 financial ability "Lowland rice. Broadcast at transplanting 0.62 kg/are urea (CAP for 0.6 m), 0.95 kg/are DAP (CAP per 0.9 m) and 0.7 kg/ha KCl (CAP per 1.3 m); 0.77 kg/are urea (CAP for 1.2 m) at panicle initiation". Therefore 0.62 kg/are of urea, 0.75 kg/are of DAP and 0.5 kg/are KCl are to be broadcast applied in passes 1.5 m wide at transplanting time. The farmer calibrates his/her eye and feel using the Inyange brand bottle lid (CAP) which is sufficient for 0.6 m for urea, 0.9 m for DAP and 1.3 m for KCl. At panicle initiation, 0.65 kg/are of urea are to be broadcast applied (one bottle lid is enough for 1.2 m).

A constraint of the paper FOT is that it requires revision by a team at the national level when there is significant change in fertilizer use costs relative to grain values.

Table 13.4a: Eastern Rwanda. Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current (REC) recommendation. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			**t/ha**				**kg/ha**	
Banana >20 t/ha	N	39.250	6.625	0.903	6.315	0.296	0.014	0.001	16	34
Maize	N	5.076	2.291	0.980	1.041	0.568	0.310	0.169	67	41
Sorghum	N	2.270	1.580	0.932	1.389	0.168	0.020	0.002	34	36
Lowland rice	N	5.204	2.292	0.975	1.220	0.571	0.267	0.125	108	80
Bush Bean	N	2.048	0.473	0.860	0.468	0.005	0.000	0.000	20	18
Soybean	N	0.810	0.148	0.899	0.142	0.006	0.000	0.000	15	18
Sweet potato	N	9.500	3.074	0.925	2.778	0.268	0.026	0.002	37	18
					0-5	**5-10**	**0-15**	**15-20**		
Maize	P	5.257	0.859	0.907	0.332	0.204	0.125	0.077	8	20
Sorghum	P	2.018	0.478	0.867	0.244	0.119	0.059	0.029	6	16
Lowland rice	P	5.766	0.937	0.919	0.323	0.212	0.139	0.091	24	15
Bean	P	2.235	0.509	0.833	0.305	0.122	0.049	0.020	12	20
Soybean	P	1.981	1.185	0.893	0.512	0.291	0.165	0.094	23	20
Banana >20 t/ha	K	37.177	3.302	0.970	0.466	0.401	0.344	0.295	66	28
Maize	K	6.226	0.626	0.924	0.204	0.138	0.093	0.062	18	0
Lowland rice	K	6.617	1.351	0.928	0.421	0.290	0.200	0.137	45	28
Bean	K	2.506	0.356	0.930	0.108	0.075	0.052	0.036	28	0
Soybean	K	2.567	0.249	0.775	0.179	0.050	0.014	0.004	11	0

† EOR was determined with the cost of using 50 kg urea at FRW 30,000, KCl at 34,000 FRW, DAP and TSP at 40,000, respectively. Commodity values (FRW/kg) used were: rice 400; maize 110; sorghum 130; soybean 400; common bean 400; banana 100; wheat 400; sweet potato and Irish potato 100. The EOR and REC are as rates of P_2O_5 and K_2O.

Table 13.4b: Southern Rwanda

Crop	Nutrient	Response coefficients, Yield = a –bc^r; r = elemental nutrient rate, kg/ha			Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			**t/ha**				**kg/ha**	
Wheat	N	3.555	1.816	0.977	0.912	0.454	0.226	0.112	78	41
Maize	N	4.326	1.459	0.979	0.695	0.364	0.191	0.100	45	41
Climbing bean	N	2.593	0.894	0.902	0.853	0.039	0.002	0.000	33	18
Lowland rice	N	5.216	1.972	0.974	1.077	0.489	0.222	0.101	105	80
Bean	N	1.704	0.433	0.924	0.393	0.037	0.003	0.000	30	18
Soybean	N	0.809	0.148	0.899	0.142	0.006	0.000	0.000	21	18
Sweet potato	N	9.500	3.074	0.925	2.778	0.268	0.026	0.002	21	18
					0-5	**5-10**	**10- 15**	**15-20**		
Wheat	P	1.357	0.312	0.878	0.289	0.101	0.035	0.012	11	20
Maize	P	3.812	1.984	0.906	0.773	0.472	0.288	0.176	17	20
Climbing bean	P	2.446	0.705	0.895	0.300	0.172	0.099	0.057	18	20
Lowland rice	P	5.817	0.815	0.770	0.594	0.161	0.044	0.012	12	15
Bean	P	2.239	0.514	0.845	0.293	0.126	0.054	0.023	13	20
Soybean	P	1.981	1.185	0.893	0.512	0.291	0.165	0.094	16	20
Wheat	K	4.730	0.526	0.863	0.274	0.131	0.063	0.030	12	0
Maize	K	6.029	0.699	0.924	0.228	0.154	0.104	0.070	19	0
Climbing bean	K	3.539	0.799	0.934	0.231	0.164	0.117	0.083	40	0
Lowland rice	K	6.631	1.099	0.935	0.314	0.224	0.160	0.114	46	28
Bean	K	2.439	0.317	0.895	0.135	0.077	0.044	0.026	21	0
Soybean	K	2.567	0.249	0.775	0.179	0.050	0.014	0.004	11	0

The Excel and paper FOTs, along with other tools to aid in fertilizer use decisions are available at http://agronomy.unl.edu/OFRA.

The calibration guidelines for fertilizer application are built into the paper FOTs but the guideline needs to be developed separately when using the Excel FOT. Applying too much or too little fertilizer reduces farmer profit. The Excel OFRA Fertilizer Calibration Tool can be used to advise farmers on application to achieve the correct rates (Figure 13.7). This tool is adapted for each country for measuring units and fertilizer choices. It considers fertilizer density which differs by fertilizer type and allows for a choice between band, point, or broadcast application.

Another aspect of fertilizer use optimization is considering other management practices and soil test information (Table 13.3). Some practices such as manure application justify reducing fertilizer rates. Intercropping calls for an increase in rates relative to that recommended for the cereal sole crop. Soil test P is typically low but when Mehlich III P is above 15 ppm, the recommended P or the money for its use should be allocated elsewhere. When soil test K <100 ppm, KCl should be applied even if not recommended by the FOT. These considerations apply generally for only one or a few of the land parcels of a farm. The intent is that Table 13.3 is back-to-back with the paper FOT for the AEZ to be provided to farmers and their advisors as a single sheet of paper.

13.6 Crop nutrient response functions by AEZ in Rwanda

The crops for which nutrient response functions were determined from past and OFRA research of 2013-15 are presented in column 1 of Table

Table 13.4c: Northwestern AEZ

Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC
	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Elemental nutrient rate change, kg/ha				Recommended nutrient rate	
		t/ha			t/ha				kg/ha	
Wheat	N	3.534	1.465	0.974	0.800	0.363	0.165	0.075	94	41
Irish potato	N	15.100	4.105	0.949	3.251	0.676	0.141	0.029	54	51
Maize	N	4.717	1.337	0.969	0.817	0.318	0.124	0.048	40	41
Climbing bean	N	2.409	0.580	0.906	0.550	0.028	0.001	0.000	29	18
Soybean	N	0.809	0.148	0.899	0.142	0.006	0.000	0.000	15	18
Bean	N	1.118	0.229	0.862	0.544	0.015	0.000	0.000	16	18
					0-5	5-10	10-15	15-20		
Wheat	P	4.000	0.557	0.815	0.357	0.128	0.046	0.017	12	20
Irish potato	P	17.354	4.327	0.859	2.303	1.077	0.504	0.236	18	23
Maize	P	4.686	0.376	0.899	0.155	0.091	0.054	0.031	17	20
Climbing bean	P	2.371	0.633	0.847	0.357	0.156	0.068	0.030	14	20
Soybean	P	1.981	1.185	0.893	0.512	0.291	0.165	0.094	9	20
Bean	P	1.075	0.212	0.898	0.293	0.126	0.054	0.023	7	20
Wheat	K	4.607	0.509	0.909	0.193	0.120	0.074	0.046	28	0
Irish potato	K	24.445	4.393	0.907	1.697	1.041	0.639	0.392	35	24
Maize	K	5.990	0.521	0.893	0.225	0.128	0.073	0.041	14	0
Climbing bean	K	3.458	0.690	0.895	0.294	0.169	0.097	0.056	27	0
Soybean	K	2.567	0.249	0.775	0.179	0.050	0.014	0.004	11	0
Bean	K	2.440	0.317	0.895	0.135	0.078	0.045	0.026	21	0

13.4a-c. The table presents the crop response functions in columns 3-5, the expected yield (t/ha) increases due to increments of applied elemental nutrients in columns 6-9 and a comparison of the EOR with recommended elemental nutrient rates (REC) in columns 10-11. Both RECs and EORs assume the crop will be well managed and that the field does not have abnormally severe constraints to crop growth such as very shallow soil, very low pH, or very low water holding capacity.

All seven crops considered for Eastern AEZ had an economic response to applied N including soybean which occurred primarily with the first 30 kg/ha of N applied (Table 13.4a). All crops except banana and sweet potato had profitable response to P with >50% of response occurring with 5 kg/ha elemental P applied in most cases. All crops except for sorghum and sweet potato were found to have profitable response to applied K.

All seven crops considered for the South Central AEZ had economic responses to applied N, P and K, with the exception of sweet potato for P. Low rates of nutrient application were very effective (Table 13.4b).

All six crops considered for the Northwestern AEZ had economic responses to applied N, P and K with much of the response occurring at low rates of nutrient application (Table 13.4c). The K EORs were determined for several crops which did not have RECs for K application.

The EOR for N was generally more than or similar to the REC. The EOR for P was generally less than the REC. The EOR for K was generally more than the REC. The EOR will change with substantial changes in fertilizer prices relative to grain values.

13.7 Conclusion

Research on optimization of fertilizer use was conducted in the Northwest, South Central and Eastern AEZ of Rwanda in 2013-15. Response functions for N, P and K applied to maize, rice, wheat, bush and climbing bean, soybean, Irish potato, sweet potato and banana were determined using results from past and recent trial results. The response functions were used in the development of FOTs to be used to determine the optimal crop-nutrient-rate combination for maximizing net returns on investment in fertilizer use, especially for finance constrained situations. Paper FOTs were introduced as well as other tools for fertilizer use decisions. The RECs were found to be generally high compared to the EOR determined from results of field research.

13.8 Acknowledgements

The authors acknowledge the financial support of the Alliance for Green Revolution in Africa (AGRA) through the OFRA project, the facilitation of Rwanda Agriculture Board (RAB), and technical support from Professor Charles Wortmann of the University of Nebraska-Lincoln and of Dr. Kaizzi C. Kayuki of the National Agricultural Research Organization of Uganda.

13.9 References

Beenart FR (1999) Feasibility Study of Production of Lime and/or Ground Travertine for the Management of Acid Soils in Rwanda. Pro-Inter Project Consultants, Brussels

Clay DC and Dejaegher Y (1987) Agro-ecological zones: The development of a regional classification scheme for Rwanda. Tropicultura, December 1987

Cyamweshi RA, Tenywa JS, Ebanyat P, Tenywa MM, Mukuralinda A and Nduwumuremyi A (2013) Phosphate sorption characteristics of andosols of the volcanic highlands of Central African Great Lakes Region. J Environ Sci Engin 2:89-96

FAO (1996) Guidelines: Agro-ecological Zoning. Food and Agricultural Organization, Soils Bulletin, Rome, Italy

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

NISR (2014) Fourth Population and Housing Census, Rwanda, 2012. Thematic Report: Population size, structure and distribution. Consulted on 28 March 2016 in microdata.statistics.gov.rw/index.php/catalog/65/download/516

14. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Tanzania

Catherine J Senkoro[1] cathysenkoro@gmail.com, George J Ley[1], Atanasio E Marandu[1], Charles Wortmann[2], Muhamadi Mzimbiri[3], John Msaky[4], Rose Umbwe[4], S D Lyimo[4]

[1]*Mlingano Agricultural Research Institute, P.O. Box 5088, Tanga, Tanzania*
[2]*University of Nebraska-Lincoln (UNL), Lincoln, NE 68583, USA*
[3]*Uyole Agricultural Research Institute, P.O. Box 400, Mbeya, Tanzania*
[4]*Selian Agricultural Research Institute, P.O. Box 2704, Arusha, Tanzania*

14.1 Importance of agriculture in Tanzania

Agriculture is the most important sector to the economy of Tanzania. It accounts for 26.4% of the total Gross Domestic Product (GDP), 30% of export earnings and 65% of raw material for domestic industries (World Bank 2010; Hepelwa et al., 2013). Over 80% of the population in rural areas depend on agriculture indicating the importance of the sector in poverty reduction and food security in the country.

The major food crops grown in the country are maize, sorghum, millet, cassava, sweet potato, Irish potato, banana, pulses, paddy and wheat. Maize is planted on 45% of total arable land. Rice is the third most important food and cash crop, generates much employment and rural income, and 99% is grown by smallholder farmers (Hepelwa et al., 2013). Common bean production occupies about 800,000 ha (Letaa et al., 2014) and is an important source of food and income for smallholder farmers with per capita bean consumption of about 19.3 kg/yr, contributing 16.9% of the protein and 7.3% of the calories for human nutrition (Rugambisa 1990). Cash crops grown in Tanzania include coffee, cashew nut, tea, cotton, tobacco, wheat and sisal. On average the crop sub sector contributes about 34.8% of the agricultural GDP.

14.2 Agro-ecological zones (AEZ) of Tanzania

The country is divided into Eastern, Northern, Southern, Southern Highlands, Western, Central, and Lake Zones (Figure 14.1). The zones are

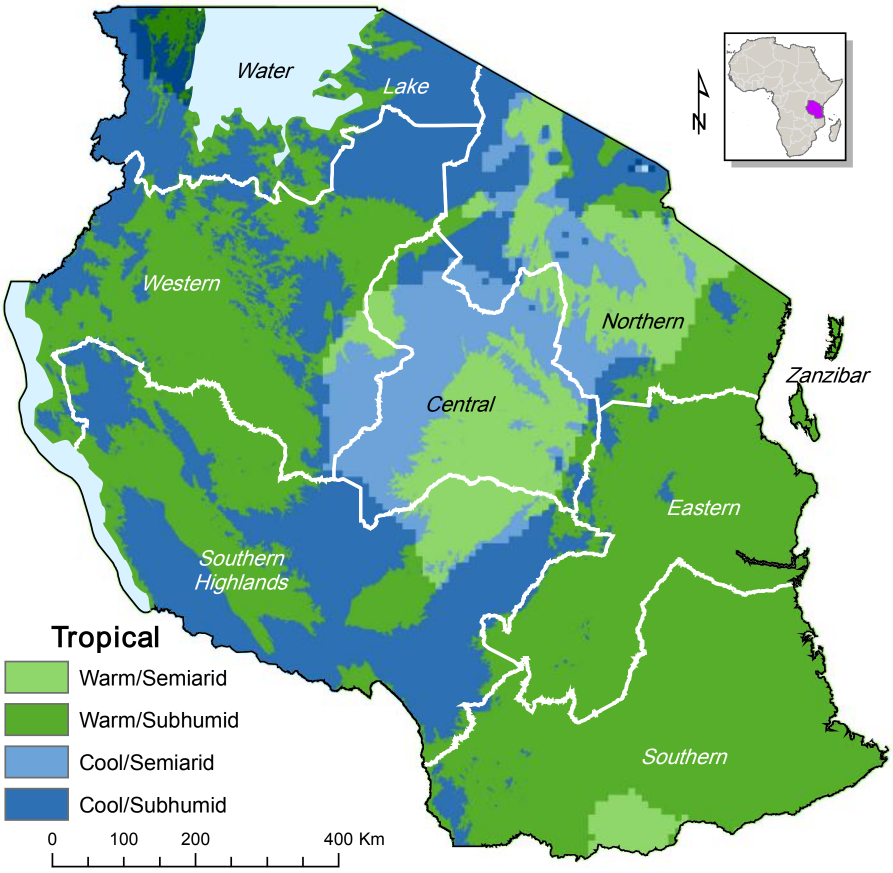


Figure 14.1: Major Agricultural Zones of Tanzania overlain on the AEZ map of HarvestChoice.

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

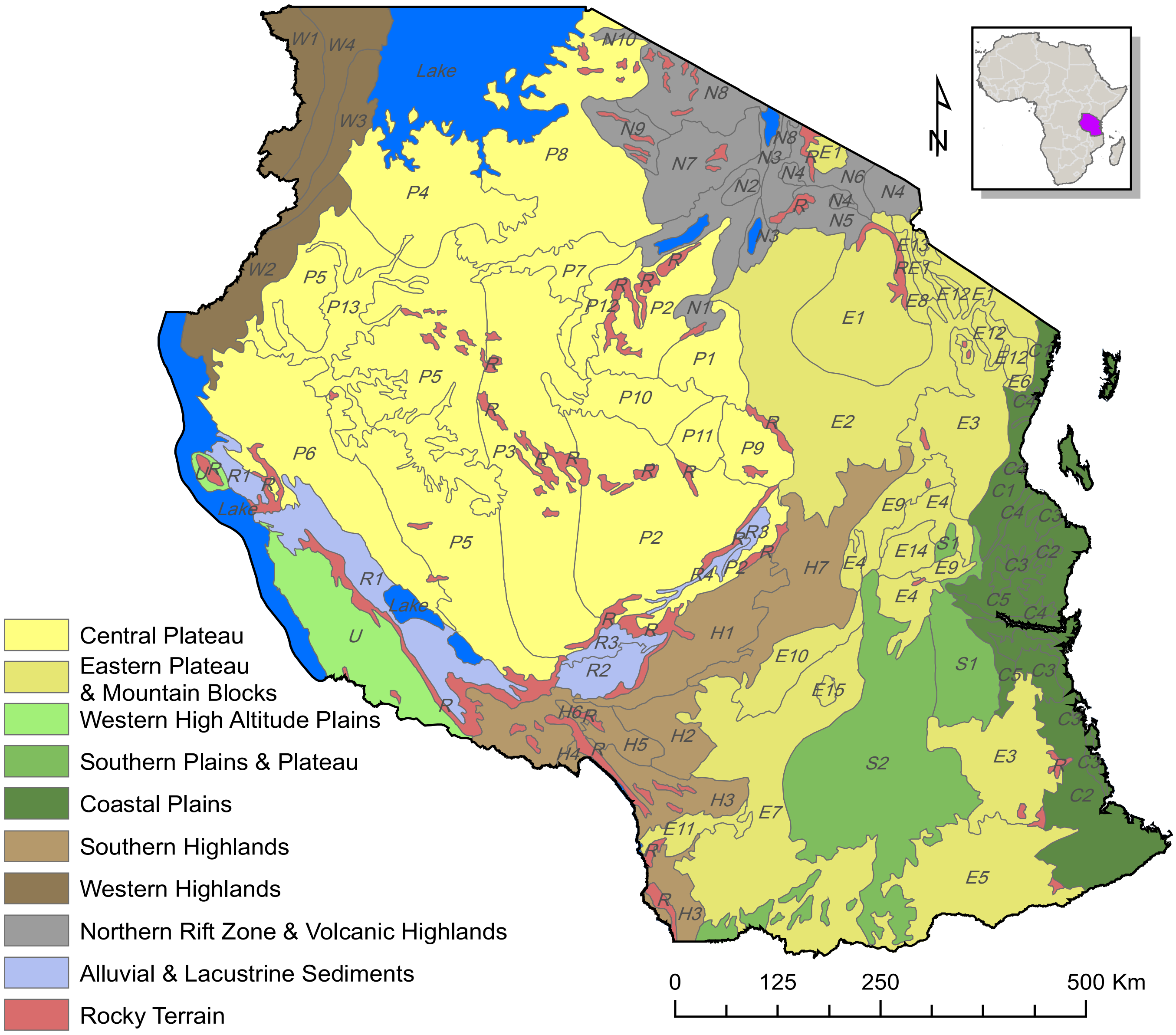


Figure 14.2: Agro-ecological Zones of Tanzania. Source: http://www.kilimo.go.tz/agricultural%20maps/Tanzania%20Soil%20Maps/Webbased%20Districts%20Agricultural%20maps/Districts%20AEZs/Tanzania%20agro-ecological%20zones.htm

further divided into 63 agro-ecological zones (AEZ) which are natural physical regions with similar climate, physiography and soil (De Pauw 1984) (Figure 14.2; Table 14.1).

Tanzania has four main climatic zones. The coast and immediate lowland is tropical with mean temperatures near 27°C, rainfall varying from 1000 to 1930 mm and high humidity, and covers much of Eastern and Southern Zones. Locations that represent parts of this climate zone include Bagamoyo, Mtwara and Kilosa (Table 14.2). Kilosa and Bagamoyo have bimodal rainfall pattern with long (March to June) and short (October to December) rain seasons (De Pauw 1984). Mtwara has mono-modal rainfall from November to May.

The climatic zone of the central plateau, represented by Dodoma, is hot and dry with mono-modal December to April rainfall of 500 to 760 mm, and with considerable daily and seasonal temperature variation (Table 14.2). The semi temperate highland climate zone covers Southern Highland and Northern Zones and is represented by Selian, Arusha and Mbeya with mono-modal rainfall of December to April. The climatic zone of the high, moist lake regions cover Lake Zone and Western Zone near Lake Tanganyika in Kigoma. There are two rainy seasons of November to December and March through May in the northern Lake Zone, e.g. Tarime, and Western Zone. The uni-modal rainfall of southern Lake Zone is from November to March as in Tabora and Ukiriguru.

Table 14.1: Application of OFRA fertilizer optimization tools by AEZ (Figure 14.2)

FOT	AEZ[†]
Eastern	All C; E <1000 m in Eastern and Northern Zones except for E1
Northern	E2 (>1000 m); N3, N4, N5, N6
Southern Highlands	H except for H4, U, E7, E14, U
Lake Zone >1300 m	N8, N9, N10, W1, W4
Lake Zone <1300 m	W3, P4, P8
Western	W2, P3, P4, P5, P6, P7, P8
Central	P1, P2, P9, P10
Southern	E <1000 m in Southern Zone, S1, S2

[†]Description of the AEZ groups:
C: Coastal plains
E: Eastern plateau and mountain blocks
H: Southern highlands
N: Northern rift zones and volcanic highlands
P: Central plateaux (plains)
R: Rocky terrain in several zones
S: Southern low altitude plains and plateau
U: Southwestern high-altitude plain
W: Western highlands

Soils of the AEZ of Tanzania were well described by De Pauw (1984) and are covered only generally in this chapter. The soil types are widely diverse and the dominant soil types are Cambisols with ferrallic properties (36%), Acrisols (8.6%), Leptosols (8.1%), Luvisols (7.3%) and Ferralsols (6.3%). The most fertile soils, apart from volcanic soils (Andosols) in the north and south, are the Vertisols (Mbuga soils) that occupy 5% of the country although these are difficult to manage being very hard when dry and easily waterlogged when wet (Mlingano ARI 2006).

14.3 Current soil fertility management

Most croplands of Tanzania have low fertility and nitrogen is the most limiting nutrient (Mowo et al., 1993; Marandu et al., 2014). Soil phosphorus availability is commonly low. Potassium and S deficiencies are locally important. There are occasional indications of localized Cu, Zn and Mn deficiencies. Current fertilizer use is reported to average 17 kg/ha/yr with most used for maize, rice and vegetable production (World Bank 2014). In 2008, a subsidy on fertilizers and seeds was introduced under the National Agricultural Input Voucher Scheme (NAIVS) to promote adoption of improved seed and fertilizers, especially for high potential maize and rice production and fertilizer use has increased from 9 to 17 kg/ha/yr since then. Generally less than 5% of farmers in 50% of the districts use fertilizers. MAFS (2012) indicated that 42% of fertilizer is used in the Southern Highlands, 17% in Shinyanga and Tabora Regions, 12% in Kilimanjaro and Arusha Regions, 10% in Morogoro Region and 5% in Kagera and Kigoma Regions. Urea accounts for about 65% of fertilizer usage.

