A linear programming model to optimize cropping pattern in small-scale irrigation schemes: an application to Mekabo Scheme in Tigray, Ethiopia

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Abstract— *Selection of a viable irrigation cropping system, while considering all agronomy and extension constraints, has always been a scientific and professional challenge for agricultural scientists and practitioners. However, this prevailing challenge can be scientifically addressed using optimization techniques among them linear programming model. The model could take in the initially introduced percentage of crops as an entry point for optimization subjected to all introduced constraints while maximizing the farming income. Favorably, Microsoft Excel program includes a linear programming solver tool, which could be utilized for this purpose. The solver tool could easily be accessed from Excel program Data menu after activating the Add-Ins part of the Excel Options.*

Accordingly, a simple and low input linear model was developed applying the Excel Solver tool to optimize the irrigation cropping pattern for the Mekabo small-scale irrigation scheme currently under construction in the Tigray region in Ethiopia. The input parameters were collected from field surveys and an assessment of the on-farm agronomic conditions. The objective function was subjected to agronomy and extension constraints as well as minimum required crop levels to comply with food security strategy. The model could find a viable solution while all constraints and optimality conditions were satisfied. A sensitivity analysis was also performed to analyze all other likely development scenarios. This paper will introduce the developed model and will discuss the processes led to the attainment of an optimized cropping pattern.

Keywords— ***Small-scale irrigation, cropping pattern, linear programming model, optimization technique.***

I. INTRODUCTION

Sustainable development of small-scale irrigation schemes has been the cornerstone of food security programs supported by government and external donors in Ethiopia since the 1980s. Many landmark strategies have been introduced to address the ongoing demand for food security, including the development of new small-scale irrigation projects. One of the principle challenges during initial stages of development of a new irrigation project is the selection of a viable cropping system that can be effectively implemented by farmers. This is usually addressed during the feasibility study where engineers attempt to identify a system which optimizes the farmers' income while considering agronomic conditions and farmers' knowledge and experience. To determine a right cropping pattern, designers have to discreetly consider various agronomy and extension constraints including crop water consumption, nutrition values, disease and pest resistance, market demand, fertilizer input, labor requirement, capital input, post harvest processing necessity, crop production level, and market prices.

Although, the selection of optimum cropping system is a scientific and professional challenge, it is believed that it can be scientifically addressed using optimization techniques such as a linear programming model. The linear programming model quantifies an optimal way of integrating constraints to satisfy the objective function to optimize crop production and profits for irrigation farmers. The linear programming model, as a reliable optimization technique, has been known in many engineering fields for years. It has also extensive application as an optimization module in several complex engineering software. However, the complex software usually require heavy license fees for installation and operation, which in most cases is beyond the financial reach of many small-scale irrigation projects. Favorably, Microsoft Excel program includes a linear programming Solver, which could be utilized for simple optimization scenarios like optimization of cropping pattern in small-scale irrigation projects. This Solver tool could easily be accessed from Data menu after activating the Add-Ins part of Excel Options. The model analyzes the cases where the existing limitations must be satisfied in a way to maximize the profit or minimize the cost (Frizzone et al., 1997). Birhanu et al. (2015) successfully used linear programming model to obtain an optimized cropping pattern for the Koga Irrigation Dam project in Ethiopia. Aparnathi and Bhatt (2014) introduced surface and ground water as constraints to their linear programming model to optimize the cropping pattern for a project under study in their region. Bertomeu and Gimenez (2006) utilized a simple linear programming model to optimize the allocation of farmers' resources and lands for maximum benefit. Frizzone et al. (1997) employed this technique for optimizing the use of water resource in the Senator Nilo Coelho irrigation project in Brazil.

The principal objective of this study is to develop a low input simple technique approach to maximize farming benefits, considering the agronomic, economic and social constraints facing a typical small-scale irrigation project in Ethiopia. Accordingly, a linear model was developed using the Microsoft Excel Solver tool to determine an optimized cropping system for the Mekabo small-scale irrigation scheme currently being developed in the Tigray region of Ethiopia. The project is located about 50 km north of the city of Mekelle. The input parameters were collected from field surveys and an assessment of on-farm agronomic factors, as well as the expertise and operational constraints of the new irrigation farmers. The objective function (Maximizing farming benefits) which includes decision variables (percentage of crops in the cropping pattern) was subjected to agronomy and extension constraints as well as minimum required crop levels to comply with the food security strategy. After inputting data in Excel sheet and running the Solver, the linear programming tool could successfully find a solution while all constraints and optimality conditions satisfied. A sensitivity analysis was also performed to analyze all other likely development scenarios. This paper will discuss the processes that led to the development of an optimized cropping system for Mekabo small-scale irrigation scheme.