Traditional soil management practices include incorporation of crop residues, fallow, use of farmyard manure, and inter-cropping or rotation of legumes and non-legumes (Shekiffu 2011). Most farmers, however, harvest or burn crop residue. In Eastern Zone, almost 70% of the farmers in cassava based production systems burned crop residues during land preparation, 12.5% farmers incorporated crop residues, 16.5% fallowed land for 1 to 3 years, 2.5% used farmyard manure, and none used fertiliser (Shekiffu 2011). In Northern Zone, crop residues are commonly burnt or harvested with no significant incorporation of organic material into the soil to maintain topsoil structure and nutrient status.

The first fertilizer recommendations were issued in 1982 for 20 AEZ and later adapted to a district basis (Harrop and Samki 1984)

Table 14.2: Mean monthly rainfall (mm), maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of selected AEZ of Tanzania

	J	F	M	A	M	J	J	A	S	O	N	D
Ilonga-Kilosa (AEZ: E9), Eastern Zone												
Rainfall	124	111	158	235	76	13	9	7	18	37	78	110
Tmax	32	31	31	30	28	27	27	28	30	31	31	32
Tmin	21	21	21	21	19	17	16	16	17	18	20	21
Bagamoyo (AEZ: C1), Eastern Zone												
Rainfall	67	68	100	222	162	36	29	27	30	63	96	115
Tmax	33	33	33	32	31	30	29	30	30	31	32	33
Tmin	24	23	23	23	22	21	20	19	19	20	22	23
Selian Arusha (AEZ: N5), Northern Zone												
Rainfall	71	68	151	289	122	27	11	13	12	33	149	106
Tmax	27	28	27	25	23	23	22	23	25	27	26	26
Tmin	14	13	15	16	15	13	12	13	13	14	15	14
Mbeya (AEZ: H5), Southern Highland Zone												
Rainfall	198	178	175	95	17	1	0	0	1	18	69	203
Tmax	23	23	23	23	22	21	21	22	25	27	27	24
Tmin	14	14	14	13	11	9	8	9	11	13	14	14
Mtwara (AEZ: C2), Southern Zone												
Rainfall	219	169	214	176	59	15	14	9	12	28	59	171
Tmax	29	29	30	30	28	28	28	28	28	29	30	30
Tmin	24	24	24	23	21	21	20	20	20	22	23	24
Dodoma (AEZ: P11), Central Zone												
Rainfall	127	111	110	64	7	0	0	1	0	4	33	122
Tmax	29	29	29	29	28	27	27	27	29	31	32	31
Tmin	18	18	18	18	16	14	13	14	15	16	18	19
Tabora (AEZ: P5), Western Zone												
Rainfall	141	138	146	109	25	0	0	0	1	18	95	190
Tmax	28	28	28	28	28	28	28	29	32	32	31	28
Tmin	17	17	18	17	17	15	14	16	17	19	19	18
Tarime (AEZ: N10), Lake Zone >1300 m												
Rainfall	68	87	132	200	131	39	26	29	48	73	129	97
Tmax	28	28	28	27	27	26	27	27	28	28	28	27
Tmin	15	15	15	16	15	14	14	14	14	15	15	15
Ukiriguru (AEZ: H5), Mwanza, Lake Zone <1300 m												
Rainfall	101	128	138	159	69	14	7	9	25	58	150	122
Tmax	28	27	28	27	28	29	29	30	31	31	28	27
Tmin	18	18	18	18	17	15	15	16	17	18	18	18

Sources: http://en.climate-data.org/location/781083/
http://www.climate-zone.com/climate/tanzania/
http://www.kilimo.go.tz/agricultural%20maps/Tanzania%20Soil%20Maps/Webbased%20Districts%20Agricultural%20maps/Districts%20AEZs/Tanzania%20agro-ecological%20zones.htm

based on results of fertilizer trials conducted by different institutions (Mowo et al., 1993). World Bank supported a project to update fertilizer recommendations for rice and maize in some AEZ in 2009 to 2012 (Marandu et al., 2014) with differentiation for production potential, e.g. the N recommendation for lowland rice in high potential (HP) areas like Mombo irrigation scheme is 120 kg N/ha but 80 kg/ha for rainfed lower potential areas.

14.4 Diagnosis of nutrient deficiencies in Tanzania

In the 2014-2015 season, 41 trials were conducted for upland crops which included a comparison of N+P+K+Mg+S+Zn+B with N+P+K to determine if one or more of the secondary or micronutrients resulted in increased yield. The overall effect of the diagnostic package was little effect on cereal yield but a 12.6% reduction in legume yield in the Southern Highlands (Figure 14.3; AEZ H3 and H5 from Figure 14.2). Bean and pigeonpea yield were increased by 15% and 27% in the Northern Zone with the diagnostic treatment but cereal yield was decreased (AEZ N3 and N6). In the Eastern Zone, cassava tuber yield was increased by 12.3% but other crops were not affected by the diagnostic package (AEZ C1). The negative effect of the diagnostic package in some situations could not be accounted for with existing data. The lack of predictable positive response indicates that application of any of these secondary or micronutrients is not likely to be profitable without more site-specific information. Further investigation is needed to determine which of these four secondary or micronutrients account for the yield increases.

14.5 Optimizing fertilizer use in Tanzania

As indicated in section 14.3, most smallholders do not use fertilizers and rates of application are generally less than currently recommended. Most smallholders live and operate under severe financial constraint and investment in fertilizer use competes with other uses of financial resources for meeting immediate needs. Fertilizer use investments must give high returns with little risk.

OFRA (Optimizing Fertilizer Use in Africa), an Alliance for a Green Revolution in Africa (AGRA) funded project, has strengthened the information basis for determining more cost-effective fertilizer use. The typical crop response to an applied nutrient is curvilinear to plateau. Such a yield response (vertical axis, y-axis) of rice to applied N (horizontal axis or x-axis) is displayed in Figure 14.4 with a steep yield increase with increasing N at low rates, a lessor rate of yield increase at higher N rates, until yield reaches a plateau with no more yield increase. This tells us that the net returns relative to amount invested at low rates of nitrogen application are greater than with higher rates. Such response curves are typical for most crops and nutrients and are essential to determining the profitability of fertilizer use for all farmers.

Another important aspect of achieving high profit from fertilizer use for financially constrained farmers is that profit potential varies with nutrients and the crops to which these are

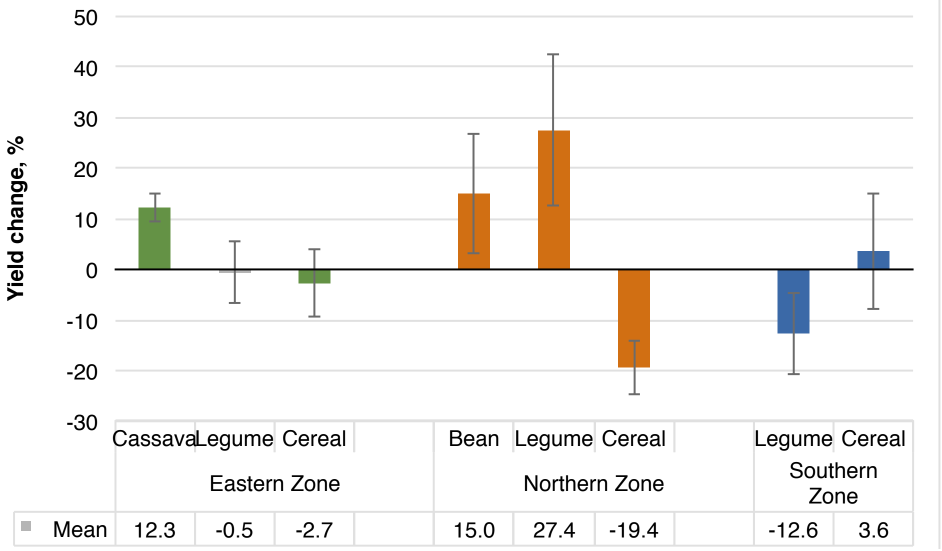


Figure 14.3: Crop response to applied secondary and micronutrients (Mg+S+Zn+B) for 48 research sites in Tanzania.

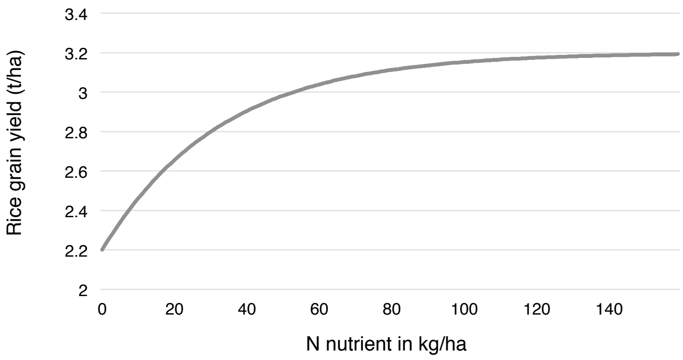


Figure 14.4: Response of lowland rice to N application in the Southern Highland Zone of Tanzania.

applied (Figure 14.5). In this figure, each curve represents the profit potential of a nutrient applied to a crop. When the slope of the curve is steep, net returns to investment are very high. As the amount invested increases (the x-axis) the slope decreases but is still upward, profit is increasing. When the slope is steep, the expected return on investment is high. The steepest slope for the Southern Highlands is with about TSh 20,000/ha (x-axis) of S applied to maize with an expected net return of nearly TSh 400,000/ha (y-axis). When TSh 100,000 is invested in N applied to rice (on x-axis), the expected mean net return is approximately TSh 1,150,000 (on the y-axis) to farmers in the Southern Highland Zone. Nitrogen applied to bean also has much profit potential at low rates and net returns to TSh 25,000 worth of N is about TSh 300,000/ha. The peak of the curves is the point of maximum profit per hectare for that nutrient applied to that crop. In this chapter, the rate at this peak is referred to as the economically optimal rate (EOR) and the rate for which farmers should strive if their fertilizer use is not economically constrained. When slopes decline, profit is declining. The financially constrained farmer wants to first take advantage of the most profitable crop-nutrient combinations for crops in their cropping system.

Making decisions in consideration of these curves for the amount of nutrient to apply to each crop is, however, very complex. The responses of the farmer's crops of interest to applied nutrients needs to be considered together with the farmer's land allocation to different crops, the value of the grain, the costs of fertilizer use, and the money available for fertilizer use need to be considered in optimizing fertilizer use for high profit. Therefore, fertilizer optimization tools which use complex mathematics to integrate economic and

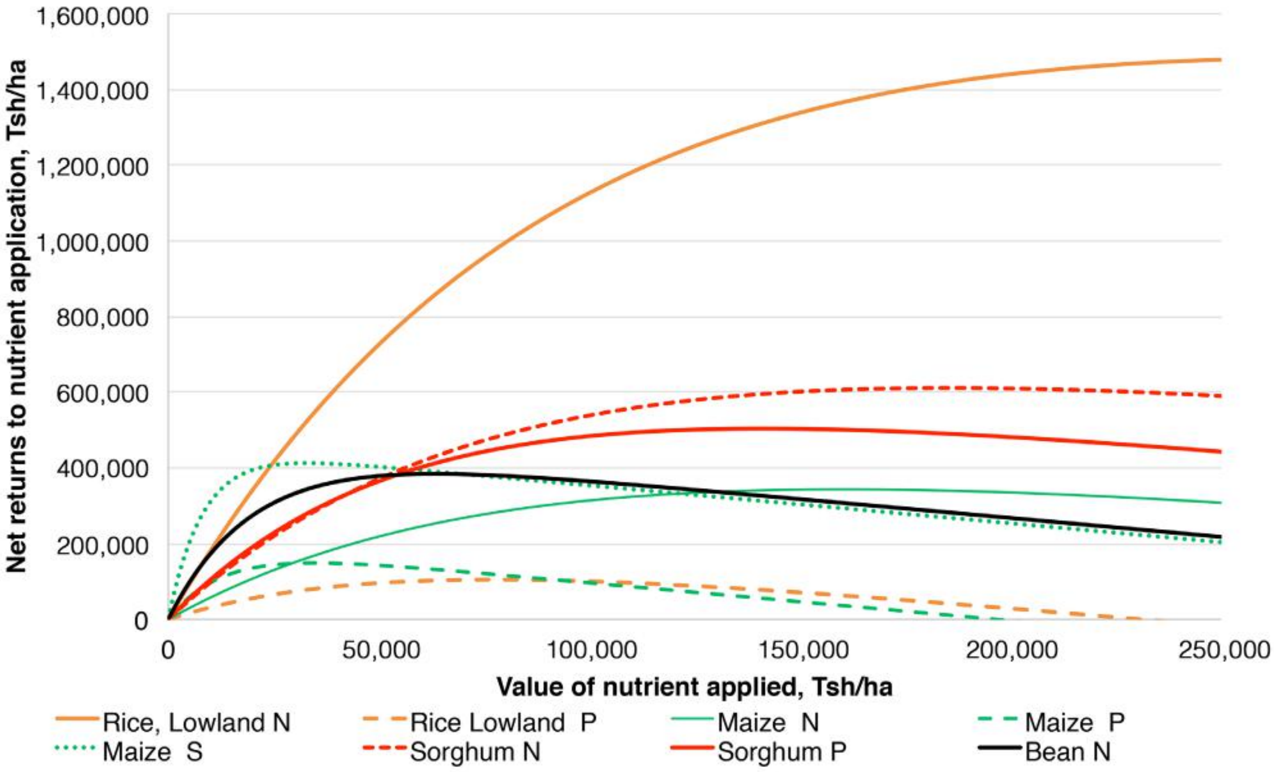


Figure 14.5: Net return from fertilizer use in the Southern Highland Zone of Tanzania. Less profitable and unprofitable nutrient applications were excluded from the figure. This graphic is dependent on grain values and fertilizer use costs. Grain values used were Tsh 1000 for rice and bean; sorghum 725; and maize 400. Fertilizer use costs were: Tsh 55,000 for urea; 65,000 for TSP; 75,000 for DAP; and 60,000 for KCl and ammonium sulphate.

agronomic information were developed using Excel Solver© (Frontline Systems Inc.).

14.6 Fertilizer use optimization tools (FOTs) for Tanzania

Fertilizer Optimization Tools (FOTs) were developed to integrate the economic and agronomic aspects of a farmer's situation with the crop nutrient response functions determined from many field research trials through complex calculations involving linear optimization (see Chapter 1). Fertilizer use optimization refers to maximizing profit from fertilizer use, either maximizing profit per hectare for farmers with adequate finance or profit on the small investment in fertilizer use by the financially constrained farmers. These easy to use tools were designed to make decisions to maximize profits from fertilizer use.

Fertilizer Optimization Tools were developed for eight zones in Tanzania as shown for the Western Zone FOT input screen (Figure 14.6) but application of FOTs are by AEZ rather than by zone (Table 14.3). The FOTs use acres rather than hectares for land area measurement as farmers are more accustomed to use of 'acres'. The user enters the land area in acres 'Area Planted, (Ac)' and expected on-farm value of the commodity considering the expected value of that kept for home consumption and that to be marketed 'Excepted Grain Value/kg'. If a crop is not planted, '0' is entered for acres. Next, the cost of using available fertilizers are entered considering the purchase price, and transport and application costs 'Cost/50 kg bag'. If the fertilizer is not available, '0' is entered for the cost. An optional fertilizer can be added under the 'Muriate if potash, KCl' row with the nutrient concentrations. Finally, the amount of money that the farmer has for fertilizer use is entered under 'Budget Constraint'. In the bottom-left, click on 'Optimize' to run the optimization.

The FOT output is in three tables (Figure 14.7). The upper table 'Application rate - kg/Ac' gives the recommended fertilizer rates for each crop. Some recommended rates are less than 10 kg/Ac and too low for feasible application; these should be reallocated such as the 2 kg/Ac DAP might instead be allocated to maize or as another fertilizer to another crop. The next table 'Expected Average Effects per Ac' addresses expected average yield increases and net return per acre due to the recommended fertilizer use. This table indicates the relative profitability associated with fertilizer applied to the different crops; we see the most profitable is with sweet potato suggesting that the farmer may want to increase area planted to sweet potato. The third table 'Total Expected Net Returns to Fertilizer' is an average estimate, adjusted for land allocated to each crop. Effects per acre and total net return are expected to be more in some years and less in other years compared with the reported expected mean. These results can only be expected if the farmer uses good agronomic practices such as variety selection, planting, and control of weeds, disease and pests.

The FOTs developed can be used to assist decision making at the district level such as to ensure that the most cost effective fertilizers are available to farmers when needed. Optimizing fertilizer use implies that other good agronomic practices are applied which implies availability of other agricultural inputs. Therefore, the FOTs can be useful in determining fertilizer supply.

Each Excel Solver© FOT has a companion paper FOT to be used when a computer is not available (Table 14.3). The paper FOT is devised for three financial ability levels. Financial ability level 1 is for the farmer who has no more money than one-third the amount required to apply fertilizer to all cropland at the rate to maximize economically optimum rate (EOR). Financial ability level 2 is for farmers with no more money than two-thirds the amount required to apply fertilizer to all cropland at EOR. Financial ability level 3 is for farmers with enough money to apply fertilizer to some cropland at EOR.

The paper tool makes assumptions about:

- measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer as in Table 14.3 where the measuring units are the Uhai water bottle lid with a volume of 7 ml and the 500 ml Uhai water bottle cut to 2-cm height giving a volume of 70 ml;
- crop row and plant spacing;
- fertilizer use costs per 50 kg bag;
- expected grain values on-farm at harvest, considering the value both for home consumption and for market; and,
- application guidelines.

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	**July 20, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Ac)***	**Expected Grain Value/kg †**
Rice, lowland Paddy	1	1000
Maize	1	650
Sorghum	1	725
Sweet Potato	1	500
Soybean	1	1200
Groundnut	1	780
	0	0
Total	**6**	

Fertilizer Selection and Prices					
Fertilizer Product	**N**	**P2O5**	**K2O**	**S**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	55,000
Triple super phosphate, TSP	0%	46%	0%	0%	65,000
Diammonium phosphate, DAP	18%	46%	0%	0%	75,000
Murate of potash, KCL	0%	0%	60%	0%	60,000
xxx	0%	%	%	0%	0

Budget Constraint	
Amount available to invest in fertilizer	300000

Figure 14.6: Input data options for the computer generated FOT.

Fertilizer Optimization					
	Application Rate - kg/Ac				
Crop	**Urea**	**TSP**	**DAP**	**KCL**	**xxx**
Rice, lowland Paddy	58	0	0	0	0
Maize	32	0	13	8	0
Sorghum	28	0	2	14	0
Sweet Potato	40	0	17	0	0
Soybean	0	28	0	5	0
Groundnut	0	8	0	0	0
0	0	0	0	0	0
Total fertilizer needed	157	36	32	26	0

Expected Average Effects per Ac		
Crop	**Yield Increases**	**Net Returns**
Rice, lowland Paddy	964	900,214
Maize	945	550,111
Sorghum	1,085	737,094
Sweet Potato	3,221	1,540,617
Soybean	701	798,609
Groundnut	113	77,436
0	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	4,604,081

Figure 14.7: Optimization output showing fertilizers needed and the expected returns.

Table 14.3: An example paper Fertilizer Optimization Tool

TANZANIA WESTERN ZONE

(AEZ: W2, P3, P4, P5, P6, P7, P8)

FERTILIZER USE OPTIMIZER: PAPER VERSION

The below assumes:

Calibration measurement is with a:

- Uhai water bottle lid (lid, 7 ml) for 4.9 g urea, or 7.7 g of DAP, TSP or KCl.
- 500 ml-Uhai water bottle (UWB; cut at 2 cm height to approximate 70 ml) to hold 49 g urea or 77 g DAP, TSP or KCl.

It is assumed maize is planted with 75 x 60 cm spacing, rice with 20 x20 cm spacing, sweet potato 100 x 30 cm, soybean 50 x 10 cm; sorghum 75 x 60 cm and groundnut 20 x 20 cm.

It is assumed crop prices per kg (TSh): 650 maize; 1000 rice; 500 sweet potato; 725 sorghum.

It is assumed 50 kg of fertilizer use costs (TSh): 55,000 urea; 65,000 TSP; 75,000 DAP and 60,000 KCl.

Application rates are in kg/ac. The minimum application rate is 15 kg/ac. Broadcast application width is 2 or 3 m.

Level 1 financial ability.	
Sorghum	Point apply urea 15 kg (1 lid per 3.2 plant hills) 6 WAP
Sweet potato	Point apply 36 kg urea (1 lid per 2 plant hills) at 6 WAP
Soybean	Broadcast 22 kg TSP (apply one UWB for 4.7 m length and 3 m width OR 1 lid for 1 m length and 3 m width) at planting
Rice	Broadcast 43 kg urea (apply one UWB for 2 m length x 2 m width) at 2 panicle initiation
Maize	Point apply 16 kg urea (1 lid per 2.5 plant hills) at 6 WAP
Level 2 financial ability.	
Sorghum	Point apply 20 kg urea (1 lid per 2 plant hills), 16 kg KCl (1 lid per 4.4 plant hills) at planting and urea 19 kg (1 lid per 2 planting hills) at 6 WAP
Sweet potato	Point apply 27 kg DAP (1 lid per 4 plant hills) at planting and 44 kg urea (1 lid per 1.5 plant hills) at 6 WAP
Soybean	Broadcast 33 kg TSP (apply one UWB for length 4.7 m and 2 m width) at planting
Rice	Broadcast 36 kg urea (apply one UWB for length 2.5 m x 2 m width) at 2 WAP and 36 kg urea (apply one UWB for 2.5 m length x 2 m width) at panicle initiation
Maize	Point apply 24 kg urea (1 lid per 2 plant hills), 18 kg DAP (1 lid per 4 plant hills) and 23 kg urea (1 lid per 2 plant hills) at 6 WAP
Level 3 financial ability (maximize profit per acre).	
Sorghum	Point apply 30 kg urea (1 lid per 1.5 planting hills), 18 kg DAP (1 lid per 4 planting hills), 20 kg KCl (1 lid per 3.3 planting hills) at planting and urea 31 kg (1 lid per 1.5 plant hills) at 6 WAP
Sweet potato	Point apply 44 kg DAP (1 lid per 4 planting holes) at planting and 53 kg urea (1 lid per 2 plant hills) at 6 WAP
Soybean	Broadcast 32 kg TSP (apply one UWB for length 5 m and 2 m width) at planting
Groundnut	Broadcast 22 kg TSP (apply one UWB for length 4.7 m and 2 m width) at planting
Rice	Broadcast 50 kg urea (apply one UWB for 2 m length) at 2 WAP and 50 kg urea (apply one UWB for 2 m length x 2 m width) at panicle initiation
Maize	Point apply 38 kg urea (1 lid per 1 planting hills), 27 kg DAP (1 lid per 2 planting hills), 18 kg KCl (1 lid per 3.9 planting hills) at planting and 37 kg urea (1 lid per 1 plant hills) at 6 WAP

The paper FOTs address the 4Rs of Nutrient Stewartship, advising on the right product, rate, time and method of application. It also advises on calibration, that is the length of band or the number of plants for the recommended fertilizer rate with one measuring unit. Consider as an example the Level 2 financial ability recommendation ‘Sorghum: point apply 20 kg urea (1 lid per 2 planting holes), 16 kg KCl (1 lid per 4.4 planting holes) at planting and urea 19 kg

(1 lid per 2 planting holes) at 6 WAP' (Table 14.3). Urea and KCl are to be applied at least 5 cm to the side of planting holes of sorghum at rates of 20 and 16 kg/ac, respectively. One Uhai bottle lid is sufficient for 2 planting holes with urea and 4.4 planting holes with KCl. Another 19 kg/ha urea are to be top dress applied at six weeks after planting by point applying at least 5 cm away from the plant; one Uhai bottle lid is sufficient for 2 planting holes.

The Excel and paper FOT are available at http://agronomy.unl.org/OFRA. The website also has training materials and other tools useful to fertilizer use optimization.

14.7 Adjusting fertilizer rates for other practices and soil test information

Fertilizer use decisions need to consider the effects of other practices that supply soil nutrients as well as soil test information (Table 14.3). Manure application to a field calls for adjustment of the recommended fertilizer rate according to the fertilizer substitution value of the manure which varies with the quality. Poultry and dairy manure have greater fertilizer substitution value than farmyard manure. Other practices with fertilizer substitution values considered in Table 14.4 include having a green manure crop and a cereal following a legume in rotation. Intercropping may require more fertilizer than the sole crop.

Soil test values are also considered. Soil test P values are often low for smallholders' fields not near the household and P should be applied according to the FOT unless the soil test P value is above 20 mg kg^{-1} by Bray 1 for soils with pH of less than 7 or above 10 ppm by Olsen for soils with pH greater than 7. Fertilizer K should be applied as recommended by the FOT unless the soil test K is less than 100 ppm, when 20 kg/ac muriate of potash or potassium sulphate should be applied.

Table 14.4: Fertilizer substitution value of good agronomic practices and soil test implications

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT CONTEXT

FERTILIZER SUBSTITUTION AND SOIL TEST IMPLICATIONS

ISFM practice	Urea	DAP or TSP	KCl	NPK 17-17-17
	Fertilizer reduction, % or kg/ac			
Previous crop was a green manure crop (azolla in lowland rice and tithonia for maize)	100%	70%	70%	70%
Farmyard manure per 1 t of dry material (low quality)	5 kg	3 kg	2 kg	10 kg
Residual value of FYM applied for the previous crop, per 1 t	2 kg	1 kg	1 kg	3 kg
Poultry manure, per 1 t dry material	9 kg	4 kg	5 kg	16 kg
Residue value of poultry manure, per 1 t dry material	2 kg	2 kg	1 kg	3 kg
Compost, per 1 t	8 kg	3 kg	3 kg	15 kg
Maize-bean intercropping	Increase DAP/TSP by 7 kg/ac, but no change in N and K compared with sole maize rates			
Maize-pigeonpea intercropping	Increase DAP/TSP by 11 kg/ac, reduce urea by 9 kg/ac, and no change in K compared with maize rates			
Maize-lablab rotation	0% reduction but more yield expected			
Rice-bean rotation	0% reduction but more yield expected			
Maize or upland rice-cowpea/pigeonpea/green gram rotation	Reduce urea by 20 kg/ha, and more yield expected			
If Bray-Kurtz I P >20 ppm, or Olsen P >10 ppm	Apply no P			
If soil test K <100 ppm	Band apply 20 kg/ac KCl			

14.8 Targeted crops and cropping systems by AEZ

Crop responses to nutrients were determined for important food crops in each zone using results of past and recent field research (Tables 14.5a-h). The first two columns are for crop and nutrient. Columns 3-5 have coefficients a, b, c for the curvilinear to plateau response function: $Y = a - bc^r$. The next four columns report the expected yield increase with increased nutrient rates compared with the lower rate, and the right-most columns report the EOR compared with the current or recently recommended rate (REC). The commodity values and fertilizer costs used in determining EOR are given in the footnote of Table 14.5a. Nutrient applications exceeding the field research based EOR is expected to result in loss of profit. Any nutrient application less than the EOR will be less than maximum potential profit per acre to fertilizer use, but lower rates are typically most profitable with financially constrained fertilizer use.

The greatest yield increases, the b value and for the first increment of applied nutrient, in Eastern Zone was with cassava for N, P and K (Table 14.5a). Lowland high potential rice also had a

Table 14.5a: Eastern Zone, Tanzania (AEZ: all C; E <1000 m in Eastern and Northern Zones except for E1; Fig. 14.2): Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations by agro-ecological zones. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response because of lack of response or lack of information

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡††**
		t/ha			t/ha				kg/ha	
Rice, lowland HP	N	6.248	3.57	0.986	1.231	0.807	0.528	0.346	150	120
Rice, lowland LP	N	4.164	1.731	0.974	0.946	0.429	0.195	0.088	111	80
Cassava	N	32.671	10.678	0.973	5.980	2.631	1.157	0.509	125	NA
Maize	N	3.344	1.442	0.964	0.962	0.320	0.107	0.035	65	60 – 80
Sorghum	N	1.693	0.748	0.94	0.631	0.099	0.015	0.002	28	30
Cowpea	N	1.223	0.383	0.923	0.348	0.031	0.003	0.000	27	NA
					0-5	**5-10**	**10-15**	**15-20**		
Rice, lowland HP	P	6.01	0.16	0.9	0.153	0.006	0.000	0.000	10	20
Rice, lowland LP	P	3.319	0.16	0.908	0.151	0.008	0.000	0.000	10	8
Cassava	P	26.875	5.994	0.940	5.057	0.790	0.123	0.019	30	15 -30
Maize	P	3.055	0.561	0.850	0.312	0.138	0.061	0.027	12	8 – 40
Sorghum	P	2.559	0.789	0.882	0.771	0.018	0.000	0.000	13	10 – 20
Cowpea	P	1.223	0.383	0.923	0.348	0.031	0.003	0.000	11	NA
Cassava	K	29.171	4.550	0.899	4.363	0.179	0.007	0.000	43	40
Maize	K	2.980	0.636	0.650	0.636	0.000	0.000	0.000	9	NA
Cowpea	K	1.111	0.168	0.780	0.168	0.000	0.000	0.000	10	NA

† EOR was determined with the cost of using 50 kg urea, TSP and KCl at Tsh 55,000, 60,000, 60,000, respectively. Commodity values (Tsh/kg) used were: rice paddy 1000; cassava 250; cowpea 700; wheat 550; bean 1000; finger millet 700 in Northern and 900 in Lake; pigeonpea 1500; soybean 1200; sweet potato 500; groundnut 780; Irish potato 800; and sorghum 300; exceptions include: 700 rice paddy for Northern; cowpea 500 in Southern and 1000 in Central; sorghum 650 to 725 in all zones except Eastern; bean 900 in Lake; and sweet potato 300 in Lake. Maize value differed widely: 250 in Southern; 400 in Southern Highland and Lake; 500 in Eastern; 650 in Western and Central; and 700 in Northern. Rice lowland HP and LP refer to expected yield more or less than 3 t/ha, respectively.

‡ Recommendations for rice and maize in Eastern and Southern Highland Zones were cited from Marandu et al. (2014).

†† Recommendations for other crops were cited from Mowo et al. (1993) and cassava from Shekiffu (2011).

Table 14.5b: Northern Zone, Tanzania (AEZ: E2 (>1000 m), N3, N4, N5, N6)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡ ††**
		t/ha			**t/ha**				**kg/ha**	
Rice, lowland	N	5.625	2.897	0.966	1.871	0.663	0.235	0.083	98	NA
Maize	N	3.159	1.191	0.976	0.616	0.297	0.143	0.069	74	45-112
Wheat HP	N	4.039	0.736	0.939	0.625	0.095	0.014	0.002	38	30
Wheat LP	N	1.868	0.353	0.913	0.330	0.022	0.001	0.000	22	
Bean	N	1.415	0.715	0.950	0.562	0.121	0.026	0.006	46	30
Finger millet	N	2.100	0.923	0.944	0.759	0.135	0.024	0.004	48	NA
					0-5	**5-10**	**10-15**	**15-20**		
Rice, lowland	P	5.665	0.828	0.871	0.815	0.013	0.000	0.000	19	NA
Maize	P	4.474	0.770	0.898	0.000	0.029	0.001	0.000	18	NA
Wheat HP	P	3.219	1.211	0.949	0.959	0.199	0.041	0.009	30	7 – 13
Wheat LP	P	1.439	0.147	0.873	0.144	0.002	0.000	0.000	4	NA
Bean	P	1.138	0.263	0.848	0.148	0.065	0.028	0.012	12	7-13
Finger millet	P	2.101	0.537	0.798	0.363	0.118	0.038	0.012	12	NA
Pigeonpea	P	2.538	0.487	0.758	0.487	0.000	0.000	0.000	9	NA
Maize	K	2.502	0.251	0.940	0.212	0.033	0.005	0.001	19	NA
Pigeonpea	K	2.535	0.127	0.666	0.127	0.000	0.000	0.000	6	NA

Table 14.5c: Southern Highland, Tanzania (AEZ: H except for H4, U, E7, E14)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡ ††**
		t/ha			**t/ha**				**kg/ha**	
Rice, lowland	N	4.085	1.851	0.974	1.011	0.459	0.208	0.094	116	80
Maize	N	4.407	1.463	0.971	0.858	0.355	0.147	0.061	67	60-120
Sorghum	N	3.409	1.204	0.969	0.736	0.286	0.111	0.043	59	NA
Bean	N	0.868	0.468	0.888	0.455	0.013	0.000	0.000	26	30
Wheat	N	2.900	1.577	0.983	0.634	0.379	0.227	0.136	125	40
					0-5	**5-10**	**10-15**	**15-20**		
Rice, lowland	P	3.703	0.233	0.880	0.110	0.058	0.031	0.016	12	40
Maize	P	3.773	0.492	0.830	0.298	0.117	0.046	0.018	13	20-40
Sorghum	P	3.608	0.967	0.890	0.938	0.028	0.001	0.000	17	NA
Bean	P	1.138	0.263	0.848	0.148	0.065	0.028	0.012	12	12
Wheat	P	2.405	0.340	0.837	0.200	0.082	0.034	0.014	12	NA
Maize	K	2.759	0.134	0.8	0.134	0.000	0.000	0.000	7	NA
Maize	S	5.008	1.135	0.7	1.135	0.000	0.000	0.000	11	NA

Table 14.5d: Western Zone, Tanzania (AEZ: W2, P3, P4, P5, P6, P7, P8)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡††**
		t/ha			**t/ha**				**kg/ha**	
Rice, lowland	N	5.646	2.896	0.974	1.582	0.718	0.326	0.148	66	NA
Maize	N	4.618	2.369	0.978	1.154	0.592	0.304	0.156	43	NA
Sorghum	N	2.289	1.634	0.972	0.937	0.400	0.170	0.073	33	NA
Sweet potato	N	18.699	7.72	0.951	6.010	1.331	0.295	0.065	53	NA
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	5.1	0.805	0.841	0.801	0.004	0.000	0.000	5	NA
Sorghum	P	2.292	0.326	0.866	0.322	0.004	0.000	0.000	0	NA
Sweet potato	P	13.033	1.437	0.912	0.530	0.335	0.211	0.133	7	NA
Soybean	P	2.533	1.78	0.85	0.990	0.439	0.195	0.086	14	NA
Groundnut	P	1.036	0.561	0.847	0.316	0.138	0.060	0.026	4	NA
Maize	K	4.9	0.555	0.899	0.532	0.022	0.001	0.000	10	NA
Sorghum	K	2.409	1.78	0.85	1.766	0.013	0.000	0.000	17	NA
Soybean	K	2.679	0.191	0.8	0.191	0.000	0.000	0.000	0	NA
Groundnut	K	1.09	0.059	0.86	0.031	0.015	0.007	0.003	0	NA

large response to N. Maize had relatively large responses to P and K. Recommended rates were near or lower than EOR. The EOR was determined for several crop-nutrients for which REC rates were missing.

Lowland rice and wheat response to applied N was relatively great and low, respectively, in comparison with other cereals in Northern Zone (Table 14.5b). All crops except for low potential wheat responded well to applied P. Only maize and pigeonpea were found to have profitable response to applied K. The EOR for N and P were generally similar or higher compared with REC rates. Numerous EOR were determined for crop-nutrients lacking REC rates.

Maize and wheat responses to N were relatively great in the Southern Highlands (Table 14.5c). Maize had a relative great response to P and S, but there was limited response to K for all crops. Wheat had a high EOR for N and lowland rice had a similar EOR compared with the REC nutrient rate but otherwise EOR and the REC were similar.

Sweet potato was found to have a large yield response to applied N in Western Zone (Table 14.5d). The cereal crops also had large responses to N application. More than 50% of the response to N occurred with 30 kg/ha N applied. All crops had good yield increases with 5 kg/ha P applied and maize and sorghum had good response to 5 kg/ha K. Recommended rates were not available for Western Zone.

In Southern Zone, all non-legumes had good yield increases with 30 kg/ha N applied and smaller increases with higher rates (Table 14.5e). Besides cassava, sorghum had a relatively large increase with P application. All crops had an economical response to 5 kg/ha of K applied. Only maize and lowland rice had recommendations for nutrient application. The EOR N was higher for high potential maize and lowland rice compared with REC. The EOR P was zero for rice due to lack of rice response to P. Several EOR values were determined for crop-nutrients without recommendations.

Sweet potato and lowland rice had large responses to N for Central Zone (Table 14.5f). All crops except maize were found to have profitable responses to applied P and cowpea was found to be responsive to K. No REC were available for this zone.

All crops had profitable response to N application, especially Irish potato, sweet potato and banana in the higher elevation parts of Lake Zone such

Table 14.5e: Southern Zone, Tanzania (AEZ: E <1000m in Southern Zone, S1, S2)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC‡ ††
		t/ha			t/ha				kg/ha	
Rice, lowland	N	4.010	1.401	0.967	0.889	0.325	0.119	0.043	85	40 - 60
Maize HP	N	3.783	1.928	0.977	0.969	0.482	0.240	0.119	61	50
Maize LP	N	2.493	1.601	0.966	1.034	0.366	0.130	0.046	47	NA
Sorghum	N	1.725	0.612	0.964	0.408	0.136	0.045	0.015	49	NA
Cassava	N	31.785	8.058	0.960	5.690	1.672	0.491	0.144	46	NA
					0-5	**5-10**	**10-15**	**15-20**		
Rice, lowland	P	2.354	0.000	0.000	0.000	0.000	0.000	0.000	20	5 – 9
Maize HP	P	3.721	0.267	0.958	0.193	0.053	0.015	0.004	3	10
Maize LP	P	2.533	0.431	0.976	0.223	0.108	0.052	0.025	24	NA
Sorghum	P	2.047	0.656	0.914	0.238	0.152	0.097	0.062	10	NA
Cowpea	P	1.110	0.181	0.900	0.074	0.044	0.026	0.015	-	NA
Cassava	P	27.634	5.270	0.877	2.536	1.316	0.683	0.354	-	NA
Groundnut	P	1.600	0.373	0.79	0.258	0.079	0.024	0.008	-	NA
Rice, lowland	K	1.748	0.114	0.800	0.077	0.025	0.008	0.003	10	NA
Maize HP	K	3.854	0.208	0.932	0.062	0.043	0.031	0.021	4	NA
Maize LP	K	2.759	0.134	2.759	0.090	0.030	0.010	0.003	4	NA
Sorghum	K	1.986	0.183	0.913	0.067	0.042	0.027	0.017	16	NA
Cowpea	K	0.821	0.134	0.800	0.090	0.030	0.010	0.003	8	NA
Cassava	K	27.674	3.314	0.908	1.269	0.783	0.483	0.298	35	NA
Groundnut	K	1.797	0.075	0.750	0.057	0.014	0.003	0.001	6	NA

as Tarime and Karagwe, and for lower elevation Lake Zone (Table 14.5g,h). All but banana in the higher elevation and lowland rice in the lower elevation had a profitable response to applied P. Maize, bean, and high potential banana had profitable yield increases with K application in the higher elevation areas but there was no evidence of response to K in the lower elevation parts of the zone. The EOR N rates were low compared with REC rates except for similar EOR and REC for rice and sorghum at the lower elevations. The EOR P varied inconsistently compared with REC P. There were no recommendations for K application.

In 21 cases with higher REC compared with the EOR, these ranged from 4 to 450% higher and were on average of 142% higher (Table 14.4a-h). In 19 cases with lower REC compared with the EOR, the REC ranged from 32 to 96% of EOR and on average were 72% less. Over all comparisons, the REC were 41% higher than EOR. No REC were available for 64% of the AEZ specific crop nutrient functions but EOR were estimated for all cases although EOR was 0 in 10% of the cases. Recommended rates were lacking but EOR were determined for cassava, cowpea, sweet potato, soybean, and pigeonpea. For other crops, REC were available for some AEZ but not for others. Applying at the REC when it is above EOR means a loss of profit potential although there will often be a yield gain. Financially constrained farmers should normally be applying at less than EOR when striving to maximize returns on their investment in fertilizer use.

14.9 Conclusion

Crop production is very important to human livelihood and economic growth in Tanzania. Yields are low and there is a need for increased fertilizer use integrated with other soil management practices and good agronomy to

Table 14.5f: Central Zone, Tanzania (AEZ: P1, P2, P9, P10)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡††**
			t/ha			**t/ha**			**kg/ha**	
Rice, lowland	N	5.15	2.238	0.976	1.158	0.559	0.270	0.130	132	NA
Maize	N	4.7	1.2	0.862	1.186	0.014	0.000	0.000	27	NA
Sorghum	N	1.599	0.099	0.98	0.045	0.025	0.013	0.007	0	NA
Sweet potato	N	18.699	7.72	0.951	6.010	1.331	0.295	0.065	89	NA
Cowpea	N	1.223	0.383	0.923	0.348	0.031	0.003	0.000	33	NA
					0-5	**5-10**	**10-15**	**15-20**		
Rice, lowland	P	5.126	0.695	0.89	0.307	0.171	0.096	0.053	22	NA
Maize	P	3.443	0.093	0.917	0.033	0.021	0.014	0.009	0	NA
Sorghum	P	2.284	0.925	0.914	0.335	0.214	0.136	0.087	24	NA
Sweet potato	P	13.033	1.437	0.913	0.525	0.333	0.211	0.134	24	NA
Cowpea	P	1.138	0.640	0.760	0.478	0.121	0.031	0.008	12	NA
					0-5	**5-10**	**10-15**	**15-20**		
Cowpea	K	1.111	0.168	0.780	0.119	0.035	0.010	0.003	12	NA

Table 14.5g: Lake Zone >1300 m elevation, Tanzania (AEZ: N8, N9, N10, W1, W4)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡††**
			t/ha			**t/ha**			**kg/ha**	
Maize HP	N	4.476	1.376	0.966	0.889	0.315	0.112	0.040	27	80
Maize LP	N	2.112	0.955	0.96	0.674	0.198	0.058	0.017	21	50
Irish potato	N	12.086	3.475	0.944	2.858	0.507	0.090	0.016	28	NA
Finger millet	N	1.690	0.790	0.892	0.764	0.025	0.001	0.000	11	30
Sweet potato	N	17.971	9.513	0.923	8.653	0.782	0.071	0.006	23	NA
Bean	N	1.016	0.269	0.78	0.269	0.000	0.000	0.000	5	NA
Banana HP	N	39.250	6.625	0.903	6.315	0.296	0.014	0.001	18	NA
					0-5	**5-10**	**10-15**	**15-20**		
Maize HP	P	4.313	1.113	0.95	0.252	0.195	0.151	0.117	12	8
Maize LP	P	2.534	0.824	0.95	0.186	0.144	0.112	0.086	9	8
Irish potato	P	12.311	3.702	0.902	1.492	0.891	0.532	0.318	12	NA
Finger millet	P	1.784	0.246	0.939	0.066	0.048	0.035	0.026	2	11
Sweet potato	P	13.257	3.828	0.911	1.426	0.895	0.561	0.352	12	NA
Bean	P	1.138	0.323	0.826	0.199	0.076	0.029	0.011	5	13
Maize HP	K	4.000	0.381	0.950	0.086	0.067	0.052	0.040	11	NA
Maize LP	K	2.615	0.101	0.940	0.027	0.020	0.014	0.011	2	NA
Bean	K	2.117	0.264	0.890	0.117	0.065	0.036	0.020	9	NA
Banana HP	K	37.177	3.302	0.970	0.466	0.401	0.344	0.295	20	NA

Table 14.5h: Lake Zone <1300 m elevation, Tanzania (AEZ: W3, P4, P8)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of elemental nutrient rate (kg/ha) on yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡††**
		t/ha			**t/ha**				**kg/ha**	
Rice, lowland	N	5.276	2.402	0.971	1.409	0.583	0.241	0.100	46	40
Maize	N	2.308	0.790	0.947	0.636	0.124	0.024	0.005	16	50 - 80
Sweet potato	N	15.716	5.672	0.95	4.455	0.956	0.205	0.044	28	NA
Sorghum	N	2.372	0.366	0.954	0.277	0.067	0.016	0.004	13	12
Bean	N	1.244	0.653	0.878	0.640	0.013	0.000	0.000	11	NA
Finger millet	N	1.690	0.790	0.892	0.764	0.025	0.001	0.000	11	30
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.032	0.083	0.858	0.044	0.021	0.010	0.004	0	8
Sweet potato	P	13.108	2.234	0.913	0.817	0.518	0.329	0.209	10	NA
Sorghum	P	2.866	0.918	0.911	0.342	0.215	0.135	0.084	9	7
Bean	P	1.231	0.249	0.81	0.162	0.057	0.020	0.007	4	13
Finger millet	P	1.784	0.246	0.939	0.066	0.048	0.035	0.026	2	11

increase productivity. Most farmers are poor and are financially constrained in fertilizer use. Therefore, returns to investment in fertilizer use need to be high to be a means to alleviating the financial constraint. Optimization of fertility use aims to maximize profit from fertilizer use, both for the farmer who is not limited in fertilizer use and can apply at EOR to all cropland and for the financially constrained farmer who needs to maximize net returns from a limited investment in fertilizer use. Field research results were applied in determining crop nutrient response functions which are the basis of FOTs which aid in choice of crop-nutrient-rate combinations specific for the farmer's context.

14.10 Acknowledgements

The authors are grateful to the Alliance for a Green Revolution in Africa (AGRA) for providing funds for OFRA the Centre for Agricultural Biosciences International (CABI). Appreciation is sincerely expressed to CABI and the Institute of Agriculture and Natural Resources, University of Nebraska - Lincoln (UNL) for guidance and advice during the implementation of project activities. They have contributed considerably to the project achievement in Tanzania. The authors acknowledge the Ministry of Agriculture, Livestock and and Fisheries for enabling the field research. Many thanks to researchers, farmers, extension officers and other people who in one way or another participated in the project activities.

14.11 References

De Pauw (1984) Soils, physiography and agro-ecological zones of Tanzania. Crop monitoring and early warning systems project GCS/URT/047. NET. Ministry of Agriculture, Dar Es Salaam. Food and Agriculture Organization of the United Nations, Rome

Harrop JF and Samki JK (1984) Fertilizer recommendations in Tanzania. Technical Paper URT/73/006, National Soil Service, Agricultural Research Institute, Mlingano, Tanzania

Hepelwa AS, Onesmo S and Mduma JK (2013) The voucher system and the agricultural production in Tanzania: Is the model adopted effective? Evidence from the panel data analysis. Report. SIDA

Letaa E, Kabungo C, Katungi E, Ojara M and Ndunguru, A (2014) Farm level adoption and spatial diffusion of improved common bean varieties in southern highlands of Tanzania. Technical report 2012 – 2013. CIAT ARI Uyole, Tanzania

MAFS (Ministry of Agriculture Food Security) (2012) Accelerated Food Security Project (Credit 4619-TA): Progress Report August 2009-June 2012. MAFC, Dar-es-Salaam

Marandu AET, Mbogoni JDJ and Ley GJ (2014) (Eds) Revised Fertilizer Recommendations for Maize and Rice in the Eastern, Southern Highlands and Lake Zones of Tanzania. Ministry of Agriculture, Food Security and Cooperatives, Department of Research and Development, Dar-es-Salaam, Tanzania

Mlingano Agricultural Research Institute (2006) Soils of Tanzania and their potential for agriculture development. ARI Mlingano, Tanga

Mowo JG, Floor J, Kaihura FBS and Magogo JP (1993) Review of Fertilizer Recommendations in Tanzania. Part 2: Revised Fertilizer Recommendations for Tanzania. National Soil Service, ARI Mlingano, Ministry of Agriculture, Tanga, Tanzania

Rugambisa J (1990) Marketing of beans in Sub-Saharan Africa and impact of market on new cultivars. In Smithson JB, Progress in Improvement of Common Bean in Eastern and Southern Africa. Proceedings of the Ninth SUA/CRSP and Second SADCC/CIAT Bean Research Workshop, Sokoine University of Agriculture, Morogoro, Tanzania, 17-22 CIAT Africa Workshop Series No. 12

Shekiffu CY (2011) Improving soil productivity in cassava-based production systems in the coast region of Tanzania. PhD Thesis. Sokoine University of Agriculture, Morogoro

World Bank (2010) Tanzania Rapid Budget Analysis for Annual Review 2010/2011. Agriculture Sector.