II. MATERIALS AND METHODS

2.1 Project context

The linear programming model would maximize or minimize the objective function subjected to all constraints while optimizing the decision variables. This process, as shown in Fig. 1, has been applied to Mekabo small-scale irrigation scheme, to optimize a cropping pattern for agricultural development.

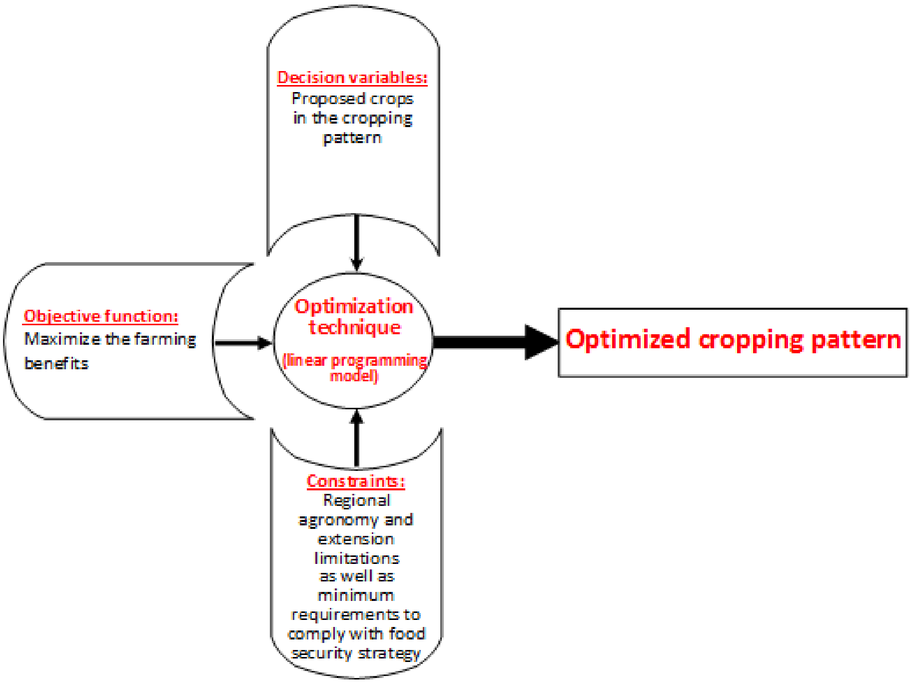

FIGURE 1 THE OPTIMIZATION PROCESS FLOWCHART FOR MEKABO SCHEME

The Mekabo small-scale irrigation scheme includes a weir constructed across the Augla river to divert irrigation water to the command area. Fig. 2 shows the view of the weir, which was financially supported and constructed by REST NGO in March 2016.

FIGURE 2. CONSTRUCTED WEIR TO DIVERT WATER TO MEKABO SMALL-SCALE IRRIGATION SCHEME

FIGURE 3. THE VIEW OF MEKABO SMALL-SCALE IRRIGATION COMMAND AREA

Fig. 3 shows the view of 60 ha irrigation command area, which accommodates 144 smallholder farmers. The target command area is presently under rain fed agriculture and is supposed to be shifted to irrigated agriculture immediately after the completion of 1.3 km conveyance canal, which is currently under construction (Fig.4) by the same local NGO (REST) responsible for the construction of weir. With the fund donated by the local Orthodox Church, farmers will construct the gravity distribution system shortly after the construction of conveyance canal.

FIGURE 4. MEKABO CONVEYANCE CANAL PRESENTLY UNDER CONSTRUCTION

The average elevation of the project area is about 1942 m above mean sea level (amsl). The types of crops selected as cropping pattern for Mekabo scheme are according to the agro-ecological suitability and socioeconomic factors studied during feasibility studies by REST NGO. The present study is, in fact, a not binding supplementary investigation conducted by the experts of Tigray SMIS (Small-scale and Micro Irrigation Support) project independent of any other efforts made by REST and the local bureau of agriculture and rural development.

2.2 Model development

A standard form of linear programming model has the following components (Anon., 2001):

- Decision variables to be optimized,
- Objective function that must be maximized or minimized and will be put subject to constrains,
- Constraints.

Definition of the above-mentioned components and their adaptation for Mekabo scheme will be discussed as follows.