World Bank (2014) Tanzania Public Expenditure Review: National Agricultural Input Voucher Scheme (NAIVS). World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/18247 License: CC BY 3.0 IGO

15. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility in Uganda

Kaizzi C. Kayuki[1] kckaizzi@gmail.com, Nansamba Angella[1] and Kabuye Frederick Musisi[2]

[1]National Agricultural Research Laboratories, P.O. Box 7065, Kampala, Uganda
[2]Uganda Soil Health Consortium, Entebbe, Uganda

15.1 Agro-ecological zones (AEZ) of Uganda

Uganda has 14 AEZ (Wortmann and Eledu 1999) (Figure 15.1). An alternative zonation has 10 production zones (MAAIF 2004) (Figure 15.2).

Central Uganda (Lake Victoria Crescent) is an extensive agricultural area receiving over 1200 mm per year of rainfall in a bimodal pattern (Table 15.1). The population density is 280 persons per km^2. The zone is subdivided into three sub-zones: west of the Nile River; east of the Nile; and the eastern section in Bugiri, Busia and Tororo Districts. About 82% of the land is farmed. Wetlands are important for plant products, environmental protection and rice cultivation. The crops are diverse. Banana is important throughout much of the zone, but particularly in the west. Bean, sweet potato, cassava and maize are the main food crops. The cereal and grain legume crops are relatively more important east of the Nile. Rice production is important in parts of Tororo, Busia and northern Iganga districts. Robusta coffee is a major cash crop throughout the zone. West of the Nile, the soils are variable but often have high clay content (Figure 15.3). Sandy clay loam soils are also common. The sub-soil has a clay loam texture in some places, which may interfere with rooting depth. Soils are often acidic and low in K, but contain moderate levels of organic matter. Crop production takes place primarily on the slopes where the soil is generally deep. Murram may limit rooting depth on the lower slopes; ridge tops and swamp fringes are generally not suitable for crop production. Clay loam soils are typical on the hill slopes east of the Nile River, where the soils are less fertile than in the west, and these soils are more often sandy

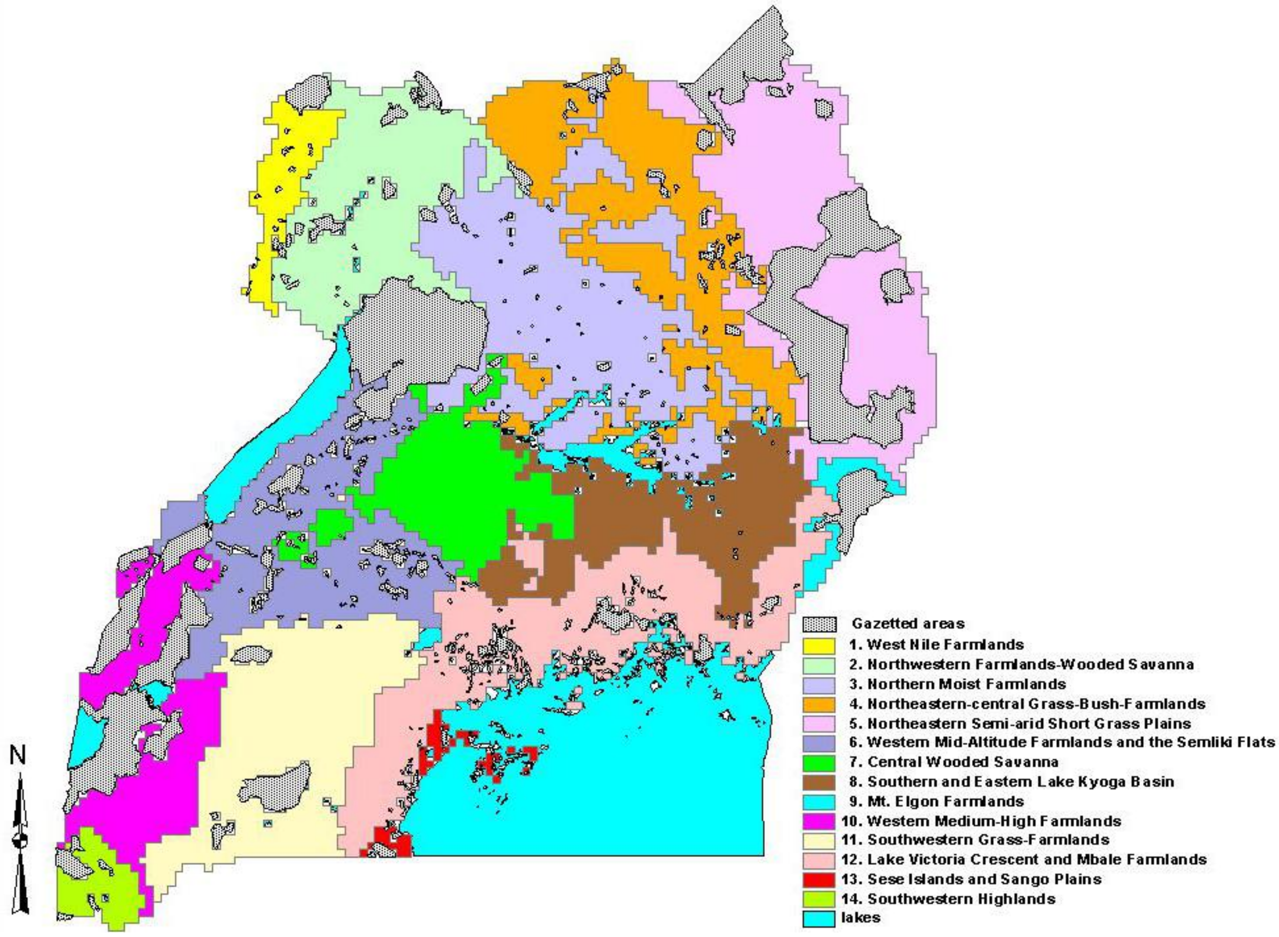


Figure 15.1: Agro-ecological zones of Uganda.

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

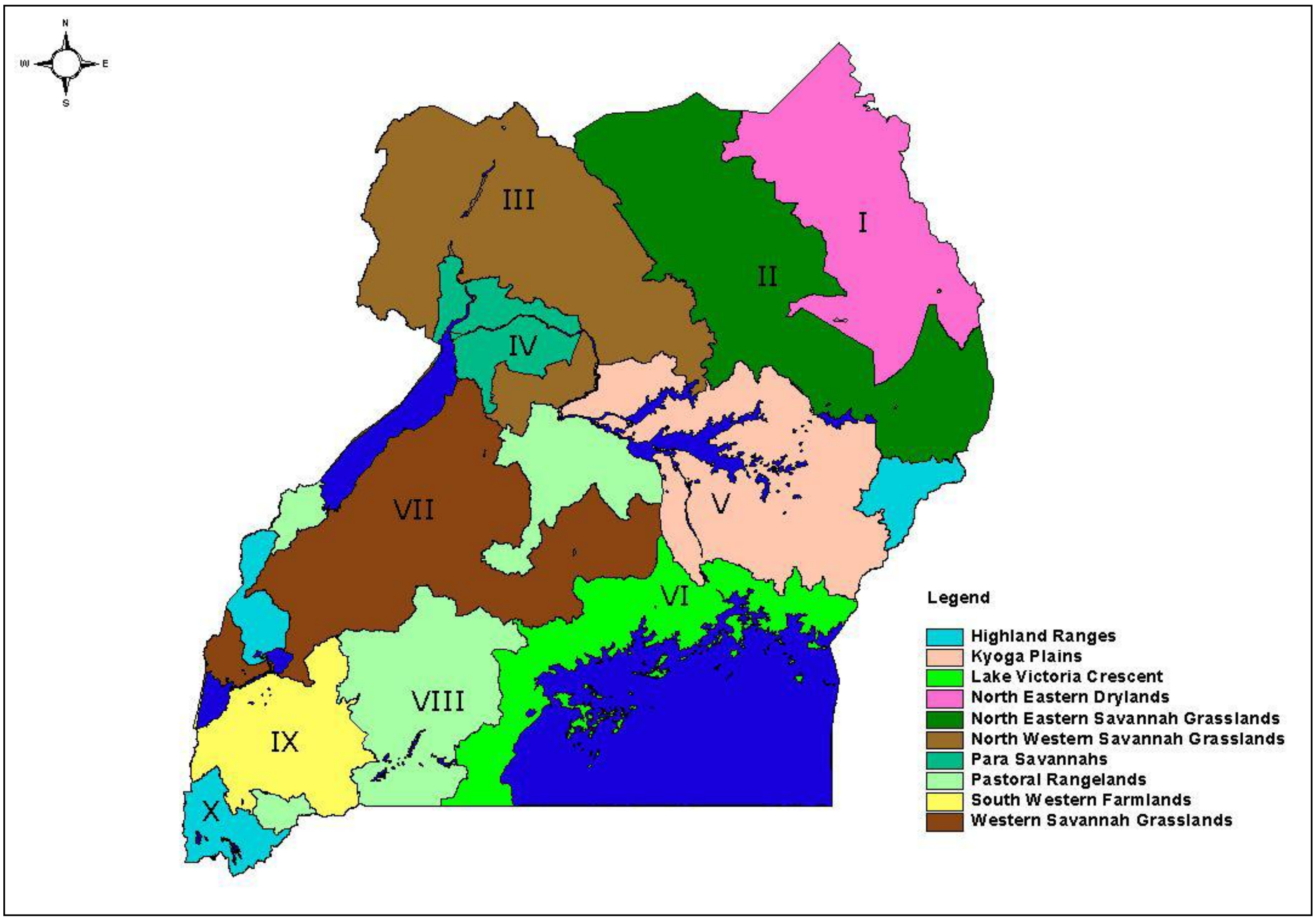


Figure 15.2: Map of agricultural production zones in Uganda.

loam and acidic, especially in the south east, where K is often deficient.

The Eastern Lake Kyoga Basin (Southern and Eastern Lake Kyoga Basin) is sub-humid with two growing seasons of similar rainfall, 560 mm during March-June and 540 mm during July-November (Table 15.1). The mean population density is 129 persons per km^2. Finger millet, banana and maize are major food crops, with more production in the southern part of the zone than in the north. Rice production in low-lying areas is important in Pallisa, northern Iganga and eastern Kamuli. Sorghum is relatively more important in Kumi and Pallisa. Cassava is a common food crop, especially in Kumi and parts of Pallisa. Cotton is the major cash crop. The soils of the western part of this zone are generally loam on the ridges and upper slopes and sandy loam on the lower slopes (Figure 15.3). In the east and north west, sandy soils derived from ancient lake deposits prevail. Soils are occasionally acidic and often have low organic matter and low nutrient supply. South and east of Kumi and near Bukedea, loam soils with good nutrient supply are common. Maize, cotton and other crops are likely to be very responsive to application of moderate amounts of N and P. Crop production is often constrained by water and nutrient deficits.

The Eastern 1400–1800 masl (Mt Elgon High Farmlands) AEZ is a very productive area with fertile soils and more than 1200 mm/yr rainfall in a bimodal pattern (Table 15.1). This AEZ is cool and wet. The southern part is warmer with less rain in July than in the north. Rainfall peaks in April and May but is generally more than 100 mm per month from March to November. The population density is 345 persons per km^2. Bean is the major food crop in terms of area, but banana is also very important. Maize and groundnut are important crops. Arabica coffee is the major cash crop. While important throughout the AEZ, the production of banana, bean and maize is more prevalent in the northern part. In the north, much of the soil is derived from volcanic parent material and the soils are

Table 15.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Uganda

	J	F	M	A	M	J	J	A	S	O	N	D
Lake Victoria Crescent – Central Uganda												
Rainfall	63	57	135	213	137	67	64	88	108	135	107	90
Tmax	29	29	29	28	27	27	27	27	28	28	28	28
Tmin	15	16	16	17	17	16	15	16	16	16	16	16
South and Eastern Lake Kyoga Basin												
Rainfall	30	69	119	170	147	87	103	151	181	179	134	65
Tmax	31	32	31	29	28	28	27	27	28	28	29	29
Tmin	16	17	17	17	17	16	16	16	16	16	16	16
Mt Elgon High Farmlands (Eastern 1400–1800 masl)												
Rainfall	32	53	100	149	167	107	111	132	98	96	86	52
Tmax	31.7	31.4	30.5	29.0	28.3	28.2	27.5	27.9	28.6	28.9	29.4	30.0
Tmin	16.4	17.0	17.2	17.5	17.3	16.7	16.5	16.3	16.2	16.2	16.4	16.3
Kapchorwa Farm – Forest (Eastern >1800 masl)												
Rainfall	40	57	92	173	217	141	197	196	129	171	113	50
Tmax	26.8	27.2	26.7	25.3	24.5	24.3	23.3	23.7	24.6	24.7	25.0	25.6
Tmin	12.1	12.1	12.3	12.4	12.5	11.9	11.8	11.6	11.6	11.8	11.9	12.0
North, Mid-West and Western (Northern Moist Farmlands)												
Rainfall	21	50	98	157	193	115	139	184	170	161	102	39
Tmax	33	33	32	30	29	28	27	28	29	30	31	31
Tmin	16	17	17	17	17	17	16	16	16	16	16	16
North, Mid-West and Western (Western Mid-Altitude Farmlands)												
Rainfall	46	71	113	205	234	165	185	210	163	201	124	56
Tmax	27.2	27.4	26.8	25.5	24.7	24.6	23.8	24.0	24.7	24.8	25.1	25.7
Tmin	12.4	12.3	12.3	12.5	12.6	12.0	11.9	11.7	11.7	11.7	11.9	12.1
South Western Highlands (1400–1800 masl) South-western medium – highlands												
Rainfall	57	71	96	122	84	25	32	53	95	113	137	89
Tmax	26.8	26.9	26.8	25.9	25.9	26.2	26.7	26.8	26.7	26.2	25.8	25.9
Tmin	13.9	14.1	14.3	14.5	14.3	13.2	13.0	13.9	14.0	14.1	14.2	13.8
South Western Highlands (1400–1800 masl) Bushenyi-N.Rukungiri Farmlands												
Rainfall	72	78	113	138	100	40	36	85	128	138	151	118
Tmax	25.6	25.7	25.5	24.7	24.5	24.8	25.2	25.4	25.4	25.0	24.6	24.8
Tmin	12.7	12.9	13.0	13.3	13.3	12.2	12.1	13.0	13.0	13.0	13.0	12.7
South Western Highlands (above 1800 masl) Kabale – Rukungiri Highlands												
Rainfall	62	84	114	150	90	27	23	56	103	105	126	88
Tmax	24	24	24	23	22	23	23	23	24	23	23	23
Tmin	10	10	10	11	11	9	9	10	10	10	10	10
South Western Highlands (above 1800 masl) Kabale – Kisoro Highlands												
Rainfall	90	119	142	173	117	42	29	76	136	158	166	120
Tmax	23.7	23.6	23.3	22.5	22.2	22.9	23.5	23.5	23.7	23.2	22.7	23.0
Tmin	11.2	11.4	11.4	11.7	11.7	10.7	10.6	11.2	11.3	11.3	11.3	11.3

typically red clay loam, well drained, highly leached, often acid, but of good nutrient supply (Figure 15.3). In the south, the surface soils more often have high sand content and lower nutrient supply.

The Eastern above 1800 masl (Kapchorwa Farm-Forest Land) AEZ is on the northern steps of Mount Elgon with above 1200 mm/yr unimodal rainfall (Table 15.1). The climate is cool and sub-humid with a long wet season from April to October and with peak rainfall in April and May. The population density is 206 persons per km^2. Much of this zone is forested; about 40% is used for crop production. Maize and bean are the main crops, with beans produced in association with other crops. Banana is also an important crop. This is the major AEZ for wheat production in Uganda. The soils are generally highly productive. In the forest zone, soils are primarily reddish-brown loam over deep clay loam sub-soil. In the farmland areas, much of the soil is derived from volcanic parent material; clay and clay loam soils are common and often acidic, but are of good nutrient supply (Figure 15.3).

The Northern Moist Farmlands are very important for annual crop production. It receives above 1200 mm/yr of unimodal rainfall (Table 15.1). The zone is sub-humid and relatively warm with rainfall well distributed from April to October, during which mean monthly rainfall exceeds 110 mm. The main dry season is December-March. Population density is 65 persons per km^2. Maize, finger millet and bean are important food crops but are not uniformly distributed. Sweet potato, cassava and sorghum are also important. Cotton, simsim (sesame) and tobacco are major cash crops. This is the major AEZ for pigeonpea and cowpea production in Uganda. Rice is becoming an important cash crop. The soils are variable and often acidic and sandy. In the West Nile, the soils are over a metre deep, sandy and acidic, and often low in nutrient availability. The soils of Gulu, Lira and Apac are generally sandy and sandy clay soils with low organic matter and low nutrient

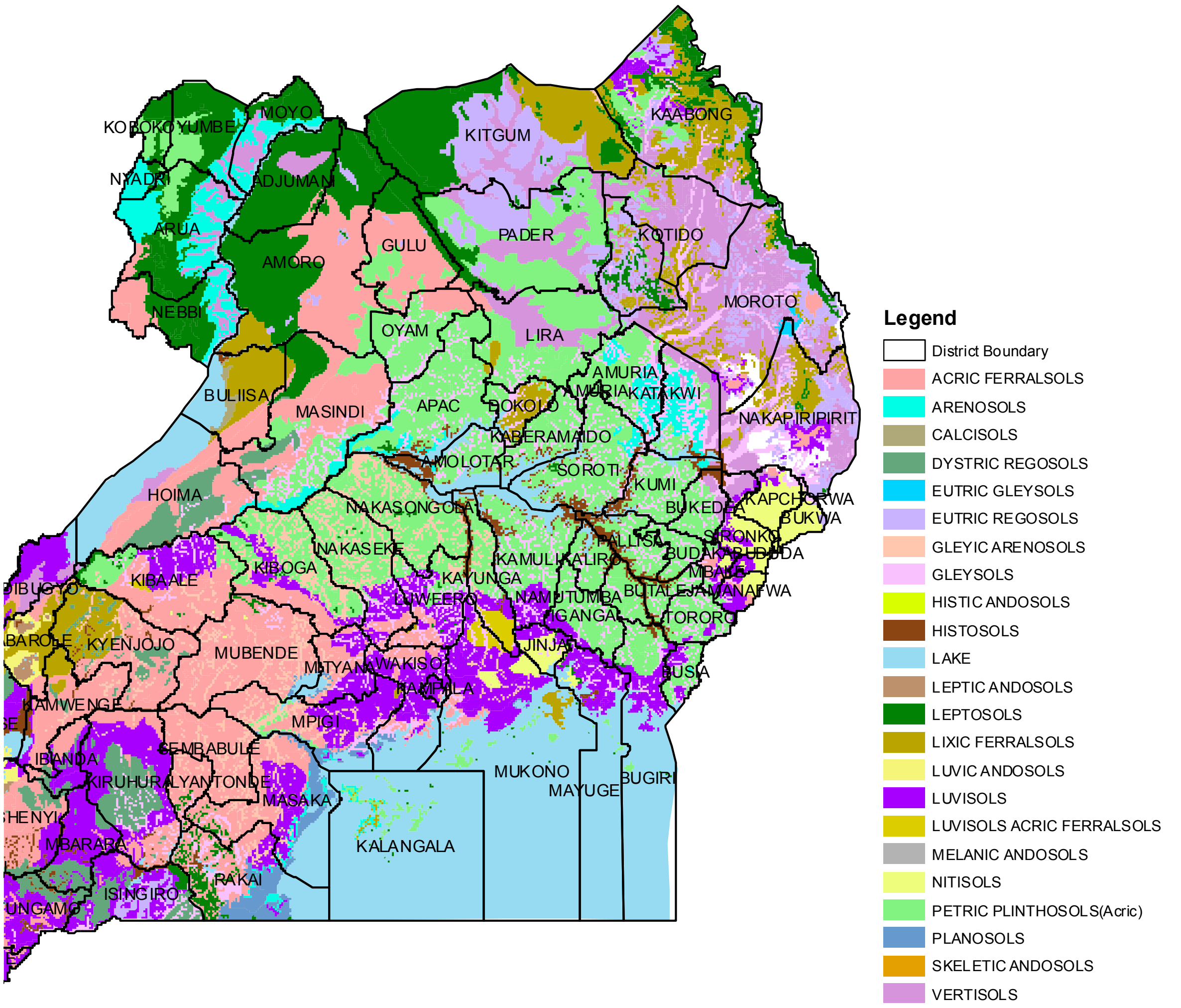


Figure 15.3: Major soil types of Uganda.

availability, but loam soils are common near Gulu town. With loam upland soils and clay valley soils of moderate nutrient supply, the land of Kigumba is of medium productivity and is important for maize and cotton production. In the south-east part, red loam soils are associated with the higher slopes, brown sandy soils are common on the lower slopes, and dark clay soils predominate in the valleys (Figure 15.3). The soils near the Pager and Agaga rivers are high in clay but are often acidic and have low nutrient supply. Throughout this AEZ, maize, cotton and other crops are likely to be very responsive to application of moderate amounts of N and P.

The Western Mid-altitude Farmlands is a large, widely dispersed and variable AEZ, receiving between 1000–1200 mm per year of bimodal rainfall (Table 15.1). The first season is shorter with mean rainfall of 360 mm during March-May and the second season receives mean rainfall of 485 mm during August-November. Population density is 78 persons per km^2. The food crops are diverse with banana the most important, followed by maize, bean and sweet potato. Maize is more important in the eastern part of the AEZ while sweet potato, cassava and groundnut are more important in Kabarole. Livestock keeping is important. The soils in the west are often shallow, coarse-textured and acidic; patches of deeper soil are cultivated (Figure 15.3). Areas in Kibale have loam soils. In northern Mubende and Kiboga, the soils are shallow except on the lower slopes where brown loam, typically a metre deep, occurs. Shallow soils at the base of rock outcrops are often intensively cultivated. In western Mubende, more productive loam and clay loam soils occur on the mid-slopes; productivity is low to medium. Maize, cotton and other crops are likely to be very responsive to application of moderate amounts of N.

South-western Highlands (1400–1800 masl) includes the South-western Medium Highlands and Bushenyi-North Rukungiri which receives 1000–1200 mm/yr of bimodal rainfall (Table 15.1). June and July are the driest and coolest months. Rainfall is sufficient for good crop productivity and is most reliable during the second season. Population density is about 202 persons per km^2. Banana is the major crop and is commercially important. Other important food crops are bean, maize and sweet potato. Cattle and goat production are major activities. The soil is typically dark, deep and often acidic, but nutrient supply is generally good in the Southwestern Medium Highlands (Figure 15.3). In Bushenyi-North Rukungiri, tea and coffee are important cash crops and the soils are commonly sandy loam in the south-west and loam in the north-east and are often acidic.

The South-western Highlands (>1800 masl) includes the Kabale–Rukungiri Highlands and Kabale-Kisoro Highlands with 1000–1200 mm and >1200 mm/yr, respectively, of bimodal rainfall (Table 15.1). June and July are the driest and coolest months. The respective mean population densities are 244 and 309 persons per km^2. Sorghum is sown in December and January and other crops are sown mainly in March for the first season. The second season is from September through December. Rainfall peaks in April and November. The main crops are banana and bean, followed by maize and sweet potato. Sorghum, finger millet and Irish potato are also important. This AEZ is important for Uganda's production of Irish potatoes. In the Kabale-Rukungiri Highlands, much of the soil is acid loam, but nutrient supply is generally good and productivity is medium to high. In the Kabale-Kisoro Highlands, the soils are dark brown, often acid and low in base, and are derived from basalt, lava, ash and, in places, phyllite (Figure 15.3). In the south, the humose brown loam soils are typically of moderate to high productivity. In the north, soils are acidic with low base supply and low productivity. Waterlogged valley soils are often high in sulphur (S), which leads them to become acidified upon aeration following drainage.

15.2 Current soil fertility management

The soils in Uganda are of inherently poor soil fertility with low nitrogen (N) and phosphorus (P) availability. Soil fertility is associated with soil organic matter in the top 20 cm depth which is susceptible to losses through erosion once vegetation cover is removed, resulting in permanent loss of soil fertility and land productivity. Nutrient removal in crop harvests and losses through runoff and soil erosion is not adequately compensated by using crop residue, manure and fertilizer resulting in negative

Table 15.2. Average nutrient depletion rates (kg/ha) in Uganda (Source: Kaizzi et al., 2004)

Agro-ecological Zone	N	P	K
West Nile and North-western	-36	-4	-26
Northern Moist	-56	-3	-37
Mt Elgon	-66	-5	-82
South-western Grassland-Farmland	-97	-4	-172
Lake Victoria Crescent and Mbale	-82	-8	-80

nutrient balances in all AEZ of Uganda (Table 15.2), especially for K in the south-west. The common practices by farmers are tillage using either hand hoes or animal traction and residue removal.

Current soil fertility management practices include the use of farmyard manure, crop residues, compost, fertilizer, plus crop rotation and, in some places and with declining frequency, leaving the land fallow for a few years. Unfortunately, manure and fertilizers are used on only 7 and 1% of the land parcels annually and by 24 and 2% of smallholders, respectively (UBOS 2006, 2010). Some farmers attempt to control runoff and erosion, but are not always successful. Others make little effort. Crop residues for land application are scarce with competing fuel and feeding demands. Manure use requires much animal labour and the nutrient content is low. Green manure production has been proven effective in supplying N to the following crop but requires land that could be used for food or cash crops and is not much practised. Transfer of plant materials from field boundary areas, or nearby fallow or grazing areas, often has potential in sub-humid areas but less potential in semi-arid areas; its practice is mostly limited to banana production.

Current fertilizer recommendations (REC) are not site specific, originate from the 1970s and call for high rates of application for maximizing yield. Examples of the existing recommendations include: for maize, apply 125 kg/ha diammonium phosphate (DAP) at planting and 125 kg/ha urea when maize is approximately 1m tall; for finger millet, broadcast apply 125 kg/ha ammonium sulphate when plants are about 15 cm tall; for sorghum, apply 110 kg/ha of SSP at planting and 110 kg/ha of CAN about 3 weeks after planting (NARO 2001).

Most farmers use little if any fertilizer and are not well informed on proper fertilizer use, time of application and suitability of different products. This also applies to their advisors. Effective fertilizer use requires a well-managed crop, but also proper use of the fertilizer. Farmers and extension advisors need to be aware of 4R Nutrient Stewardship including: applying the right source of nutrients, at the right rate, at the right time, and with the right method. Fertilizer use is very costly in Uganda. Sales and demand are low and the fertilizer supply chain is not well developed. Fertilizer subsidies are needed at least on an interim basis to sufficiently increase demand for fertilizer, so the supply chain can become more efficient (Kaizzi 2012).

15.3 Diagnosis of nutrient deficiencies in Uganda

Trials supported by the Optimizing Fertilizer Recommendations in Africa (OFRA) project were conducted both on farmers' fields (OFT) and at research stations (RMT). The mean response of finger millet was 124, 14 and 3% to N, P and K over 33 site-season-variety comparisons. The trials included treatments to determine if the nutrient package of N+P+K+Mg+S+Zn+B, referred to as a diagnostic treatment, compared with N+P+K resulted in increased yield of finger millet. The results indicate that one or more of Mg, S, Zn and B are limiting yield as observed from yield increases of 39 and 64% in on-farm trials (OFT) in Palissa and Tororo, respectively. The average effects of the diagnostic treatment ranged from negative to a 29% increase with researcher managed trials in Tororo and Apac, respectively (Figure 15.4).

The results of foliar sample analyses are revealing (Table 15.3). Foliar levels of N and P

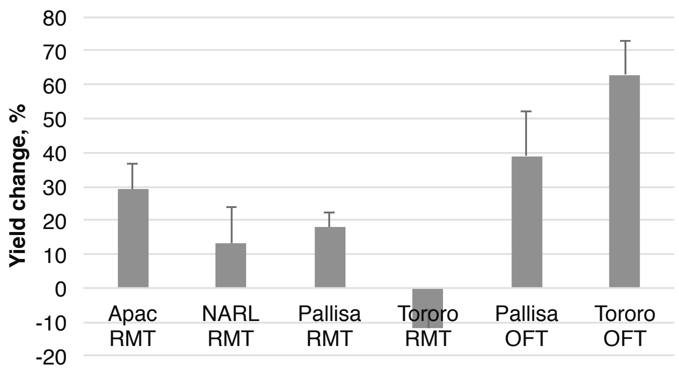


Figure 15.4: Mean increases in finger millet grain yield due to the application of Mg+S+Zn+B in Uganda.

Table 15.3: Foliar nutrient contents for finger millet samples taken from plots with applications of N, P and K at planting plus in-season N application. The critical value for interpretation of foliar results were determined in consideration of other warm season cereals as no values specific for finger millet were found. Means of 18 samples per location

Location	B	Ca	Cu	Fe	K	Mg	Mn	Na	P	S	Zn	N	Mo
Apac	4.34	0.86	5.57	218	2.13	0.28	256	32.9	0.19	0.17	27.8	1.58	0.74
NARL	5.00	0.91	6.17	836	2.78	0.23	397	46.4	0.33	0.22	50.9	1.64	1.20
Palissa OFT	3.75	0.80	4.85	311	2.17	0.23	262	33.3	0.21	0.13	29.3	1.30	2.05
Tororo OFT	3.86	0.83	5.15	180	2.10	0.24	248	34.2	0.20	0.14	28.6	1.44	1.12
Critical value	3	0.2	3	20	1.2	0.1	15		0.22	0.11	15	2.8	0.1

were most frequently low relative to the critical values used in interpretation of the results, even though N, P and K had been applied to sample plots. The results indicate that boron (B) and S are the most likely nutrients applied in the diagnostic package to have resulted in the large yield increases due to the diagnostic package for the OFT of Tororo and Palissa. The B and S mean levels were low compared with National Agricultural Research Laboratories (NARL) and Apac and because the foliar levels were relatively near the critical levels. Soil organic matter is the major source of S and B; finger millet response to N in these trials was great suggesting that the rate of nutrient mineralization from soil organic matter is low. Both S and B are subject to leaching loss. Another micronutrient of interest is molybdenum (Mo) which is low at some locations relative to the critical value but high for the Palissa OFTs. Further investigation is needed to validate these observations, the extent and conditions of the occurrence of deficiencies, and the economics of application.

15.4 Optimizing fertilizer use in Uganda

Optimization of fertilizer use in this chapter, as developed by OFRA, refers primarily to maximizing farmer profit from fertilizer use, given that most Uganda farmers are severely limited in their management options by poverty. However, the profit needs to be achievable without much risk.

Determination of the profit potential for farmers from their fertilizer use decisions requires information on the typical response of a crop to an applied nutrient in an AEZ. Responses were determined using curvilinear to plateau, or asymptotic quadratic-plateau, functions taking the form of an exponential rise to a maximum or plateau yield as this form of response is most typical when numerous site-years of data are considered (Figure 15.5).

The asymptotic function was $Y = a - bc^r$, where Y was yield (t/ha), a was the maximum or plateau yield (t/ha), b was the maximum gain in yield (t/ha) due to nutrient application, and c^r represented the shape of the quadratic response, where c was a curvature coefficient and r the nutrient application rate (t/ha).

The typical form of crop response to a nutrient has economic implications for the farmer. The curvilinear to plateau yield responses (y-axis) of maize, upland rice, sorghum, finger millet and bean to applied N (x-axis) are displayed in Figure 15.5. The magnitude of response, b, and the shape of the curve differ by crops, but all crop responses have a steep yield increase with increasing N at low rates (i.e. up to 20 kg/ha N applied). The rate of yield increase is less at higher N rates with little yield increase for some crops with >40 kg/ha N; yield eventually reaches a plateau with no more practical yield increase in response to increasing N rates. The levelling off of the curve implies that factors other than N are more limiting to crop yield. The response curves presented are typical for most crops and nutrients. The response implies that the net returns to low rates of N are greater than with higher rates. This has implications for risk as application at lower rates not only has potential

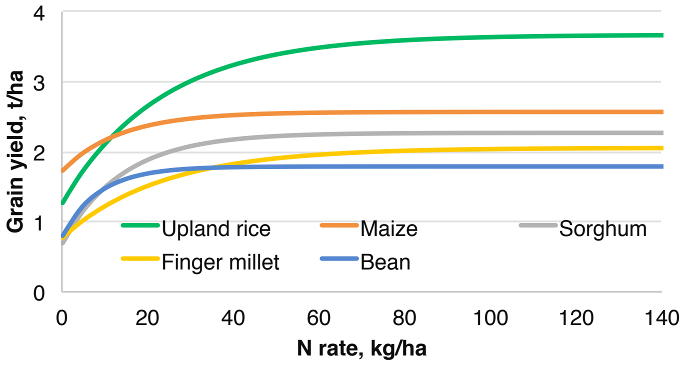


Figure 15.5: Nitrogen response curves for different crops.

for higher returns per unit of investment but the same fertilizer value can be applied over more land and to more crops as compared to applying at higher rates.

Another important aspect of achieving high profit from fertilizer use for financially constrained farmers is the unique specificity of crop response to a particular applied nutrient. This is due to the magnitude and shape of the crop response to a nutrient, but also the value of the produce (revenue) and fertilizer use costs (costs). In Figure 15.6, the amount of money invested in one nutrient applied to one crop is on the x-axis and the y-axis shows net returns to investment in nutrient application. Each curve represents the profit potential of a nutrient applied to a crop. Net returns to investment are very high if the slope of the curve is steep. With increased rates of application, the slope decreases, but profit is increasing if the curve continues upward. The peak of the curve is the point of maximum profit per hectare, referred to in this chapter as the economic optimum rate (EOR). When slopes decline, profit is declining. The financially constrained farmer can maximize profit potential by taking advantage of the crop-nutrient combinations that will give the highest benefit to cost ratio for the limited investment in fertilizer use.

Upland rice response to N has the greatest profit potential, partly due to the high value of the grain. Also very profitable are: P applied to groundnut and a low rate of N applied to bean. The fourth most profitable crop response to specified nutrient is N applied to finger millet. Several other less profitable options have lower lying curves. When a farmer's ability to use fertilizer is finance constrained, it is important to take advantage of the crop-nutrient-rates that have the most profit potential given the farmer's cropping system and financial context. The farmer who can apply fertilizer to all cropland at EOR is less concerned about crop-nutrient choices, but about their EOR.

Decisions of crop-nutrient-rate choices for maximizing a farmer's profit potential is very complex as the nature of the crop-nutrient responses needs to be considered as well as the farmer's land allocation to different crops, the produce value, the costs of fertilizer use and the money available for fertilizer use. Therefore, easy to use fertilizer use optimization tools (FOTs) were developed which use linear programming to consider reiteratively the economic and agronomic information using Excel Solver© (Frontline Systems Inc.). The FOTs are available at http://agronomy.unl.edu/OFRA.

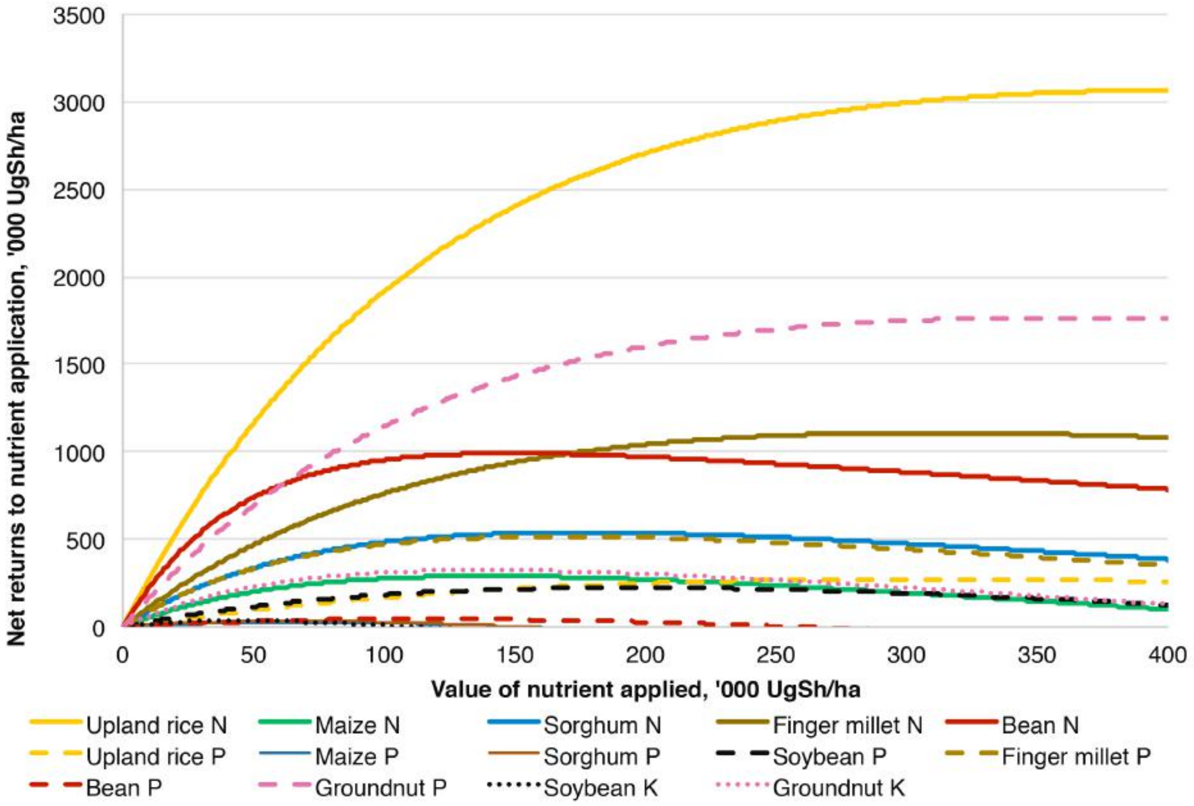


Figure 15.6: Net returns on investment depend on choice of crop-nutrient-rate combinations for eastern Uganda – Lake Kyoga Basin.

The Excel FOT requires that the Solver add-in be enabled. Instructions for enabling the Solver add-in are provided in a worksheet of the FOT 'Help and Instructions'. Instructions are also given for enabling macros, another essential step to using the Excel FOTs. More detailed instructions are available in Extension Training Materials at http://agronomy.unl.edu/OFRA. When enabled the Solver add-in appears under the Data tab on the Quick Access Toolbar.

The data input includes: the farmer's allocation of land to each crop of interest; estimated farm gate value per kg of produce at harvest time, considering that some is for home consumption (the most valuable) and that the surplus will be marketed; and the cost of using different fertilizers (Figure 15.7). The amount of money which the farmer has to invest in fertilizer use is also entered. Clicking on the 'Optimize' button then runs the optimization calculations. In the example, the farmer wishes to plant six crops to six acres of land. If no land is allotted to a crop or if the crop value is not given, the crop is not considered. In the example, DAP is given a cost of zero and it is not considered in the optimization. The budget constraint to fertilizer use is UgSh 600,000.

The output panel displays the recommended fertilizer rates for each crop, the expected mean yield increases and net returns for each crop, and the expected mean total net return to investment in fertilizer (Figure 15.8). The approach strives to maximize profitability of fertilizer use through consideration of the farmer's financial constraint, costs and prices of inputs and outputs, and farmer's cropping system. It identifies the crop-nutrient-rate combinations expected to maximize returns on investment in fertilizer.

In the example, some fertilizer has been recommended for all crops. In some cases, such as TSP applied to maize and banana, the amount is too small for feasible application and the fertilizer or the money should be allocated to another crop or fertilizer. The fertilizer needed totalled to 118, 148 and 31 kg of urea, TSP and KCl, respectively. The average expected total net return to the UgSh 600,000 invested in fertilizer use is UgSh 2,729,469. If a crop has a high net return to fertilizer use, such as upland rice in this example, the farmer may try allocating more land to the crop to determine if total profit is adequately increased, although more than profit from fertilizer use needs to be considered in land allocation.

Often farmers and their advisors are not able to use the Excel Solver© FOT due to lack of access to a computer. Therefore a paper FOT was developed for each AEZ. The paper FOT for Eastern Uganda – Lake Kyoga basin is given as an example (Table 15.4).

The paper FOT is devised for three financial levels based on the farmer's budget constraint for fertilizer use. The level 1 financial ability is for the poor farmer who has less than one-third the amount of budget required to apply fertilizer to all cropland at EOR; level 2 is for the farmer with less than two-thirds but greater than one-third of the money required to apply fertilizer to all cropland at EOR; and level 3 is for the farmer with enough money to apply fertilizer at EOR to at least some of the cropland.

The paper tool makes assumptions about the: measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer; crop inter-row and intra-row spacing; the fertilizer use costs per 50 kg bag; and the expected commodity values on-farm at harvest, considering the value both for home consumption and for market.

Consider as an example level 1 financial ability recommendations in the paper FOT for the Lake Kyoga Basin 'Finger millet: broadcast 14 kg/ac DAP at planting (CAP for 2.4 m); 17 kg/ac urea at 2nd weeding (CAP for 1.2 m)'. Therefore, the farmer should broadcast apply 14 kg/ac of DAP to finger millet at planting. This is calibrated using a Highland brand water bottle lid which is sufficient for 2.4 m when the application width is 1 m. The farmer should also broadcast apply 17 kg/ac of urea to finger millet at the second weeding. This is calibrated using a Highland water bottle lid which is sufficient for 1.2 m when the application width is 1 m.

Fertilizer use decisions need to consider the effects of other practices that supply soil nutrients as well as soil test information (Table 15.4). Typically, a farmer may apply such a practice to only one or a few parcels of several land parcels that comprise the farm's cropland. For example, manure application to a parcel

Central

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	July 23, 2016

Crop Selection and Prices		
Crop	Area Planted (Ac)*	Expected Grain Value/kg †
Maize	1	600
Banana	1	800
Upland rice	1	1500
Beans	1	1200
Soybeans	1	1000
Groundnuts, unshelled	1	2400
Total Acres	**6**	

Fertilizer Selection and Prices				
Fertilizer Product	N	P2O5	K2O	Price/50 kg bag ¶*
Urea	46%	0%	0%	120000
Triple super phosphate, TSP	0%	46%	0%	120000
Diammonium phosphate, DAP	18%	46%	0%	140000
Murate of potash, KCL	0%	0%	60%	100000
xxx	17%	17%	17%	140000

Budget Constraint	
Amount available to invest in fertilizer	600000

Figure 15.7: Input screen of the fertilizer optimizer tool for Central Uganda.

Fertilizer Optimization					
	Application Rate - kg/Ac				
Crop	Urea	TSP	DAP	KCL	xxx
Maize	35	0	4	0	0
Banana	21	0	20	0	0
Upland rice	44	0	26	0	0
Beans	15	0	16	0	0
Soybeans	0	30	0	4	0
Groundnuts, unshelled	0	47	0	22	0
Total fertilizer needed	**116**	**77**	**67**	**26**	**0**

Expected Average Effects per Ac		
Crop	Yield Increases	Net Returns
Maize	632	282,572
Banana	947	650,146
Uplandrice	689	854,427
Beans	429	433,048
Soybeans	353	273,608
Groundnuts, unshelled	423	860,012

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	3,353,781

Figure 15.8: Output of the FOT.

Table 15.4: Example of paper fertilizer optimization tool

UGANDA FERTILIZER USE OPTIMIZER:
Eastern Lake Kyoga Basin

The below assumes:
Cost of fertilizer use for 50 kg bag (UgSh): urea, TSP and KCl is 120,000/-; DAP is 140,000/-.
Grain values (UgSh/kg): maize 600; Sorghum 500; finger millet 1200; upland rice paddy 1500; bean 1200; soybean 1000; and groundnut unshelled 2500.
Calibration measurement units: a Highland water bottle cap (CAP) that holds 7.5 ml, about 5.25 g urea, 8.25 g DAP, TSP or KCl; and Highland water bottle cut at 2 cm (2-cm bottle) holds 59.3 ml, 41.5 g urea and 65.2 g of DAP, TSP or KCl.
Row spacing: maize 75 x 30 cm; sorghum, 60 cm; finger millet and upland rice, 20 cm; banana 3 x 3 m; bean 60 cm; soybean and groundnut 45 cm.
Rates are at least 10 kg/ac. **Broadcast width** is 1 m.

Level 1 financial ability.	
Finger millet	Broadcast 14 kg/ac DAP at planting (CAP for 2.4 m); 17 kg/ac urea at 2nd weeding (CAP for 1.2 m)
Sorghum	Band 11 kg/ac urea after 2nd weeding (CAP for 3.2 m)
Upland rice	Broadcast 13 kg/ac DAP at planting (CAP for 2.6 m); 17 kg/ac urea at panicle initiation (CAP for 1.2 m)
Bean	Band apply 12 kg/ac urea at planting time (CAP for 3.0 m band)
Groundnut	Band apply 14 kg/ac DAP and 12 kg TSP at planting time (2-cm bottle to cover 4.2 m band for DAP and 6.7 m band for TSP)
Level 2 financial ability.	
Maize	Point apply 17 kg/ac urea at planting (CAP for 3.1 plants); apply 17 kg/ac urea at second weeding (CAP for 3.1 plants)
Finger millet	Broadcast 22 kg/ac DAP at planting (CAP for 1.5 m); apply 17 kg/ac urea at 2nd weeding (CAP for 1.2 m)
Upland rice	Broadcast 23 kg/ac DAP at planting (CAP for 1.5 m); 38 kg/ac urea at panicle initiation (CAP for 0.6 m)
Sorghum	Band 19 kg/ac urea at 2nd weeding (CAP for 1.9 m)
Bean	Band 18 kg/ac urea at planting (CAP for 2 m band)
Soybean	Band 25 kg/ac TSP at planting (CAP for 3.0 m band)
Groundnut	Apply 40 kg/ac DAP at planting (CAP for 2.9 m band)
Level 3 financial ability (maximize profit per acre).	
Maize	Point apply 10 kg/ac DAP at planting (CAP for 16 plants); band 43 kg/ac urea at 2nd weeding (CAP for 2.2 plants)
Finger millet	Apply 28 kg/ac DAP at planting (CAP for 1.2 m); apply 41 kg/ac urea at 2nd weeding (broadcast 2-cm bottle for 0.5 m)
Sorghum	Band 14 kg/ac DAP at planting (CAP for 4 m); 24 kg urea at 2nd weeding in a band (CAP for 2.5 m)
Upland rice	Broadcast 31 kg/ac DAP at planting (CAP for 1.1 m); 54 kg/ac urea at panicle initiation (CAP for 0.4 m)
Bean	Apply 14 kg/ac urea (CAP for 2.5 m band); 27 kg/ac DAP at planting time (CAP for 2.1 m band)
Soybean	Band 37 kg/ac TSP at planting time (CAP for 2 m band)
Groundnut	Band 40 kg/ac DAP time (CAP for 1.9 m); 14 kg/ac TSP and 13 kg/ac KCl at planting time (CAP for 5.3 m band for each)

may justify allocating some of the recommended fertilizer to another parcel of land. The fertilizer substitution value varies with the quality of manure; poultry and dairy manure have greater fertilizer substitution value than farmyard manure. If intercropping, the fertilizer rate should be increased relative to the sole cereal crop recommendation. Soil test P is commonly low for smallholder fields not near the household. Phosphorus should be applied according to the

FOT, unless the Mehlich III soil test P value is above 15 ppm when the fertilizer P should be applied to another piece of land or the money used differently. Potassium should be applied according to the FOT unless soil test K is below 100 ppm, then more KCl should be applied than indicated by the FOT.