2.2.1 Decision variables

Decision Variables are the combination of mathematical expressions in the objective function to be optimized by the model. The goal is to find values for the coefficient of decision variables to provide the best rate of the objective function (Anon., 2001). For the Mekabo scheme, the types of crops being planted are the decision variables that the percentage of which is to be optimized. The food security strategy for Ethiopia recommends that specific crops be included in any proposed cropping system in order to improve the nutrition and fiber values in the farmers' family diet. The proposed cropping types for the Mekabo scheme includes vegetables (potato, tomato, and cabbage), cereals (corn, and barley), pulses (beans, peas, and lentils), and fruits (mango, and papaya). Table 1 identifies these eleven crops plus a provision for fields to be fallowed as part of the cropping rotation. The twelve decision variables x_1, x_2, x_3,..... x_{12}, and their coefficients c_1, c_2, c_3,..... c_{12}, for Mekabo scheme, are presented in Table 1.

TABLE 1
THE DECISION VARIABLES

Crops		Decision variable	Coefficient	Element in the objective function
Vegetables	Potato	x_1	c_1	$c_1 * x_1$
	Tomato	x_2	c_2	$c_2 * x_2$
	Cabbage	x_3	c_3	$c_3 * x_3$
Cereals	Corn	x_4	c_4	$c_4 * x_4$
	Barley	x_5	c_5	$c_5 * x_5$
Pulses	Beans	x_6	c_6	$c_6 * x_6$
	Peas	x_7	c_7	$c_7 * x_7$
	Lentils	x_8	c_8	$c_8 * x_8$
Cash crops	Watermelon	x_9	c_9	$c_9 * x_9$
Fruits	Mango	x_{10}	c_{10}	$c_{10} * x_{10}$
	Papaya	x_{11}	c_{11}	$c_{11} * x_{11}$
Fallow	No crop	x_{12}	c_{12}	$c_{12} * x_{12}$

2.2.2 Objective function

The Objective Function is a mathematical expression that combines the decision variables and their coefficients to achieve the goal of maximum farm benefits (Anon., 2001), and is expressed as follows.

$Z\ f(x_1, x_2, x_3, \ldots x_n)$

The highest farm benefit for the Mekabo irrigation scheme means the highest farming income resulting from an optimized combination of crops being grown and subjected to the constraints. The general form of objective function (Z) could mathematically be expressed as follows(Schulze, 1998).

$$Max Z \approx \sum_{j=1}^{n} c_j x_j \qquad Where: \quad j = 1 \ \ to \ \ n$$

Given the twelve decision variables (n=12) in case of Mekabo scheme, then the objective function could be developed as follows:

$$Max Z \approx c_1 x_1 + c_2 x_2 + c_3 x_3 + \ldots\ldots\ldots\ldots\ldots\ldots\ c_{12} x_{12}$$

Where Z is the farm gross income resulting from growing the 11 optimized crops and C_1, C_2, C_3, ...C_{12} are the coefficients in the objective function related to an increase in Z (the objective function value).

2.2.3 Constraints

The constraints are mathematical expressions to represent limits in the model related to agronomic, farmer knowledge, and food security requirements. The model assesses and identifies possible solutions that respect these limits in order to achieve the optimum objective function (Anon., 2001). Based on the assessments carried out, 22 constraints were identified for the Mekabo scheme. The constraints are generally expressed as follows:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} x_j \leq b_i$$

or

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij} x_j \geq b_i \qquad Where: \ j = 1 \ to \ n \quad and \quad i = 1 \ to \ m$$

Where $a$ij are the coefficients for the introduced constraints and bi are the values for the defined constraints. The expansion of the above expression for n number of decision variables (crops) and m number of constraints in Mekabo scheme are defined as:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \dots\dots + a_{1n}x_n \le b_1$$
$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \dots\dots + a_{2n}x_n \le b_2$$
$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \dots\dots + a_{3n}x_n \le b_3$$
$$\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots$$
$$a_{m1}x_1 + a_{m2}x_2 + a_{m3}x_3 + \dots\dots + a_{mn}x_n \le b_m$$

For the current study, considering the 22 defined constraints, (m = 22) and the 12 defined decision variables (n=12), the expression can be developed as follows:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \dots\dots + a_{112}x_{12} \le b_1$$
$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \dots\dots + a_{212}x_{12} \le b_2$$
$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + \dots\dots + a_{312}x_{12} \le b_3$$
$$\vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots$$
$$a_{221}x_1 + a_{222}x_2 + a_{223}x_3 + \dots\dots + a_{2212}x_{12} \le b_{22}$$

In order to prevent accidental negative values for the decision variables, the following assumption should also be added to constraints:

$$x_j \ge 0$$

In case of current study, the above-mentioned equation expands to:

$$x_1 \ge 0;\ x_2 \ge 0;\ x_3 \ge 0;\ \dots\dots\ x_{12} \ge 0$$

However, in Mekabo scheme because of allocation of minimum percentage of crops in the cropping pattern, there is no need to include the non-negativity constrains in the model.