15.5 Targeted crops by AEZ

Results for past and recent OFRA-supported trials conducted in Uganda were used to determine response functions by AEZ for maize, upland rice, sorghum, banana, soybean, groundnut, wheat and finger millet. Data from similar growing conditions in Rwanda and Kenya were used to determine response functions for Irish potato. Maize and bean were addressed for all seven AEZ (Table 15.5a-g). Soybean and groundnut were addressed for four AEZ and finger millet and Irish potato for three AEZ. Upland rice, wheat, sorghum and high potential banana were addressed for two AEZ and low potential banana for one AEZ. There was AEZ differentiation of response functions for maize, finger millet, soybean and groundnut. For other crops, the research results did not indicate differentiation of response functions by AEZ and some repetition occurs in Table 15.5a-g.

All non-legumes and bean responded well to applied N. More than 50% of the yield response to N occurred with 30 kg/ha N applied except for Irish potato which had a relatively more linear response. All targeted crops had an economic response to P. Soybean, groundnut and banana responded to K, but the cereals did not have economic responses to K. Data availability for Irish potato response to K was inadequate to develop a reliable response function.

Results presented in Tables 15.5a-g indicate that the current N and P recommendations (REC) for maize and banana are higher than the EOR. The same applies to K on banana and N on groundnut and wheat. This implies that

Table 15.4: Fertilizer use in an ISFM framework

FERTILIZER USE WITHIN AN INTEGRATED SOIL FERTILITY MANAGEMENT FRAMEWORK

FERTILIZER SUBSTITUTION AND SOIL TEST IMPLICATIONS

ISFM practice	Urea	DAP or TSP	KCl	NPK 17-17-17
	Fertilizer reduction, % or kg/acre			
Previous crop was a green manure crop	100%	70%	70%	70%
Fresh vegetative material (e.g. prunings of lantana or tithonia) applied, per 1 t of fresh material	4 kg	2 kg	2 kg	8 kg
Farmyard manure per 1 t of dry material	5 kg	3 kg	2 kg	10 kg
Residual value of FYM applied for the previous crop, per 1 t	2 kg	1 kg	1 kg	3 kg
Dairy or poultry manure, per 1 t dry material	9 kg	4 kg	5 kg	16 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	2 kg	2 kg	1 kg	3 kg
Compost, per 1 t	8 kg	3 kg	3 kg	15 kg
Residual value of compost applied for the previous crop, per 1 t	3 kg	2 kg	1 kg	5 kg
Rotation	0% reduction but more yield expected			
Cereal-bean intercropping	Increase DAP/TSP by 7 kg/ac, but no change in N and K compared with sole cereal fertilizer			
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 11 kg/ac, reduce urea by 9 kg/ac, and no change in K compared with sole cereal fertilizer			
If Mehlich III P >15 ppm	Apply no P			
If soil test K <100 ppm	Band apply 20 kg/ac KCl			

Table 15.5a: Central Region - Lake Victoria Crescent. Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions are not presented because of lack of response or lack of information

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop†	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
			t/ha			**t/ha**			**kg/ha**	
Maize	N	3.711	1.823	0.960	1.287	0.378	0.111	0.033	53	60
Banana <20t	N	7.60	1.95	0.92	1.80	0.14	0.01	0.00	40	100
Upland rice	N	2.06	1.28	0.97	0.81	0.30	0.11	0.04	77	46
Bean	N	1.79	0.99	0.89	0.96	0.03	0.00	0.00	30	26
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.91	0.20	0.84	0.12	0.05	0.02	0.01	5	25
Banana <20t	P	19.64	0.68	0.88	0.33	0.17	0.09	0.04	16	30
Upland rice ††	P	2.21	0.63	0.82	0.40	0.15	0.05	0.02	15	10
Bean ††	P	1.81	0.29	0.93	0.09	0.06	0.04	0.03	14	10
Soybean	P	1.66	0.98	0.88	0.46	0.24	0.13	0.07	18	20
Groundnut	P	1.79	0.94	0.89	0.40	0.23	0.13	0.07	27	10
Banana <20t	K	6.85	1.58	0.84	0.92	0.39	0.16	0.07	39	100
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	0	0
Groundnut	K	1.720	0.221	0.942	0.057	0.042	0.031	0.023	14	42

†EOR was determined with the cost of using 50 kg urea and TSP, DAP and KCl at UgSh 120,000, 140,000 and 100,000, respectively. Commodity values (UgSh/kg) used were: paddy rice 1500; maize 600; banana 800; sorghum 500; finger millet 1200; Irish potato 800; bean 1200; groundnut (unshelled) 2400; and soybean 1000.

‡NARO 2001; Nyombi 2013.

††Upland rice and Irish potato have recommended K rates of 11 and 28 kg/ha but the EORs were determined to be 0 kg/ha.

farmers do not recover part of the money they have invested in buying the excess N, which is wastage of their scarce resource. The reverse is true for N and P applied to upland rice, sorghum, finger millet, Irish potato and wheat. In this situation farmers lose money by not achieving the economically optimum yield in response to applied nutrients (i.e. they get lower yield and profit than they would have got if they increased the rates applied).

The EOR and REC differed inconsistently for crop-nutrients (Tables 15.5a-g). The REC for maize N, except for lower altitude eastern Uganda, bean N, Irish potato N, soybean P, and soybean K, were somewhat similar compared with EOR determined from field research results. The REC for upland rice N and P, finger millet N and P, sorghum N and P, wheat P, bean P and groundnut P were considerably lower than EOR. The REC for banana N, wheat N, maize P, banana P, banana K and groundnut K were considerably higher than EOR. Currently fertilizer prices in Uganda are very high. If the prices can be reduced through more efficient supply and/or subsidies, the EOR will increase assuming no significant change in the relative commodity values. Most Ugandan farmers are financially constrained in fertilizer use and should apply at rates below EOR to take advantage of the steeper parts of response curves.

15.6 Conclusion

Nutrient response functions were generated from present and past research for maize, upland rice, finger millet, sorghum, wheat, beans, soybean, groundnut and banana, and from similar AEZ in Rwanda and Kenya for Irish potato. The response functions were used in the development of FOTs and to determine the optimal crop-nutrient-rate combination for

Table 15.5b: Eastern Uganda – Lake Kyoga Basin (Eastern and Southern Lake Kyoga Basin)

		Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**t/ha**				**kg/ha**	
Upland rice	N	3.670	2.400	0.958	1.738	0.480	0.132	0.037	83	46
Maize	N	2.569	0.838	0.930	0.743	0.084	0.010	0.001	28	60
Sorghum	N	2.270	1.580	0.932	1.389	0.168	0.020	0.002	35	0
Finger millet	N	2.056	1.283	0.958	0.929	0.256	0.071	0.020	61	40
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	31	0
					0-5	**5-10**	**10-15**	**15-20**		
Upland rice	P	3.790	0.556	0.947	0.133	0.101	0.077	0.059	29	10
Maize	P	2.911	0.342	0.880	0.162	0.085	0.045	0.024	8	25
Sorghum	P	2.305	0.362	0.839	0.212	0.088	0.037	0.015	7	0
Soybean	P	1.219	0.559	0.905	0.220	0.134	0.081	0.049	15	20
Finger millet	P	2.210	0.629	0.820	0.396	0.147	0.054	0.020	14	10
Bean	P	1.810	0.286	0.926	0.091	0.062	0.042	0.029	14	10
Groundnut	P	1.792	0.937	0.893	0.405	0.230	0.131	0.074	27	10
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	8	0
Groundnut	K	1.720	0.221	0.942	0.057	0.042	0.031	0.023	29	42

Table 15.5c: Eastern Uganda: 1400–1800 masl (Mt Elgon High Farmlands)

		Response coefficients, Yield = $a - bc^r$; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**t/ha**				**kg/ha**	
Maize	N	3.711	1.823	0.960	1.287	0.378	0.111	0.033	53	60
Banana	N	39.400	6.560	0.905	6.232	0.312	0.016	0.001	46	100
Irish potato	N	12.560	2.277	0.985	0.830	0.527	0.335	0.213	116	100
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	31	26
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.910	0.203	0.840	0.118	0.049	0.021	0.009	5	25
Banana	P	19.640	0.680	0.875	0.331	0.170	0.087	0.045	0	30
Irish potato	P	15.326	3.303	0.944	0.827	0.620	0.465	0.348	40	10
Bean	P	1.810	0.286	0.926	0.091	0.062	0.042	0.029	14	10
Soybean	P	1.662	0.979	0.880	0.464	0.244	0.128	0.068	18	21
Groundnut	P	1.792	0.937	0.893	0.405	0.230	0.131	0.074	27	10
Banana	K	34.810	8.712	0.969	1.269	1.084	0.926	0.791	0	100
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	15	0
Groundnut	K	1.720	0.221	0.942	0.057	0.042	0.031	0.023	29	42

Table 15.5d: Eastern Uganda: above 1800 masl (Kapchorwa Farmlands – Forest)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
			t/ha			**t/ha**			**kg/ha**	
Maize	N	3.711	1.823	0.960	1.287	0.378	0.111	0.033	53	60
Banana	N	7.603	1.953	0.918	1.803	0.138	0.011	0.001	40	100
Wheat	N	3.113	0.570	0.904	0.542	0.026	0.001	0.000	24	50
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	31	26
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.910	0.203	0.840	0.118	0.049	0.021	0.009	5	25
Banana	P	19.640	0.680	0.875	0.331	0.170	0.087	0.045	15	30
Wheat	P	2.616	0.605	0.900	0.248	0.146	0.086	0.051	16	12
Bean	P	1.810	0.286	0.926	0.091	0.062	0.042	0.029	14	10
Soybean	P	1.662	0.979	0.880	0.464	0.244	0.128	0.068	18	21
Groundnut	P	1.792	0.937	0.893	0.405	0.230	0.131	0.074	27	10
Banana	K	6.850	1.583	0.841	0.917	0.386	0.162	0.068	39	100
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	15	0
Groundnut	K	1.720	0.221	0.942	0.057	0.042	0.031	0.023	28	42

Table 15.5e: Northern, mid-west and western Uganda: (Northern Moist Farmlands, and Western Mid-Altitude Farmlands)

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
			t/ha			**t/ha**			**kg/ha**	
Upland rice	N	3.670	2.400	0.958	1.738	0.480	0.132	0.037	83	46
Maize	N	3.771	1.828	0.960	1.291	0.379	0.111	0.033	53	60
Sorghum	N	2.270	1.580	0.932	1.389	0.168	0.020	0.002	35	0
Finger millet	N	1.608	0.876	0.957	0.642	0.172	0.046	0.012	52	40
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	31	26
					0-5	**5-10**	**10-15**	**15-20**		
Upland rice	P	3.790	0.556	0.947	0.133	0.101	0.077	0.059	29	10
Maize	P	3.910	0.203	0.840	0.118	0.049	0.021	0.009	5	25
Sorghum	P	2.305	0.362	0.839	0.212	0.088	0.037	0.015	7	0
Soybean	P	1.662	0.979	0.880	0.464	0.244	0.128	0.068	18	20
Finger millet	P	1.841	0.446	0.900	0.183	0.108	0.064	0.038	17	10
Bean	P	1.810	0.286	0.926	0.091	0.062	0.042	0.029	14	10
Groundnut	P	1.792	0.937	0.893	0.405	0.230	0.131	0.074	27	10
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	15	0
Groundnut	K	1.720	0.221	0.942	0.057	0.042	0.031	0.023	58	42

Table 15.5f: South-western Highland: 1400–1800 masl (South-western medium-highlands, Bushenyi-N.Rukungiri Farmlands)

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**t/ha**				**kg/ha**	
Maize	N	3.711	1.823	0.960	1.287	0.378	0.111	0.033	53	60
Banana	N	39.400	6.560	0.905	6.232	0.312	0.016	0.001	48	100
Irish potato	N	12.560	2.277	0.985	0.830	0.527	0.335	0.213	115	100
Finger millet	N	1.608	0.876	0.957	0.642	0.172	0.046	0.012	52	40
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	29	26
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.910	0.203	0.840	0.118	0.049	0.021	0.009	5	25
Banana	P	19.640	0.680	0.875	0.331	0.170	0.087	0.045	15	30
Irish potato	P	15.326	3.303	0.944	0.827	0.620	0.465	0.348	44	10
Soybean	P	1.662	0.979	0.880	0.464	0.244	0.128	0.068	20	21
Finger millet	P	1.841	0.446	0.900	0.183	0.108	0.064	0.038	17	10
Bean	P	1.810	0.286	0.926	0.091	0.062	0.042	0.029	11	10
Banana	K	34.810	8.712	0.969	1.269	1.084	0.926	0.791	83	100
Soybean	K	1.761	0.099	0.900	0.041	0.024	0.014	0.008	18	0

Table 15.5g: South Western Highland: above 1800 masl (Kabale–Rukungiri Highlands, Kabale–Kisoro Highlands).

	Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha				Effect of nutrient element rate (kg/ha) on yield increase				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC‡**
		t/ha			**t/ha**				**kg/ha**	
Maize	N	3.771	1.828	0.960	1.291	0.379	0.111	0.033	53	60
Irish potato	N	12.560	2.277	0.985	0.830	0.527	0.335	0.213	46	100
Wheat	N	3.113	0.570	0.904	0.542	0.026	0.001	0.000	11	50
Bean	N	1.790	0.989	0.892	0.957	0.031	0.001	0.000	12	26
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	3.910	0.203	0.840	0.118	0.049	0.021	0.009	5	25
Irish potato	P	15.326	3.303	0.944	0.827	0.620	0.465	0.348	20	10
Wheat	P	2.616	0.605	0.900	0.248	0.146	0.086	0.051	18	12
Bean	P	1.810	0.286	0.850	0.159	0.071	0.031	0.014	11	10

maximizing net returns on investment in fertilizer use. Paper FOTs were developed for each AEZ to be used by farmers and their advisors who do not have access to a computer. A fertilizer calibration tool was developed to guide farmers in application to achieve the correct rate of fertilizer application.

Current recommended fertilizer application rates were found to be generally high compared to the EOR determined from results of field research. The results presented show the potential of the FOT in improving on the profitability of farming. Responses to secondary and trace elements call for more research to determine the extent and conditions of the occurrence of deficiencies, and the economics of application and which nutrients are limiting production in Uganda.

15.7 Acknowledgements

The authors are grateful to the Alliance for a Green Revolution in Africa (AGRA) for funding the study through CABI, to Professor Charles Wortmann from the University of Nebraska-Lincoln for the technical support and for the support of the Government of Uganda.

15.8 References

Kaizzi CK (2012) One-kg Challenge: Can financial services help increase the use of fertilizer in Ugandan farming? In Agricultural Finance Year Book, 2011. Bank of Uganda

Kaizzi CK, Ssali H and Kato E (2004) Estimated nutrient balances for selected Agroecological zones of Uganda. National Agricultural Research Organization (NARO) Mimeo, Kampala, Uganda

Ministry of Agriculture, Animal Industry and Fisheries [MAAIF] (2004) Increasing incomes through exports: a plan for zonal agricultural production, agro-processing and marketing for Uganda. MAAIF, Entebbe, Uganda

NARO (National Agriculture Research Organization) (2001) Agriculture in Uganda, Vol. I. Crops. Fountain Publishers, Kampala, Uganda

Nyombi K (2013) Towards sustainable highland banana production in Uganda: opportunities and challenges. African J Food, Agric, Nutr Develop 13:7544–7561

UBOS (Uganda Bureau of Statistics) (2006) National Household Survey, Agricultural Module, Kampala, Uganda

UBOS (Uganda Bureau of Statistics) (2010) National Household Survey 2009/10. www.ubos.org/UNHS0910/unhs200910.pdf

Wortmann CS and Eledu CA (1999) Uganda's agro ecological zones: A guide for planners and policy makers. Centro Internacional de Agricultura Tropical, Kampala, Uganda

16. Optimizing Fertilizer Use within the Context of Integrated Soil Fertility Management in Zambia

Brian Gondwe gkasemuka@gmail.com and Davy Nkonde

Zambia Agriculture Research Institute (ZARI), Mt Makulu Research Station, Lusaka

16.1 Introduction

Fertilizer use is an important part of soil fertility management and for substantially increased levels of crop production but it has to be adequately profitable to the farmer to justify the investment. High rates of return are especially important to farmers with little money available for fertilizer use.

The Zambia Agricultural Research Institute partnered with national agricultural research organizations of 12 other countries to improve the field-research-derived information base needed for optimizing fertilizer use for high profitability to farmers.

This chapter provides background information of agricultural systems and current soil fertility management practices in the three regions of Zambia. It provides a conceptual basis for optimization of fertilizer use and introduces decision tools to aid farmers and their advisors in determining the fertilizer use options expected to be most profitable to farmers. The nutrient application rates expected to maximize net returns per hectare to fertilizer use are compared to current recommendations with the latter typically higher than the economically optimum rates.

16.2 Agricultural systems of Zambia

Zambia is divided into three agro-ecological regions based on rainfall (Figure 16.1) (http://en.climate-data.org/). Region I is characterized by mean annual rainfall of less than 800 mm and is dominated by slightly acid to alkaline Luvisols (Table 16.1). Region II has mean annual rainfall ranging from 800-1000 mm. Region III has mean annual rainfall of above 1000 mm and comprises half of the land area of Zambia.

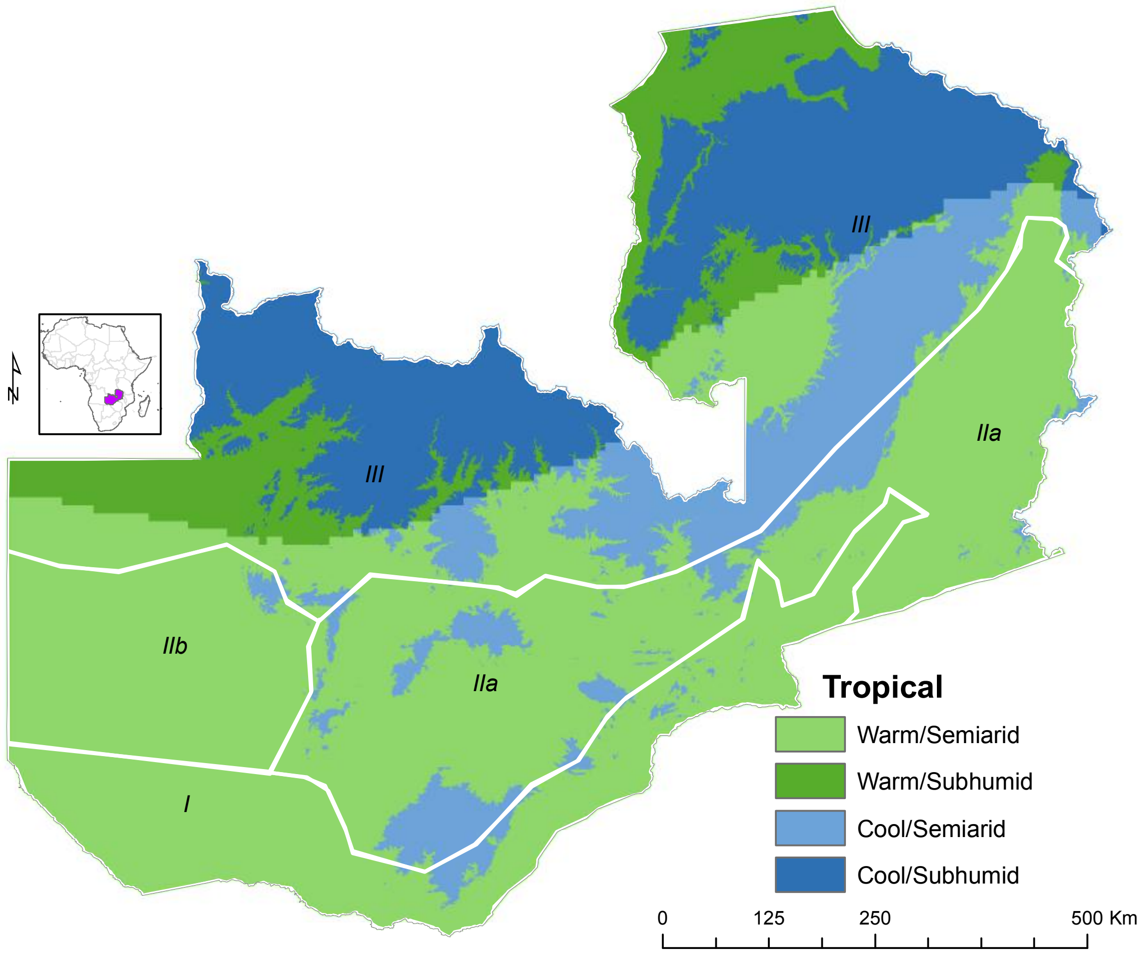


Figure 16.1: Agro-ecological regions of Zambia.

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

Zambia has the November to April rainy season, the cool dry season of May to August and the hot dry season of August to November. The annual rainfall decreases from an average of 1000 mm in the northern part of the country to an average of 800 mm in the southern part. The annual temperature ranges between 18°C to 20°C. The highest annual average temperature is 32°C and the lowest temperature average is 4°C.

Region I is the low rainfall region of Zambia (Table 16.1). It covers major valleys of Gwembe, Lunsemfwa and Luangwa in the south and south-eastern margin of the country, and is about 23% of Zambia's total land area. Mean annual rainfall is less than 800 mm, erratic and often of high intensity. Long dry spells during the rainy season limit crop and livestock production. The length of the cropping season ranges between 60-90 days. The dominant soils in the valley areas are slightly acid to alkaline and generally have higher levels of fertility than soils of plateau areas. Soil acidity is a dominant constraint to crop production.

Region II is commonly classified as the medium rainfall region of Zambia (Table 16.1). It forms a central band stretching from western to eastern Zambia. The region is characterized by a mean annual rainfall of between 800 to 1000 mm and has a cropping season of 90-150 days. The dominant soils are sandy, acidic and have low nutrient reserves and poor water retention capacity. These soils are prone to leaching of nutrients after heavy rainfall and to water stress during dry spells because of their limited ability to retain nutrients and water. Region II is divided into sub-regions IIa and IIb. The combination of moderately fertile soil with medium rainfall and a moderately long growing season makes sub-region IIa the most productive region of the country for most arable crops particularly maize, wheat, soybean, groundnut and tobacco. Sub-region IIb comprises the Kalahari sand plateau and Zambezi flood plains in Western Province and other parts of Region II not covered by Kalahari sands. The area of Region II is approximately 27.4 million hectares. The dominant soils include sandveld soils which are moderately leached, medium to strongly acid with sandy top soils overlying loamy subsoil. They also include some moderately weathered, moderate to slightly acidic red to strong brown soils derived from limestone. In low lying areas or flood plains, there may be slightly acidic to neutral heavy dark cracking clays.

Table 16.1: Mean monthly rainfall (mm) and maximum and minimum temperature (°C; Tmax; Tmin) for representative locations of AEZ of Zambia (http://en.climate-data.org)

	J	F	M	A	M	J	J	A	S	O	N	D
Region I (Choma)												
Rainfall	203	161	85	28	7	1	0	0	1	23	93	198
Tmax	26.9	26.8	26.8	26.4	24.8	22.4	22.9	25.4	29.2	30.9	29.4	27.2
Tmin	16.7	16.4	15.2	12.1	7.8	4.7	4.8	6.5	10.7	14.3	16.2	16.6
Region IIa (Lusaka)												
Rainfall	231	191	147	18	0	0	0	0	0	10	91	150
Tmax	26	26	26	26	25	23	23	25	29	31	29	27
Tmin	17	17	17	15	12	10	9	12	15	18	18	17
Region IIb (Mongu)												
Rainfall	213	190	145	43	5	0	0	1	3	35	106	198
Tmax	29.3	29.3	29.4	30.3	29.1	27.0	27.2	30.4	34.4	35.3	32.2	29.5
Tmin	18.8	19.0	18.6	16.7	12.9	9.9	9.5	12.0	16.0	18.4	18.4	18.3
Region III (Kasama)												
Rainfall	281	232	235	89	12	0	0	0	3	21	150	274
Tmax	26.0	26.0	26.0	26.2	25.5	24.5	24.6	26.7	29.3	31.0	28.6	26.5
Tmin	16.1	16.2	16.1	15.2	12.5	10.0	9.5	11.0	13.7	16.0	16.5	16.2

Region III is the high rainfall region in the northern part of the country and has a rain-fed crop growing season of 140-200 days. Soils are highly weathered and highly leached, acidic, depleted of nutrients and of low productivity compared with the soils of Regions I and II.