2.2.4 Rating and setting the constraints limits

Based on the field investigations conducted by SMIS project experts, the 22 agronomic, farmer knowledge, and nutrition constraints were identified in the design of the cropping system for the Mekabo scheme (Table 2). These constraints include key issues such as water demand, crop disease and pest resistance, market price, level of fertilizer input, intensity of labor requirement, capital requirements, and post-harvest processing requirements. The significance of each constraint was ranked according to a crop performance ranking approach (CPR). The performance ranking approach was adapted from the Global Assessment Functioning method used in other scientific investigations. The ranking reflects the possibility of improved agricultural inputs (water management, seed, fertilizer, pesticides, labor, capital) and the likelihood of better agricultural practices after the farmers receive training and other extension services to shift from current rain fed agriculture to irrigated agriculture when the Mekabo scheme is fully functional. This approach includes a rating index for each crop that ranges from 1, which signifies very low/weak potential, to 100, which indicates very high/excellent potential. Table 2 shows the crop performance ranking index utilized for constraints for the Mekabo irrigation scheme.

TABLE 2
CROP PERFORMANCE RANKING APPROACH UTILIZED FOR THE MEKABO IRRIGATION SCHEME

Step	CPR index	Definition	Description
1	1-10	Very low/Weak	Lowest condition possible
2	11-20	Poor	Needs fundamental improvement
3	21-30	In adequate	Needs moderate improvement
4	31-40	Low	Needs some improvement
5	41-50	Satisfactory	Needs slight improvement
6	51-60	Acceptable	Fulfils the needs
7	61-70	Good	Average conditions
8	71-80	Favorable	Above average conditions
9	81-90	Very good	Meets perfectly all the requirements
10	91-100	Very high/Excellent	Highest condition possible

A minimum or maximum required value was also defined to introduce a necessary limit for each constraint. Table 3 presents the rated agronomy and farmer knowledge constraints for crops in the proposed cropping system as inputs to the model.

TABLE 3
RATING AGRONOMY AND FARMER KNOWLEDGE CONSTRAINTS FOR CROPPING PATTERN

No	Agronomy & extension index	Rating according to CPR approach 1= very low/weak 100= very high/excellent											Condition	Minimum or maximum required to comply with improved irrigated agricultural practices
		Vegetables			Cereals		Pulses			Cash crops	Fruits			
		Potato	Tomato	Cabbage	Corn	Barley	Beans	Peas	Lentils	W/melon	Mango	Papaya		
1	Water demand	65	70	60	50	40	40	45	40	80	30	30	≤	50
2	Nutrition	60	70	70	80	80	70	70	85	60	75	70	≥	70
3	Disease resistance	60	50	70	50	70	60	65	70	70	80	80	≥	60
4	Pest resistance	80	80	85	40	80	70	80	85	80	80	80	≥	60
5	Market demand	100	95	70	90	70	65	50	40	90	95	95	≥	50
6	Fertilizer input requirement	80	80	70	85	60	60	55	50	85	40	40	≤	70
7	Labor requirement	100	100	80	50	40	65	65	60	90	20	20	≤	50
8	Capital requirement	90	90	70	50	40	50	50	50	90	30	30	≤	50
9	Post harvest processing needs (due to rapid perishability)	60	70	60	30	20	30	40	30	80	90	90	≤	50

To support the food security strategy for the Mekabo scheme, a minimum required cropping percentage (Table 4) was defined. This ranged from 2% of the total cropping area for grains, 5% for vegetables, 5% for fruits, and 15% for corn, which is considered the main cereal crop. In total, 56% of cropping area was allocated to the strategic crops, which left only 44% of the cropping area to be determined by the model.

TABLE 4
CROPPED AREA REQUIRED TO MEET FOOD NUTRITION REQUIREMENTS

Crop		Condition	Suggested minimum level of cropped area per hectare (%)	Rationale
Vegetables	Potato	≥	5	To improve nutrition level in the family diet
	Tomato	≥	5	
	Cabbage	≥	2	
Cereals	Corn	≥	15	To improve fiber level in the family diet
	Barley	≥	3	
Pulses	Beans	≥	2	To improve nourishment in the family diet
	Peas	≥	2	
	Lentils	≥	2	
Cash crops	Watermelon	≥	5	To improve the family income
Fruits	Mango	=	5	To improve nourishment in the family diet
	Papaya	=	5	
Fallow	No crop	=	5	To improve soil conditions
Committed cropping pattern		-	**56**	-

2.2.5 Application of the model

The Microsoft Excel program includes a linear programming solver tool, which was applied to the Mekabo small-scale irrigation scheme to optimize the cropping system. The Solver tool could be accessed from Data menu after Add-Ins part is activated in Excel Options (Anon., 2013). The solver toll was activated and was run (Microsoft Excel 2007 help) for Mekabo scheme, after defining the decision variables and introducing the set of constraints. Table 5 presents all 22 constraints arranged in Excel sheet and utilized for the analysis by the model.

TABLE 5
ALL CONSTRAINTS INCLUDED IN THE MODEL

	Potato			Tomato			Cabbage			Corn			Barley			Beans			Peas			Lentils			W/melon			Mango			Papaya			Fallow		Required	
Subject to	a_{j1}	x_1	+	a_{j2}	x_2	+	a_{i3}	x_3	+	a_{i4}	x_4	+	a_{i5}	x_5	+	a_{i6}	x_6	+	a_{i7}	x_7	+	a_{i8}	x_8	+	a_{i9}	x_9	+	a_{i10}	x_{10}	+	a_{i11}	x_{11}	+	a_{i12}	x_{12}	Cond.	Min. req.
Const 1	65	x_1	+	70	x_2	+	60	x_3	+	50	x_4	+	40	x_5	+	40	x_6	+	45	x_7	+	40	x_8	+	80	x_9	+	30	x_{10}	+	30	x_{11}	+	0	x_{12}	≤	50
Const 2	60	x_1	+	70	x_2	+	70	x_3	+	80	x_4	+	80	x_5	+	70	x_6	+	70	x_7	+	85	x_8	+	60	x_9	+	75	x_{10}	+	70	x_{11}	+	0	x_{12}	≥	70
Const 3	60	x_1	+	50	x_2	+	70	x_3	+	50	x_4	+	70	x_5	+	60	x_6	+	65	x_7	+	70	x_8	+	70	x_9	+	80	x_{10}	+	80	x_{11}	+	0	x_{12}	≥	60
Const 4	80	x_1	+	80	x_2	+	85	x_3	+	40	x_4	+	80	x_5	+	70	x_6	+	80	x_7	+	85	x_8	+	80	x_9	+	80	x_{10}	+	80	x_{11}	+	0	x_{12}	≥	60
Const 5	100	x_1	+	95	x_2	+	70	x_3	+	90	x_4	+	70	x_5	+	65	x_6	+	50	x_7	+	40	x_8	+	90	x_9	+	95	x_{10}	+	95	x_{11}	+	0	x_{12}	≥	50
Const 6	80	x_1	+	80	x_2	+	70	x_3	+	85	x_4	+	60	x_5	+	60	x_6	+	55	x_7	+	50	x_8	+	85	x_9	+	40	x_{10}	+	40	x_{11}	+	0	x_{12}	≤	70
Const 7	100	x_1	+	100	x_2	+	80	x_3	+	50	x_4	+	40	x_5	+	65	x_6	+	65	x_7	+	60	x_8	+	90	x_9	+	20	x_{10}	+	20	x_{11}	+	0	x_{12}	≤	50
Const 8	90	x_1	+	90	x_2	+	70	x_3	+	50	x_4	+	40	x_5	+	50	x_6	+	50	x_7	+	50	x_8	+	90	x_9	+	30	x_{10}	+	30	x_{11}	+	0	x_{12}	≤	50
Const 9	60	x_1	+	70	x_2	+	60	x_3	+	30	x_4	+	20	x_5	+	30	x_6	+	40	x_7	+	30	x_8	+	80	x_9	+	90	x_{10}	+	90	x_{11}	+	0	x_{12}	≤	50
Const 10	a_{101}	x_1	+	a_{102}	x_2	+	a_{103}	x_3	+	a_{104}	x_4	+	a_{105}	x_5	+	a_{106}	x_6	+	a_{107}	x_7	+	a_{108}	x_8	+	a_{109}	x_9	+	a_{1010}	x_{10}	+	a_{1011}	x_{11}	+	a_{1012}	x_{12}	=	1
Const 11	a_{111}	x_1																																			≥	0.05
Const 12				a_{122}	x_2																																≥	0.05
Const 13							a_{133}	x_3																													≥	0.02
Const 14										a_{144}	x_4																										≥	0.15
Const 15													a_{155}	x_5																							≥	0.03
Const 16																a_{166}	x_6																				≥	0.02
Const 17																			a_{177}	x_7																	≥	0.02
Const 18																						a_{188}	x_8															≥	0.02
Const 19																									a_{199}	x_9											≥	0.05
Const 20																												a_{2010}	x_{10}								=	0.05
Const 21																															a_{2111}	x_{11}					=	0.05
Const 22																																		a_{2212}	x_{12}		=	0.05