16.3 Current soil fertility management

Farmers have traditional practices for soil and water management. Conservation basins are used to harvest water in Regions I and IIa. Shifting of livestock pens is an indigenous practice of confining a herd of cattle on a small piece of land at night for three to four days and then moving to enrich the soil with excreted urine and faeces. Farmers address acid soils in Region III with the slash and burn practice known locally as chitemene. These practices are insufficient to maintain productivity under intensive cropping and need to be integrated with other practices (Bekunda et al., 2010). Such practices may include conservation tillage, crop rotation with legumes, improved soil cover with mulch, cover crops and crop residues, application of manure and other organic material, and fertilizer use.

Two limitations of using organic materials as nutrient sources are that nutrient release is often out of synchrony with crop demand and nutrient contents are commonly very low. Agro-forestry such as tree fallows may be an acceptable practice for breaking hard pans, fixing nitrogen and capturing and recycling leached nutrients. Integrating organic resources with fertilizer use is often the best option for enhancing soil nutrient availability. Use of biochar is of interest to some on acid soils with low cation exchange capacity (CEC) as it is a carbon form that persists in the soil and adds to CEC and water-holding capacity. Use of lime is important to productivity of acid soils in Region III. Use of wood ash to amend acid soils is a common traditional farming practice but the available quantity is small outside of areas of slash and burn.

Fertilizer is an expensive input and efficient use is important for good profitability and to reduce nutrients lost to the environment and soil acidification due to nitrogen application. The negative effects of nutrient application are reduced through efficient fertilizer use and the practice of the 4Rs of Nutrient Stewardship, that is, to apply the right product at the right rate, at the right time and using the right method, especially for N fertilizers as N is easily lost. Much of the fertilizer N should be applied shortly before or during periods of rapid vegetative growth of crops, approximately six weeks after planting maize. The farmer is the final decision-maker in determining practices suited to local soil, weather, cropping system and social economic conditions but the 4Rs of fertilizer use are a good framework for making decisions.

Efficient fertilizer use requires a healthy and well managed crop. Minimizing potential yield-limiting situations allows for maximum response to applied fertilizer. Use of recommended and adopted varieties, cultural practices and pest control helps maximize fertilizer response. Also important to profitable and efficient fertilizer use may be consideration of soil test information and the effects of other practices such as manure application and use of lime or wood ash to reduce soil acidity.

16.4 Fertilizer use optimization

Normally farmers wish to maximize profit from fertilizer use. This may be to maximize net returns per hectare resulting from fertilizer use. In the case of financially constrained fertilizer use, profit maximizing means to achieve high returns on their small investment. Investment in fertilizer competes with other uses of financial resources by the financially constrained. In order to meet immediate livelihood needs, fertilizer investments must give high returns with little risk. Therefore, fertilizer use optimization refers to maximizing profit from fertilizer use according to the farmer's agronomic and economic situation.

The nature of crop response to applied nutrients, over a large number of trials, is usually curvilinear and reaching a plateau, as illustrated by the typical cowpea response to applied P in Zambia (Figure 16.2). With the first 5 kg/ha of elemental P, or 11 kg of phosphate, applied there is a very good yield increase. The yield increase continues up to 10 kg/ha (22 kg/ha of phosphate.) Yield increases past 10 kg/ha is very low and probably not enough to pay for the cost of applying additional P. Therefore, the potential for profit per unit of investment is greatest at low input rates.

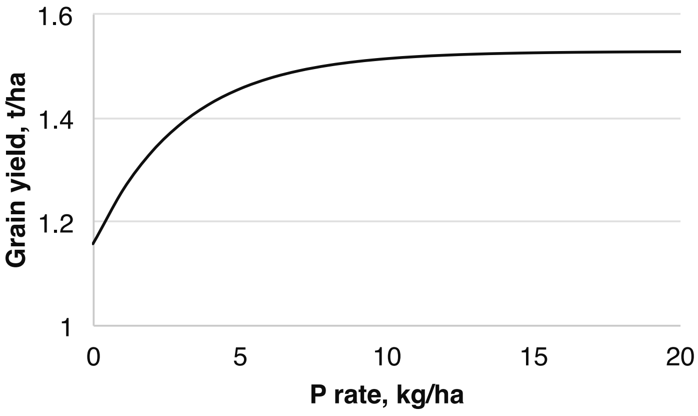


Figure 16.2: Response curve of cowpea for P application.

There are several mathematical formulas that are used to model fertilizer response. Creating an equation to represent crop response to a fertilizer input allows economic analysis to determine the return on an investment over a range of prices and costs. In this case the curvilinear to plateau yield response to applied nutrient is represented by the equation $Y = a - bc^r$ where Y is yield, a is yield at the plateau, b is the yield increase due to application of the concerned nutrient, c is a determinant of the shape of the response curve, and r is the nutrient application rate. Crop nutrient response equations were determined for maize, cowpea and soybean in all three regions. In addition, sorghum was addressed in Regions I and III, bean in Regions II and III, and groundnut in Region I.

Another important aspect of achieving high profit from fertilizer use for financially constrained farmers is the need to know the return of a kwacha invested over a range of nutrients applied to a range of crops. In other words, which nutrients applied to which crops bring the most return for the amount available to invest?

An example of the data needed to make these decisions is shown in Figure 16.3. In this graph from Region III, the x-axis (horizontal axis) is Zambia kwacha (ZMK), net returns are on the y-axis. Each line represents the profit potential of a nutrient applied to a crop. When the slope of the curve is steep, it shows that the net returns per ZMK 100 invested per hectare are very high. As the amount invested (the x-axis) in a crop-nutrient increases, the slope decreases but if still upward then the profit is increasing. Where a curve peaks is its point of maximum profit per hectare. The greatest rate of return

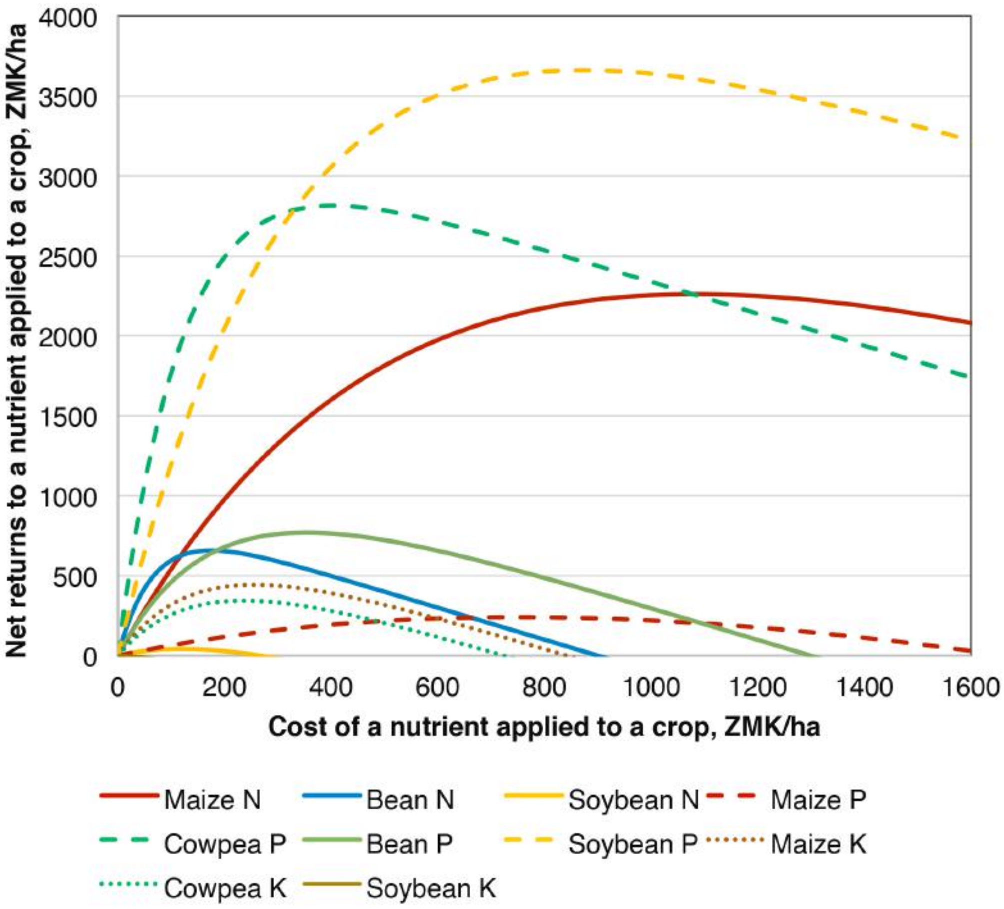


Figure 16.3: Nutrient returns to investment in nutrient application in Region III of Zambia.

per kwacha invested is achieved with K applied to cowpea, followed by similar profitability with bean N and cowpea P. When slopes decline, total profit is declining. However, only a small amount of applied nutrient is needed with these options before the profit potential peaks. Application of N to maize is more profitable compared with the lower lying curves until about ZMK 800 worth of N is applied at which point P applied to maize at low rates is of similar profit potential. Applications of P to bean and soybean have modest profit potential at low rates of application. An example application of the information in Figure 16.3 is that in this case, the farmer who has ZMK 1000 for fertilizer and one hectare for each crop would near optimization by applying: ZMK 200 each of P and K to cowpea; ZMK 200 of N to bean; and ZMK 400 of N to maize.

16.5 Fertilizer optimization tools for Zambia

Decisions on choices of amount of each fertilizer to apply to each crop are very complex if the intent is to maximize potential for profit and if the farmer prefers to have several different crops. The nature of the response of each crop to each applied nutrient needs to be considered, but also the farmer's land allocation to different crops, the expected value of the grain on-farm near harvest time considering the value of the grain kept for home consumption and that to be marketed, the costs of fertilizer use and the money that the farmer has available for fertilizer use. Therefore, easy to use fertilizer optimization tools (FOTs) have been developed which use complex mathematics of linear programming to integrate economic and agronomic information (http://agronomy.unl.edu/OFRA).

The FOTs work in Excel Solver© (Frontline Systems Inc., Incline Village, NV, USA). Use of the FOT requires that the add-in Solver be activated and that macros are enabled; this is addressed in the 'Help and Instructions' worksheet of the FOT and in more detail in an FOT user manual in Extension Training Materials at http://agronomy.unl.edu/OFRA.

The data input screen (Figure 16.4) requires entry of the land area to be planted to each crop and the estimated on-farm value per kilogram of grain near harvest time. The cost of using different fertilizers and the available money of the farmer for fertilizer use are also entered. The optimize button is left-clicked to run the optimization. The output includes: the amount of fertilizer to apply to each crop; the expected average yield increases and net returns to fertilizer use per hectare; and the total net returns to fertilizer use for the farm (Figure 16.5).

For each Excel FOT, there is a companion paper FOT to be used when a computer is not available (Table 16.2). The paper FOT has three financial levels as follows: Level 1 for the poor farmer who has no more money than one-third of the required amount to buy the fertilizer to apply to all the cropland at the rates to maximize profit per hectare, also referred to as the economically optimal rate (EOR); level 2 for the farmer who has no more than two-thirds of the money to apply fertilizer to all cropland at EOR; and level 3 for the farmer with enough money to apply fertilizer to some cropland at EOR. The paper FOT begins by stating assumptions: the volume of measuring units to be used by farmers in adjusting their eyes and feel for applying the right rate of fertilizer; inter- and intra-row spacing of plants; the costs of fertilizer use per 50 kg bag; and the expected commodity values on-farm at harvest, considering the value of both home consumption and for market.

The paper FOT advises on the fertilizer to use and the application rate for each crop according to the farmer's financial level but also includes the method and time of application, thereby advising on the 4Rs of fertilizer use. It also advises on calibration to help the farmer to adjust his/her eyes and feel to the rate of application, that is a water bottle lid full of fertilizer is sufficient for so many metres of band application or so many plants.

In using the paper FOT for Region II (Table 16.2), first consider the farmer's financial ability for fertilizer use. If the farmer has little money, begin with financial level 1 which has options for three crops. For example, one recommendation is 'For maize, point dress 45 kg/ha urea 6 WAP (1 CAP for 5 plants)'; therefore 45 kg/ha urea is to be applied at least 5 cm from the maize plants at 6 weeks after planting with one water bottle lid sufficient for 5 plants. If the farmer has money in excess of

Zone 2

Producer Name:	xxx
Prepared By:	xxx
Date Prepared:	**July 23, 2016**

Crop Selection and Prices		
Crop	**Area Planted (Ha)***	**Expected Grain Value/kg †**
Maize	3	1.5
Cowpea	0.25	9
Bean	0.5	13
Soybean	0.5	8
Total	**4.25**	

Fertilizer Selection and Prices					
Fertilizer Product	**N**	**P2O5**	**K2O**	**xx**	**Costs/50 kg bag ¶***
Urea	46%	0%	0%	0%	350
Triple super phosphate, TSP	0%	46%	0%	0%	0
NPK	10%	20%	10%	0%	400
Blank	0%	0%	0%	0%	0
	0%	0%	0%	0%	0

Budget Constraint	
Amount available to invest in fertilizer	1250

Figure 16.4: The input sheet for the Excel Solver Fertilizer Optimization Tool.

Fertilizer Optimization					
	Application Rate - kg/Ha				
Crop	**Urea**	**TSP**	**NPK**		
Maize	36	0	0	0	0
Cowpea	0	0	44	0	0
Bean	35	0	0	0	0
Soybean	0	0	69	0	0
	0	0	0	0	0
	0	0	0	0	0
	0	0	0	0	0
Total fertilizer needed	126	0	46	0	0

Expected Average Effects per Ha		
Crop	**Yield Increases**	**Net Returns**
Maize	673	756
Cowpea	266	2,040
Bean	266	3,213
Soybean	368	2,392
	0	0
	0	0
	0	0

Total Expected Net Returns to Fertilizer	
Total net returns to investment in fertilizer	5,579

Figure 16.5: The output sheet for the Excel Solver Fertilizer Optimization Tool.

Table 16.2: Fertilizer use optimizer paper

Zambia Fertilizer Use Optimizer: Region II.
Prepared Davy Nkonde
April 2016

The below assumes:
Calibration measurement is with a water bottle lid (CAP); contains 8 ml, 5.6 g urea, 8 g NPK.
Row spacing: maize at 75 x 30 cm; cowpea at 60 x 15 cm; bean at 60 x 15 cm.
Grain prices per kg (ZMK): 2 maize; 8 cowpea; and 13 bean.
50 kg of fertilize use costs (ZMK): 350 urea; 400 NPK.
Application rates are in kg/ha.

Level 1 financial ability.	
Maize	Point dress 45 kg/ha urea 6 wap (1 cap for 5 points)
Bean	Band dress 52 kg/ha npk applied at planting (1 cap for 3 m)
Cowpea	Band dress 46 kg/ha npk applied at planting (1 cap for 3 m)
Level 2 financial ability.	
Maize	Point dress 97 kg/ha urea 6 wap (1 cap for 2.5 points)
Bean	Band dress 85 kg/ha npk applied at planting (1 cap for 2 m)
Cowpea	Band dress 61kg/ha npk applied at planting (1 cap for 2 m)
Level 3 financial ability (maximize profit per acre).	
Maize	Point dress 147 kg/ha urea 6 wap (1 cap for 1.5 points)
Bean	Band dress 117 kg/ha npk applied at planting (1 cap for 1 m)
Cowpea	Band dress 76 kg/ha npk applied at planting (1 cap for 2 m)

the level 1 options, level 2 options should be considered. Fertilizer use options within levels have similar profit potential.

16.6 Fertilizer use in an integrated nutrient management framework

Fertilizer use decisions need to consider the effects of other practices that supply soil nutrients as well as soil test information (Table 16.3). The use of green manure and the application of manure calls for adjustment of fertilizer rates to be applied. The fertilizer substitution value varies with the quality of manure. Poultry and dairy manure are expected to have greater fertilizer substitution value than farmyard manure. Other practices with fertilizer substitution value include bringing material such as tree prunings into the field, rotations and intercropping. Soil test information should be considered. When soil test information is not available, soil test P should be considered low and fertilizer P applied according to the FOT recommendations. If soil test K is found to be very low, apply K even if not recommended by the FOT. As an example, 'For each 1 t of fresh leguminous leafy tree prunings applied (e.g, Gliricidia, Leucaena, Sesbania, Senna)', the urea, TSP or DAP, or NPK rate can be reduced from the FOT recommendation for the field by 10, 1 and 6 kg/ha, respectively. The prunings may be from alleys within the field, field boundary areas, or nearby treelots.

16.7 Crops addressed by region for optimized fertilizer use

The crops and nutrients addressed by Optimising Fertilizer Recommendations in Africa (OFRA) research in 2013-15 are given in column 1-2 of the three parts of Table 16.4. The response coefficients a, b, and c for the above defined equation $Y = a - bc^r$ are reported in columns 3-5. The effects on changes in nutrient rates on yield increases are reported in columns 6-9. The elemental nutrient application rates at EOR and as currently recommended in Zambia (REC) are given in columns 10-11.

Maize and sorghum had >1100 and >400 kg/ha, respectively, responses to applied N in Region I but the sorghum response was not economical (Table 16.4a). Groundnut had a sufficient response to N to justify a low rate of application

Table 16.3: Fertilizer use in an ISFM framework: fertilizer substitution and soil test implications

ISFM practice	Urea	DAP or TSP	NPK 10-20-10+6S
	Fertilizer reduction, % or kg/ha		
Previous crop was a green legume manure crop (Mucuna, Crotalaria and Lablab)	100%	8 kg	28 kg
Early incorporation of a green legume manure (Mucuna, Crotalaria and Lablab) crop	57 kg	3 kg	11 kg
For each 1 t of fresh leguminous leafy tree prunings applied (e.g. Gliricidia, Leucaena, Sesbania, Senna)	10 kg	1 kg	6 kg
Farmyard manure per 1 t of dry material	2 kg	1 kg	1 kg
Residual value of FYM applied for the previous crop, per 1 t	1 kg	0.4 kg	0.4 kg
Dairy or poultry manure, per 1 t dry material	24 kg	7 kg	14 kg
Residual value of dairy and poultry manure applied for the previous crop, per 1 t	5 kg	1.4 kg	3 kg
Compost, per 1 t/ha dry wt	20 kg	1 kg	20 kg
Doubled-up legume-technology (pigeonpea)	In the second year of rotation a mean reduction of over 50 kg urea		
Cereal-bean intercropping	Increase DAP/TSP by 18 kg/ha, but no change in N and K compared with sole cereal fertilizer		
Cereal-other legume (effective in N fixation) intercropping	Increase DAP/TSP by 20 kg/kg, reduce urea by 30 kg/ha, and no change in K compared with sole cereal fertilizer		
If Mehlich III P >18 ppm	Do not apply P		
If soil test K < 0.25 cmol/kg	Apply 20 kg/ha KCl		

at planting or shortly after emergence. All crops responded to P application but the response was not economical for sorghum. Maize and groundnut responded to K application. With the exception of P applied to groundnut, EOR was always less than REC for Region I indicating that those with the financial ability to apply according to the recommendations are over-applying and losing profit potential.

Maize and bean had an economic response to N in Region II and all crops considered had a profitable response to some level of P (Table 16.4b). Only cowpea had an economical response to K because of the high value given to the grain. The EOR were always less than REC except for P application to maize.

Yield increases with nutrient application in Region III were greater than in other regions. Maize and sorghum had economic responses to N and all crops had economic responses to P. Maize responded to applied K. As in other regions, EOR were low compared with REC but the maize P and K rates were similar.

The RECs in Zambia are high compared with the EOR determined from field research in 28 of 31 comparisons. Across all crop nutrient recommendations, the RECs were on average 112% more than the EOR. Farmers who apply at REC are therefore over-applying fertilizer and missing much profit opportunity as compared to using rates nearer to EOR. Financially constrained farmers need to apply rates of less than EOR and as determined by use of the FOT.

Another concern that arises from analyses and interpretation of research information is associated with the very limited availability of fertilizer types in Zambia. Urea is the only single nutrient fertilizer that is regularly available to farmers. All other nutrient needs must be met using the NPK blend of 10-20-10. The restricted availability of fertilizer types is based on the assumption that a nationally determined

Table 16.4a: Region I: Response functions, expected yield increases (t/ha) for crop-nutrients, and OFRA economically optimal rate (EOR) to maximize profit per hectare compared to current or recent (REC) recommendations. P_2O_5 = P x 2.29; K_2O = K x 1.2. Some functions have zero response or insufficient information to determine EOR.

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effects of elemental nutrient rate (kg/ha) changes on grain yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			**t/ha**				**kg/ha**	
Maize	N	2.130	1.192	0.974	0.651	0.295	0.134	0.061	43	112
Sorghum	N	2.828	0.473	0.977	0.238	0.118	0.059	0.029	0	66
Groundnut	N	1.260	0.075	0.800	0.075	0.000	0.000	0.000	10	15
Cowpeas	N	1.465	0.154	0.835	0.154	0.001	0.000	0.000	0	30
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	4.133	0.532	0.858	0.285	0.133	0.062	0.029	6	17
Soybean	P	1.407	0.250	0.916	0.089	0.057	0.037	0.024	11	34
Sorghum	P	2.774	0.408	0.865	0.211	0.102	0.049	0.024	6	17
Groundnut	P	1.337	0.273	0.898	0.116	0.067	0.038	0.022	16	13
Cowpea	P	0.720	0.084	0.900	0.034	0.020	0.012	0.007	16	26
Maize	K	3.539	0.455	0.900	0.186	0.110	0.065	0.038	14	17
Groundnut	K	1.260	0.075	0.800	0.050	0.017	0.005	0.002	10	13

† EOR was determined with the cost of using 50 kg urea and NPK at ZMK 350 and 400, respectively. Commodity values (ZMK/kg) used were: maize 1.5; sorghum 1.5; cowpea 9.0; groundnut 8.0; soybean 8.0; and bean 13.

Table 16.4b: Region II.

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effects of elemental nutrient rate (kg/ha) changes on grain yield				Recommended nutrient rate	
Crop	**Nutrient**	**a**	**b**	**c**	**0-30**	**30-60**	**60-90**	**90-120**	**EOR†**	**REC**
		t/ha			**t/ha**				**kg/ha**	
Maize	N	4.906	2.572	0.982	1.080	0.626	0.363	0.211	84	112
Bean	N	0.838	0.293	0.862	0.289	0.003	0.000	0.000	23	30
Soybean	N	1.131	0.046	0.929	0.041	0.004	0.000	0.000	0	-
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.853	1.794	0.972	0.238	0.206	0.179	0.155	23	17
Cowpea	P	1.529	0.371	0.720	0.299	0.058	0.011	0.002	10	26
Bean	P	0.884	0.058	0.869	0.029	0.015	0.007	0.004	7	26
Soybean	P	1.359	0.608	0.868	0.309	0.152	0.075	0.037	8	34
Maize	K	4.084	0.097	0.900	0.040	0.024	0.014	0.008	0	17
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	15	25
Soybean	K	1.402	0.508	0.781	0.360	0.105	0.030	0.009	0	-

blend is better for farmers than allowing them to apply fertilizers according to their perceived needs. All crops in all regions responded to P but to apply P, farmers need to use their scarce financial ability to pay for the N and K in the NPK blend. However, only 6 of the 14 crop by region considerations had an economic response to some applied N and 5 of 14 had an economic response to K. In addition, blends are more costly to supply than the basic fertilizers from which blends are produced. These factors add to real costs of applying nutrients which give

Table 16.4c: Region III.