The model also requires average crop production rates and their prices as an input. This information, shown in Table 6, was collected from the market.

TABLE 6
AVERAGE CROP PRODUCTION RATES AND PRICES

Category	Crop	Production rate (kg/ha)	Farm gate price (ETB/kg)
Vegetables	Potato	9,500	8
	Tomato	12,000	12
	Cabbage	20,000	5
Cereals	Corn	5,000	5
	Barley	2,000	8
Pulses	Beans	2,100	17
	Peas	1,400	18
	Lentils	1,000	36
Cash crops	Watermelon	10,000	9
Fruits	Papaya	22,500	12
	Mango	12,600	15

Figure 5 identifies the range and variation of crop production rates and their prices.

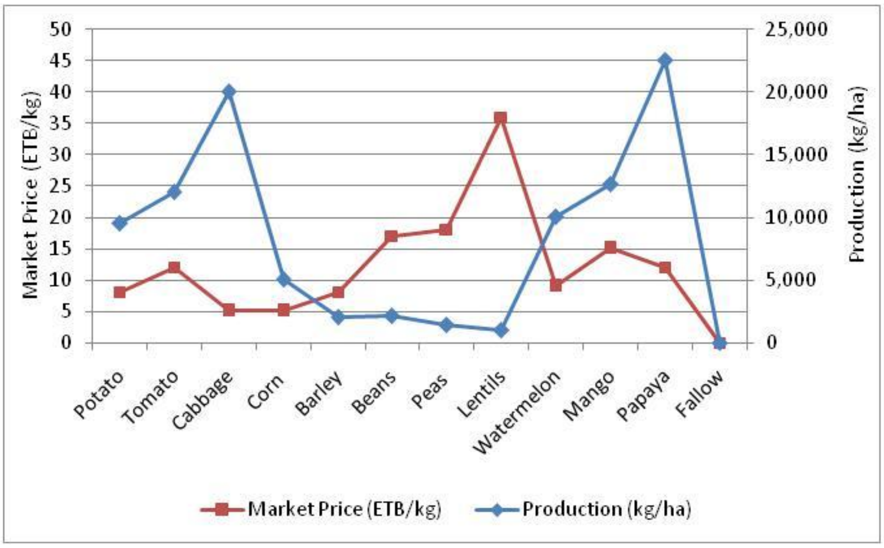

FIGURE 5. THE RANGE OF AVERAGE CROP PRODUCTION AND THEIR MARKET PRICE

To run the Solver tool for the Mekabo scheme, three consecutive sets of row cells (Table 7) are allocated in the Excel sheet for model-calculated optimized cropping pattern, crop production, and market price. The Solver also requires a single cell be allocated for the objective function results (Max Z (ETB/ha)). Before the Solver could run the program, it prompts Solver Parameters to be included. These parameters for Mekabo scheme include the sum of products of cells of model-calculated optimized cropping pattern and the values in each row of cells of constraints (Anon., 2013). All 22 constraints were added one by one to the sub window in the Solver Parameter window. By checking the "Max" button in the Solver window in order to instruct the model to maximize the income, the percentage of cropping pattern is re-calculated and is presented in the allocated cells in the Excel sheet.

TABLE 7
THE EXCEL SHEET DATA ARRANGEMENT FOR OBJECTIVE FUNCTION

	Potato	Tomato	Cabbage	Corn	Barley	Beans	Peas	Lentils	W/melon	Mango	Papaya	Fallow
Model-calculated optimized cropping pattern (ha)	0.05	0.05	0.03	0.29	0.32	0.02	0.02	0.02	0.05	0.05	0.05	0.05
Crop production (kg/ha)	9,500	12,000	20,000	5,000	2,000	2,100	1,400	1,000	10,000	12,600	22,500	0
Market price (ETB/kg)	8	12	5	5	8	17	18	36	9	15	12	0
Max Z (ETB/ha)	**57,498**											

III. RESULTS AND DISCUSSION

3.1 Optimal Solution of the Model

Accounting for all identified constraints, the model maximized the farm income (Objective Function) for the Mekabo scheme, while optimizing the percentage of crops in the cropping pattern. In the Solver Result window a message reading "Solver found a solution" followed by "All constraints and optimality conditions are satisfied" signified the successful end of maximization process. Table 8 shows that the initial total percentage of crops introduced to the model was (56%); however, as was specified in one of the constraints, the model increased the cropping patter to 1.0 (100%) and contributed the balance (44%) to other crops.

TABLE 8
THE OPTIMIZED CROPPING PATTERN

Crop		Suggested minimum crop level in the cropping pattern to comply with food security strategy and a balanced family diet	Optimized cropping pattern by model	Balance
Vegetables	Potato	0.05	0.05	0.0
	Tomato	0.05	0.08	+ 0.03
	Cabbage	0.02	0.02	0.0
Cereals	Corn	0.15	0.15	0.0
	Barley	0.03	0.44	+ 0.41
Pulses	Beans	0.02	0.02	0.0
	Peas	0.02	0.02	0.0
	Lentils	0.02	0.02	0.0
Cash crops	Watermelon	0.05	0.05	0.0
Fruits	Mango	0.05	0.05	0.0
	Papaya	0.05	0.05	0.0
Fallow	No crop	0.05	0.05	0.0
Total cropping pattern		**0.56**	**1.00**	**0.44**

Table 9 and Fig 6 demonstrate that the percentage of only two crops increase in the optimized cropping pattern. Tomato increased from 5% to 8% (3% increase), and barley increased from 3% to 44% (41% increase). The percentage of other crops remained the same.

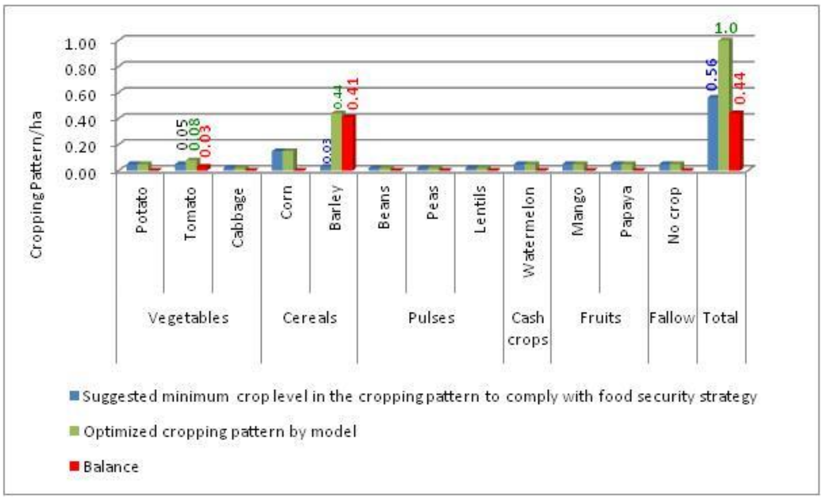

FIGURE 6. COMPARISON BETWEEN OPTIMIZED CROPPING PATTERN AND THE INITIAL ONE

The linear programming model is a dynamic system. The present optimized cropping pattern is the outcome of the current assessment of the 22 identified constraints. If these constraints change, a different outcome may emerge. The presented result signifies the fact that farmers could get the maximum income (57,498 ETB/ha) if all of their farm products are sold at the market. However, it is recognized that some crop production is dedicated for in-house consumption. The cropping system is designed to comply with the healthy food security strategy, and still have crop products available for sale to the market for cash.

3.2 Sensitivity Analysis

A sensitivity analysis was performed to assess the impacts on net farm income of changing cropping system. The sensitivity analysis was applied to at least one crop from each crop category. Table 9 shows there is a high level of sensitivity to the changes in the area grown of vegetables as well as vegetables and cereals combined. However, low sensitivity was observed from the imposed changes to cereals and cash crops.