		Response coefficients, Yield = a – bc^r; r = elemental nutrient rate, kg/ha			Effects of elemental nutrient rate (kg/ha) changes on grain yield				Recommended nutrient rate	
Crop	Nutrient	a	b	c	0-30	30-60	60-90	90-120	EOR†	REC
		t/ha			t/ha				kg/ha	
Maize	N	5.100	2.600	0.973	1.446	0.636	0.280	0.123	71	112
Bean	N	0.429	0.100	0.798	0.100	0.000	0.000	0.000	0	30
Sorghum	N	4.071	0.730	0.964	0.487	0.162	0.054	0.018	23	66
					0-5	**5-10**	**10-15**	**15-20**		
Maize	P	2.900	1.600	0.972	0.215	0.187	0.162	0.141	18	17
Cowpea	P	1.529	0.371	0.720	0.299	0.058	0.011	0.002	10	26
Bean	P	0.429	0.100	0.798	0.068	0.022	0.007	0.002	9	26
Sorghum	P	4.047	0.651	0.856	0.352	0.162	0.074	0.034	10	17
Soybean	P	1.457	0.607	0.883	0.281	0.151	0.081	0.043	22	34
Maize	K	4.863	0.563	0.896	0.238	0.137	0.079	0.046	16	17
Cowpea	K	1.563	0.081	0.898	0.034	0.020	0.011	0.007	15	25
Soybean	K	0.837	0.019	0.908	0.007	0.005	0.003	0.002	0	-

profitable returns. The implication is especially great for the finance constrained farmer as the added cost is a lost opportunity of investing in the nutrients with potential to give high rates of return.

16.8 Acknowledgements

The OFRA project was funded by the Alliance for a Green Revolution in Africa with CABI management. The authors wish to express gratitude to the OFRA team for all the logistical arrangements made toward development of this fertilizer recommendation book chapter. We are also grateful to OFRA resource personnel, among them Professor Charles Wortmann of the University of Nebraska-Lincoln and Dr KC Kaizzi of the National Agricultural Research Organization of Uganda.

16.9 Reference

Bekunda M, Sanginga N and Woomer PL (2010) Restoring soil fertility in Sub-Sahara Africa. Advan Agron 108:183-236

17. Enabling Fertilizer Use Optimization in Sub-Saharan Africa

Harrison Rware h.rware@cabi.org[1], Kayuki C. Kaizzi[2], Catherine J. Senkoro[3], Wondimu Bayu[1], George Oduor[1] and James Watiti[1]

[1]*CABI, P.O. Box 633-00621, Nairobi, Kenya*
[2]*National Agricultural Research Laboratories, P.O. Box 7065, Kampala, Uganda*
[3]*Mlingano Agricultural Research Institute, P.O. Box 5088, Tanga, Tanzania*

17.1 Introduction

Low soil fertility in sub-Saharan Africa (SSA) is associated with low crop productivity. Most small-scale farmers in SSA apply little or no fertilizers to their crops due to financial constraints and other socio-economic factors. Many use manure, compost and crop residue as nutrient sources but the supply is generally small relative to need and these materials often have alternative uses such as for fodder, thatch and fuel. The farmer's major dilemma on fertilizer use has always been poverty and low ability for fertilizer purchase. After taking care of their basic survival needs, they need high benefit to cost ratios at little risk for investments to be competitive.

The Optimising Fertilizer Recommendations in Africa (OFRA) project developed a fertilizer use optimization approach that enables farmers to maximize net returns from their investment in fertilizer use while reducing risks compared with conventional fertilizer recommendations (Chapter 1). The approach considers crop nutrient response functions determined from field research together with the economic and agronomic context of the farmer. It guides the farmer to the choice of the crop-nutrient-rate combinations with the greatest profit potential for the farmer's situation. It reduces risk for the financially constrained farmer by applying fertilizer at lower rates and often to more crops than with typical fertilizer recommendations. This combined with the 4R Nutrient Stewardship (http://soilhealthconsortia.org/files/Newsletter%203rd%20edition.pdf) contributes to nutrient use efficiency and low nutrient loss. Fertilizer use optimization has been developed for 67 agro-ecological zones (AEZ) or recommendation domains of 13 countries including Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Rwanda, Tanzania, Uganda and Zambia. For each of these AEZs, Excel and paper fertilizer optimization tools (FOT) were developed (http://agronomy.unl.edu/OFRA).

This chapter discusses the methodology used by OFRA to transfer the fertilizer use optimization approach to technology uptake pathways and the lessons drawn from this process. We discuss how farmer demand for fertilizer use optimization was generated, how stakeholders were engaged, how farmer advisors were trained and how the advisors worked to enable optimization of fertilizer use by farmers.

17.2 Enabling fertilizer use optimization by farmers

Fertilizer use optimization is an innovative approach for enabling financially constrained farmers to optimize profit from limited investment in fertilizer and thus enable them to increase fertilizer use and improve their income. The greatly improved profit opportunity is expected to result in increased fertilizer use by smallholders and thereby increase productivity, income and food security, and for many, break out of the cycle of poverty. Fertilizer use optimization is also relevant to farmers with adequate finance for fertilizer use who wish to maximize profit from fertilizer use.

Enabling fertilizer use optimization requires application of much research-derived information through OFRA decision tools enabling choice of fertilizer use options with the greatest profit potential for the farmer's situation.

Country-specific stakeholder engagement plans were developed so as to effectively take fertilizer use optimization to technology uptake pathways and finally to farmers. A country OFRA team guides this enablement (Figure 17.1). Some of the immediate enabling activities were: creating farmers' awareness and demand so

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

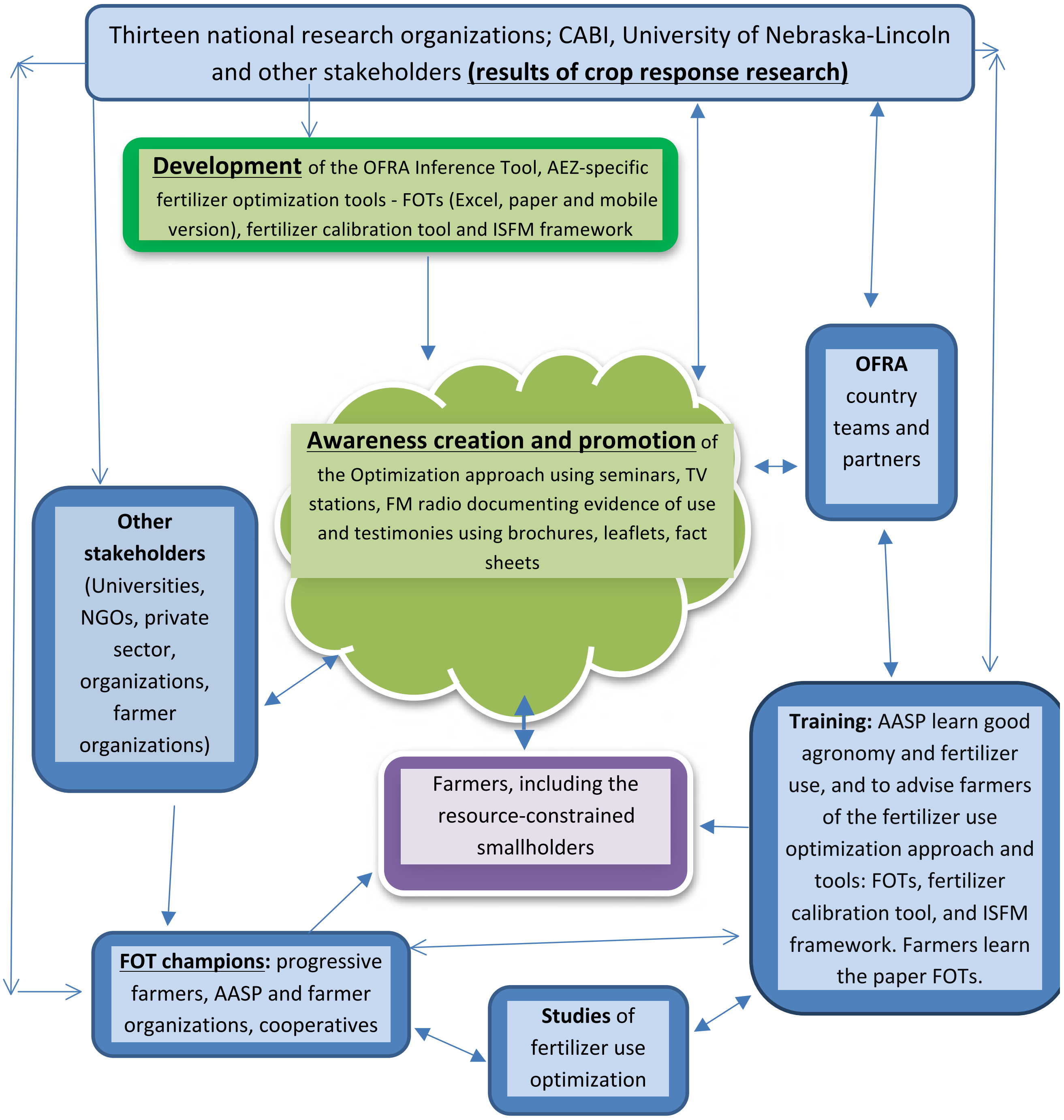


Figure 17.1: A framework for promotion and enabling of fertilizer use optimization.

that farmers request their advisors' help or seek to learn to optimize on their own and thereby drive rapid adoption; creating broad stakeholder support and securing adequate human and financial resources; and training farmer advisors, including government and non-government extension workers and fertilizer retail staff.

Effective delivery of a practice or approach to farmers requires that they become aware, interested and convinced of the benefit opportunity so that the adoption process becomes demand driven. Awareness of fertilizer use optimization aimed at farmers and other stakeholders is through diverse means including mass media. Once interest and farmer demand is created, farmers are likely to look to their advisors for assistance to apply fertilizer use optimization.

Other stakeholders important to successful adoption of fertilizer use optimization include researchers, extension workers, agro-dealers, farmer cooperatives, CGIAR centres,

Table 17.1: Stakeholders for fertilizer use optimization

Stakeholder	Geographical coverage	Major Roles/Mandate
CABI	International	Communications, research†, data management, extension, coordination
University of Nebraska-Lincoln	International	Training, research, geospatial analysis, science development, scientific reporting
Universities	National/regional	Training, research, education
IFDC, CGIAR, IPNI, AGRA	International	Funding, research, further development of the approach, improvement of the FOTs
NARS	National	Research, training, extension
African research associations	Regional	Research, further development of the approach, improvement of the FOTs
AFSIS	Regional	Research and geospatial analysis
Government	National	Policy, extension, resource mobilization
Private sector	National/regional	Extension, enterprise development, credit facilities
Farmer organizations	National/regional	Extension, credit facilities, resource mobilization, training farmers
NGOs	National and international	Adaptive research, extension and training

† Research throughout refers to research for further improvement of fertilizer use optimization for strengthening response functions, adding more important crops, and adding more nutrients including micro- and secondary nutrients.

universities, NGOs and policy makers (Table 17.1). Equally important to facilitation of adoption is that stakeholders do not stymie dissemination of fertilizer use optimization. Extension workers and other farmer advisors are especially important and necessary to achieve adoption of fertilizer use optimization and therefore need to fully understand and own the approach and tools (http://agronomy.unl.edu/OFRA).

Training to prepare extension and other farmer advisors to apply the fertilizer use optimization approach and use the OFRA tools is a major task requiring many human and financial resources. The stakeholders who control such resources need to be convinced of the priority of fertilizer use optimization (Figure 17.1). Many farmers are capable of learning to use the paper version of the Fertilizer Optimizer Tool but need some initial training. Technical support, such as by subject matter specialist at district levels, is needed to assist and monitor farmer advisors. On-going study of farmer adoption is expected to review additional lessons for more efficient on-going and future roll-out.

17.3 Creating demand for fertilizer use optimization

Farmer and other stakeholder demand for fertilizer use optimization has been achieved through communication of success stories and lessons from Uganda where promotion of the optimization approach began in 2012. OFRA partnered with the BMGF-funded African Soil Health Consortium (ASHC) to prepare for communicating the benefits of fertilizer use optimization (http://africasoilhealth.cabi.org/tools/fertilizer-tools/fertilizer-optimisation-tools/). Country-specific flyers were developed for use by the countries in creating awareness of fertilizer use optimization with researchers, extension workers, agro-dealers and farmers' organizations. Furthermore, different forums and media were used to create awareness including radio (Radio Africa in Tanzania), print media (Seeds of Gold in Kenya and Uganda newspapers), TV, video documentaries, national and international seminars, country soil health consortia (CSHC) forums, and regional and international conferences. Four articles were developed from studies conducted in Uganda to understand the challenges and opportunities for farmer adoption and distributed to 500 stakeholders in other countries to guide their planning for enablement of fertilizer use optimization.

Farmers who have seen the benefit of fertilizer use optimization in Uganda work with their advisors in fertilizer use decisions. Fertilizer use optimization has been presented to research stakeholders through numerous international conferences and journal publications (e.g. Jansen et al., 2013; Kaizzi et al., 2013), this 17-chapter book and other journal articles are in preparation. The promotion of fertilizer use optimization through the media and other channels is expected to generate demand from scientists and other stakeholders to learn more about the approach and adapt it to suit farmer interests.

17.4 Training farmer advisors on fertilizer use optimization

Government and non-government extension staff and fertilizer-supplying agro-dealers are typically important sources of information for farmers concerning fertilizer use. In Uganda, the fertilizer optimization approach was deployed by training researchers of the National Agricultural Research Organization (NARO), extension staff of the National Agricultural Advisory Services (NAADS) and other farmer advisors on the principles of fertilizer use optimization and in the use of FOTs (FOT; http://agronomy.unl.edu/OFRA). During the 2-day training events, conceptual/informational sessions covered soil and crop management and use of organic materials and fertilizers. Trainees had hands-on experience with the FOTs and associated tools. Nine agro-ecological zones were targeted.

Over 1000 farmer advisors were trained in Uganda, Kenya and Tanzania. Using lessons from Uganda, the approach was popularized in Kenya and Tanzania through mass media and seminars. In Kenya, a training event was held at KALRO headquarters for farmer advisors, agro-dealers, farmers and researchers. In Tanzania, events have been held at Sokoine University of Agriculture and Selian Agriculture Research Institute.

Extension training materials include English and French versions of three Microsoft PowerPoint presentations, a manual for fertilizer use optimization and practical exercises (http://agronomy.unl.edu/OFRA).

The trainees learn a 3-step process to aiding farmers in deciding on fertilizer use. First, they practically learned to use the Excel and/or paper versions of the FOT for generating fertilizer recommendations specific to the farmer's context. They then learned to use a fertilizer calibration tool and to advise farmers on how to achieve the correct rates of fertilizer application. The third step was to adjust the recommended fertilizer rates in consideration of soil test information and other soil fertility management practices, e.g. use of crop rotation, use of organic materials such as farmyard manure and intercropping. These fertilizer rate adjustments were made using a fertilizer substitution table that accompanies the FOT (see Chapters 4-16).

17.5 Lessons learned

At the time of writing (May 2016), FOTs have been developed for 67 recommendation domains across the 13 OFRA countries. Most countries are in the early stages of enabling fertilizer use optimization with farmers and their advisors. Therefore, the following lessons were drawn mostly from reflection on experiences from Uganda where enablement of fertilizer use optimization by farmers began in 2012.

- Given the diversity of the stakeholders involved in enabling fertilizer use optimization, communication support was critical to ensure that harmonized messages were passed to the diverse stakeholders. Information materials needed to be packaged for different audiences such as researchers, farmer advisors including fertilizer retail dealers, fertilizer manufacturers, policy makers and farmers. Experience in Uganda showed that farmer advisors needed training on integrated soil fertility management, including fertilizer use, to support the delivery and use of fertilizer use optimization. Policy makers also required information to support adoption and scale-up of fertilizer use optimization within their national frameworks.
- Having paper FOT versions was essential for advisors and farmers to optimize fertilizer use when a computer was not available.
- Essential to fertilizer use optimization was good agronomy and fertilizer use practices including the 4Rs of fertilizer use (right source at the right rate, right time and right method of application). Other yield limiting factors typically

reduce crop response to fertilizer application and fertilizer use can be ineffective in situations where another constraint such as soil water deficit is too severe. These points needed to be addressed in training advisors and in their advising farmers on integrated soil fertility management.

- Follow-up with trainees to determine how they were delivering the FOT and the effectiveness of the methodology used was essential. There was a need to establish the extent of use of the FOT by the different stakeholders.
- Technical advisory support and backup was needed for farmer advisors assisting with fertilizer use optimization.
- Migrating the FOT to a Mobile App was also important for FOT access on their mobile phone. This worked briefly in Uganda but should be exploited further in future.
- Assisting more capable farmers to learn to use paper FOTs on their own is very important.
- In enabling farmers to use fertilizer use optimization, extension workers and other advisors might use complementary activities such as farme-led demonstrations, farmer field schools and farmer-to-farmer extension to inform farmers.
- The FOTs can be used to demonstrate the profit potential of good choices in fertilizer use to micro-finance and other agricultural lending institutions to convince them to improve credit access and terms for fertilizer use by smallholders. Also, actors in the fertilizer supply chain can use the FOTs to assess profit potential for fertilizer use with different crops in an AEZ and ensure supply of fertilizers with the most profit potential. It is expected that as farmers learn which fertilizers have greater profit potential, demand for these fertilizers will increase and suppliers need to be ready to respond. These actors may include farmer associations where effective, as the associations can influence fertilizer supply decisions.
- Sustainability of fertilizer use optimization can be enhanced through on-going support of private and public sectors and of regional and international organizations (Table 17.1; Fig. 17.1).
- Linking with the existing opportunities, such as the CABI-supported Plantwise plant clinics implemented in all OFRA countries, are potential platforms for awareness creation and sustainability. This was confirmed by the results of a follow-up study on the challenges and lessons in enabling fertilizer use optimization in Uganda, which revealed the value of working through plant clinics if well-coordinated. One extension worker suggested that the curriculum that is used to train the plant doctors could be expanded to include fertilizer use optimization and use of OFRA tools.

17.6 Conclusion

Fertilizer use optimization is the maximization of the profit potential of fertilizer use according to the farmer's context while keeping risk low. It was based on field research from which crop-nutrient response functions were developed and applied in the development of FOTs for 67 AEZs of 13 countries.

Enabling fertilizer use optimization at the farm level is in early stages for most countries but considerable experience has been gained from Uganda, as well as Kenya and Tanzania. As with any extension effort, early creation of farmer awareness of the potential benefits of fertilizer use optimization is very important in order to make adoption demand driven.

Engagement with diverse stakeholders is needed to gain the necessary resources and avoid obstacles in enabling fertilizer use optimization. Much training of farmer advisors is needed. More capable farmers need to learn to use the paper FOTs on their own. Diverse partnerships are needed for sustained support of fertilizer use optimization.

17.7 Acknowledgements

OFRA is funded by the Alliance for a Green Revolution in Africa (AGRA) and jointly led by the Centre for Agriculture and Bioscience International (CABI) and the University of Nebraska-Lincoln.

17.8 References

Kaizzi KC, Wortmann C and Jansen J (2013) More profitable fertilizer use for poor farmers. Better Crops 97:4-6

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

List of Abbreviations

4Rs	right product, rate, time and method of application of fertilizers
ac	acre
AE	agronomic efficiency
AEZ	agro-ecological zone
AfSIS	Africa Soil Information Service
AGRA	Alliance for a Green revolution in Africa
ai	Aridity Index
B	Boron
BNF	biological nitrogen fixation
CA	conservation agriculture
Ca	calcium
C	carbon
CAIMA	Centrale d'Approvisionnement en Intrants et Matériels Agricoles, Niger
CAN	calcium ammonium nitrate
CEC	cation exchange capacity
cm	centimetre
Cu	copper
DAP	diammonium phosphate
DE	Distance from Equator
DEM	digital elevation model
EOR	economically optimal rate
FAO	Food and Agriculture Organization of the United Nations
FBO	farmer-based organization
FCFA	CFA franc
Fe	iron
FGN	Federal Government of Nigeria
FMSP	Federal Market Stabilization Program, Nigeria
FOT	Fertilizer optimization tool
FYM	farmyard manure
GAP	good agricultural practices
GDP	gross domestic product
GH₵	Ghana cedi
GIS	Geographic Information System
ha	hectare
HP	high potential
ISFM	Integrated Soil Fertility Management
K	potassium
KCl	potassium chloride
kg	kilogram
KSh	Kenya Shilling
LP	Linear programming
LP	low potential
masl	metres above sea-level
meq	milliequivalent
Mg	magnesium
MKW	Malawi kwacha
Mn	manganese
Mo	molybdenum
MOP	muriate of potash (KCl)
mt	metric ton
MZM	Mozambique metical
N	nitrogen
Na	sodium
NGO	non-governmental organisation
NPK	nitrogen, phosphorus, potassium
OFRA	Optimising Fertilizer Recommendations In Africa
OFT	on-farm trials
OM	organic matter
P	phosphorous
PET	potential evapotranspiration
ppm	parts per million
REC	current recommended rate (of fertilizer application)
RMT	research-managed trials
RP	rock phosphate
RwF	Rwanda franc
S	sulphur

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

SARI	Savanna Agricultural Research Institute, Ghana
SOC	soil organic carbon
SSA	Sub-Saharan Africa
SSP	single superphosphate
t	ton
TA	Tropical Alpine
ts	Temperature Seasonality
TSP	triple superphosphate
UgSh	Uganda Shilling
WAP	weeks after planting
WAT	weeks after transplanting
yr	year
ZMK	Zambia kwacha
Zn	zinc

List of Crops and Other Plants with Scientific Names

Azolla	*Azolla spp.*
Banana	*Musa acuminata (AAA-EA)*
Barley	*Hordeum vulgare*
Cabbage, kale	*Brassica oleracea*
Cashew nut	*Anacardium occidentale*
Cassava	*Manihot esculenta*
Cocoa	*Theobroma cacao*
Cocoyam	*Xanthosoma spp*
Coffee	*Coffea spp*
Common bean	*Phaseolus vulgaris*
Cotton	*Gossypium spp*
Cowpea	*Vigna unguiculata*
Faba bean	*Vicia faba*
Finger millet	*Eleusine coracana*
Green gram	*Vigna radiata*
Groundnut	*Arachis hypogaea*
Irish potato	*Solanum tuberosum*
Kale, cabbage	*Brassica oleracea*
Kikuyu grass	*Pennisetum clandestinum*
Lablab	*Lablab purpureus*
Maize	*Zea mays*
Mango	*Mangifera indica*
Mucuna	*Mucuna pruriens*
Oil palm	*Elaeis guineensis*
Pearl millet	*Pennisetum glaucum*
Pigeonpea	*Cajanus cajan*
Pineapple	*Ananas comosus*
Plantain	*Musa* × *paradisiaca*
Pyrethrum	*Chrysanthemum spp*
Rice	*Orizae sativa, Orizae glaberrima*
Rubber	*Hevea brasiliensis*
Sesame	*Sesamum indicum*
Sisal	*Agave sisalana*
Sorghum	*Sorghum bicolor*
Soybean	*Glycine max*
Striga	*Striga spp*
Sunflower	*Helianthus annuus*
Sweet potato	*Ipomoea batatas*
Taro	*Colocasia esculenta*
Tea	*Camellia sinensis*
Teff	*Eragrostis tef*
Tiger nut	*Cyperus esculentus*
Tobacco	*Nicotiana tabacum*
Wheat	*Triticum aestivum*
Yam	*Dioscorea alata*

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

This book was first published in 2017 by OFRA

CABI, P.O. Box 633-00621, Nairobi, Kenya

Tel: +254 (0)20- 2271000/ 20 Fax: +254-20-712 2150 Email: Africa@cabi.org

Website: www.cabi.org/ashc