TABLE 9
SENSITIVITY ANALYSIS OF LINEAR PROGRAMMING MODEL FOR MEKABO SCHEME

Test	Change scenario			Model outcome				
	Variable in cropping pattern to change	Crop to touch	Change to optimized cropping pattern (out of 1 ha)	Analysis modality	Income (ETB)	Change in income (%)	Sensitivity	Cropping pattern status
0	No change	-	-	Reached feasible solution	57,498	-	-	Recommended
1	Vegetables percentage	Potato	+ 0.10	No feasible solution	51,531	-10	High	Needs improvement
2	Vegetables percentage	Potato	- 0.05	Reached feasible solution	60,898	6	High (relatively)	Not-recommended (lacks vegetables)
3	Cereals percentage	Corn	+ 0.10	Reached feasible solution	56,265	-2	Low	Recommended
4	Cereals percentage	Corn	- 0.10	Reached feasible solution	58,731	2	Low	Not-recommended (lacks cereals)
5	Pulses percentage	Beans	+ 0.10	No feasible solution	55,350	-4	Medium	Needs improvement
6	Pulses percentage	Beans	- 0.02	Reached feasible solution	58,171	1	Medium (relatively)	Not-recommended (lacks pulses)
7	Cash crop percentage	W/melon	+ 0.05	No feasible solution	57,080	-1	Low	Needs improvement
8	Cash crop percentage	W/melon	- 0.05	Reached feasible solution	59,131	3	Low	Not-recommended (lacks adequate compensation)
9	Vegetables and Cereals percentage	Potato & Corn	+ 0.10	No feasible solution	51,735	-10	High	Needs improvement
10	Vegetables and Cereals percentage	Potato & Corn	- 0.05	Reached feasible solution	61,515	7	High	Not-recommended (lacks adequate vegetables & cereals)

Figure 7 shows that when vegetables, pulses, and combined vegetables & cereals levels are increased, the model exhibited a lower income values. This generally signifies that one or more constraints could not be satisfied during the optimization process by the model. Achieving a feasible solution in these cases may mean that the assessment values for constraints need to be improved. This could be obtained by reconsidering better on-farm water management, increased fertilizer, additional pesticide inputs, improved seed varieties, increased labor, additional capital input, and increased post harvesting management. The last column in Table 9 shows the optimized cropping pattern scenario that satisfies all the constraints and could be recommended to the farmers.

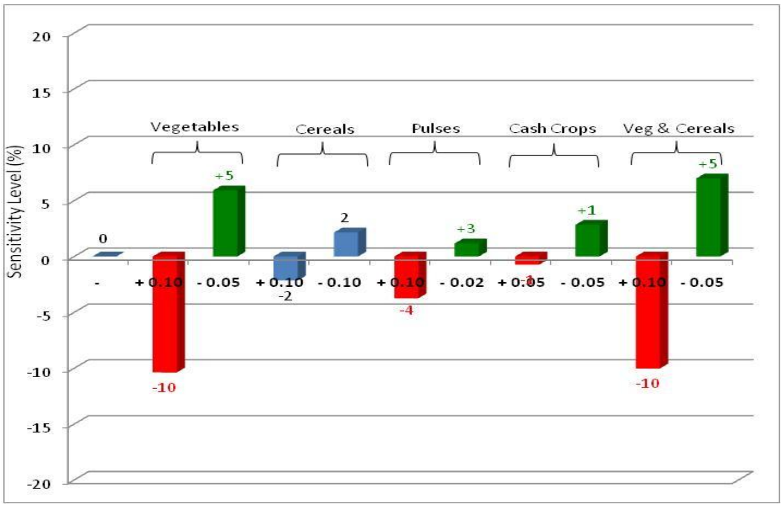

FIGURE 7. SENSITIVITY ANALYSIS FOR THE MEKABO SCHEME

IV. SUMMARY AND CONCLUSIONS

a. The linear programming model for Mekabo scheme successfully optimized the cropping pattern for maximum income while satisfying all of the imposed constraints.

b. With the current sets of constraints and input data, the model showed a high level of sensitivity to the changes in the percentage of vegetables as well as vegetables and cereals combined.

c. The model exhibited low sensitivity for the imposed changes to cereals and cash crops.

d. During sensitivity analysis the model could not find a feasible solution in some circumstances because the conditions of one or more constraints could not be satisfied during the optimization process. Achieving a feasible solution in these cases may mean that the assessment values for constraints need to be improved. This could be achieved by reconsidering a better on-farm water management, increased fertilizer, additional pesticide inputs, improved seed varieties, increased labor, additional capital input, and increased post harvesting management.

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