Adopting a Beneficial Carbon Farming in the Cropping Pattern Using an Optimization Technique: A Case Study

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***Abstract*— *Plants can capture CO_2 from the air and sequester it in the leaves through photosynthesis. Even additional carbon sequestration could be achieved by allowing higher cropping intensity on the same piece of land in a single cropping season. There is a growing demand that agricultural developers and practitioners consider carbon farming in the design of cropping patterns in order to intensify carbon sequestration and trade it as a carbon credit for extra financial benefits. However, adopting a sustainable carbon farming while respecting the farmer's needed income and food security may seem a difficult task. Nevertheless, this fundamental challenge can be addressed using an optimization technique such as simplex linear programming (SLP). The Microsoft Excel program includes a SLP solver tool, which can easily be accessed from the Excel program Data menu after activating the Add-Ins part of the Excel Options. In this study, seven scenarios were developed to be analyzed by the SLP to investigate the various options of adopting carbon farming into the cropping pattern while maximizing either the individual or the combined benefits of farmer's income and farmer's food security for the Mekabo irrigation scheme in Ethiopia. The result shows that the optimized cropping pattern in scenario seven best satisfies the farmer's food security and farmer's income while still stimulating extra financial benefits from carbon farming. Alley cropping, multi-species-cover cropping, and no-till planting in scenario seven could encourage the highest rate of additional carbon sequestration so it could better contribute to the alleviation of global warming. This paper will discuss how the SLP is developed and applied leading to the attainment of an optimized cropping pattern while the financial benefit is maximized.*

***Keywords*— carbon farming, optimization technique, simplex linear programing, cropping pattern.**

I. INTRODUCTION

With the growing threat of global warming, it is expected the industries that can not halt releasing Carbon Dioxide (CO_2) into the atmosphere, at least try to offset their emissions through partnering with carbon mitigators who can remove CO_2 from the air on their behalf. This process has triggered the birth of carbon credit exchange (CCX) in the global market and is still rising. Crops cultivated in the agricultural lands are known to be a consistent driver for capturing CO_2 from the air and sequestering it into different forms of carbon through photosynthesis. Even additional carbon sequestration could be achieved by allowing higher cropping intensity on the same piece of land in a single cropping season. Crops cultivated in the millions of ha of agricultural lands in any given country can significantly contribute to the massive carbon sequestration in the plants and soils. Accordingly, there is a growing demand that agricultural developers and practitioners accommodate carbon farming in the cropping pattern as an integrated part of their agricultural practices for both its positive environmental impact and financial benefits from selling the carbon credit in the CCX market.

The land-based carbon sequestration is measured in metric tons per hectare and one metric ton earns one carbon credit. In California – the only state in the US with a full-fledged cap-and-trade program – the current value of a carbon credit is around $12 to $13. Alberta, which has the most robust carbon market in Canada rewards several agricultural practices with carbon credits of up to $30 per credit [1]. According to the global pricing of various types of carbon credits, the current carbon credit produced from plantation ranges from $US 2.2 to 20^+ depending on the project type, size, location, and other determining factors [2].

Adopting carbon farming in the cropping pattern while several agronomic and environmental constraints should also be considered may seem a challenging task. However, an optimization technique such as the Simplex Linear Programming (SLP) can assist to tackle this complex issue. The SLP quantifies an optimal way of integrating the constraints to optimize crop production, financial profits, and carbon farming. Favorably, the Microsoft Excel includes a Linear Programming Solver, which could be applied to solve this optimization problem. The principal objective of this paper is to use the SLP as a case study example to investigate different carbon sequestration scenarios to define the best beneficial option.

II. MATERIALS AND METHODS

2.1 The Mekabo Irrigation Scheme

The selected case for this study is the Mekabo small-scale irrigation scheme, which is located about 50 km north of the city of Mekelle (center of the Tigray state). It features a weir constructed across the Augla river to divert irrigation water to the command area. Fig. 1 shows a view of the weir and the irrigation command area, which was financially supported and constructed by the REST NGO in March 2016.

FIGURE 1. The weir and irrigation command area for Mekabo small- scale irrigation scheme

The 60-ha irrigation land accommodates 144 smallholder farmers and receives gravity water from a 1.3 km stone paved conveyance canal diverted from the weir. The input parameters for this study were collected from the field survey during the implementation of SMIS Project (A small-scale irrigation support project funded by the governments of Canada and the Netherlands during 2014-2019). Some other inputs were produced by visiting the area and assessing the field parameters. The types of crops cultivated in the Mekabo irrigation scheme are almost according to the results of agro-ecological suitability and socio-economic studies performed during the feasibility study conducted by REST NGO. Given the necessity of satisfying the farmers' nutritious diet, the types of crops for the Mekabo irrigation scheme include vegetables (potato, tomato, and cabbage), cereals (corn and barley), pulses (beans, peas, and lentils), fruits (mango, and papaya), and fallow.

2.2 Scenarios

To ensure the study is inclusive of the farmer's food security demand, farmer's income, and additional carbon farming benefits, seven cropping pattern scenarios were developed and presented in table 1. These initial cropping patterns would be optimized by the SLP while utilizing the constraints to maximize either the individual or the combined benefits of farmer's income, farmer's food security demand, and additional carbon farming. To gain the benefits of additional carbon farming, no specific crop was added to the cropping pattern; instead, the cropping intensity was raised and suitable crops were paired on the same piece of land sharing the same growing season.

TABLE 1
THE SEVEN SCENARIOS FOR OPTIMIZATION

Scenario	Subject of Optimization
Scenario 1	Farm income
Scenario 2	Farmer's food security
Scenario 3	Additional carbon farming
Scenario 4	Combined benefits of additional carbon farming and farm income
Scenario 5	Combined benefits of additional carbon farming and farmer's food security
Scenario 6	Combined benefits of farmer's food security and farm income
Scenario 7	Combined benefits of farm income, farmer's food security, and additional carbon farming

The Carbon Cycle Institute (CCI) has identified a collection of eighteen (18) different agricultural practices depicted in fig. 2 that introduce various choices of increasing the amount of carbon sequestering [3], [4], [5]. Among the various carbon sequestration practices introduced by CCI, the alley-cropping (number 2), multi-species-cover cropping (number 11), and the no-till planting (number 18) are considered low input and simple technique practices that could easily be adopted in the Mekabo small-scale irrigation scheme and will be discussed below.

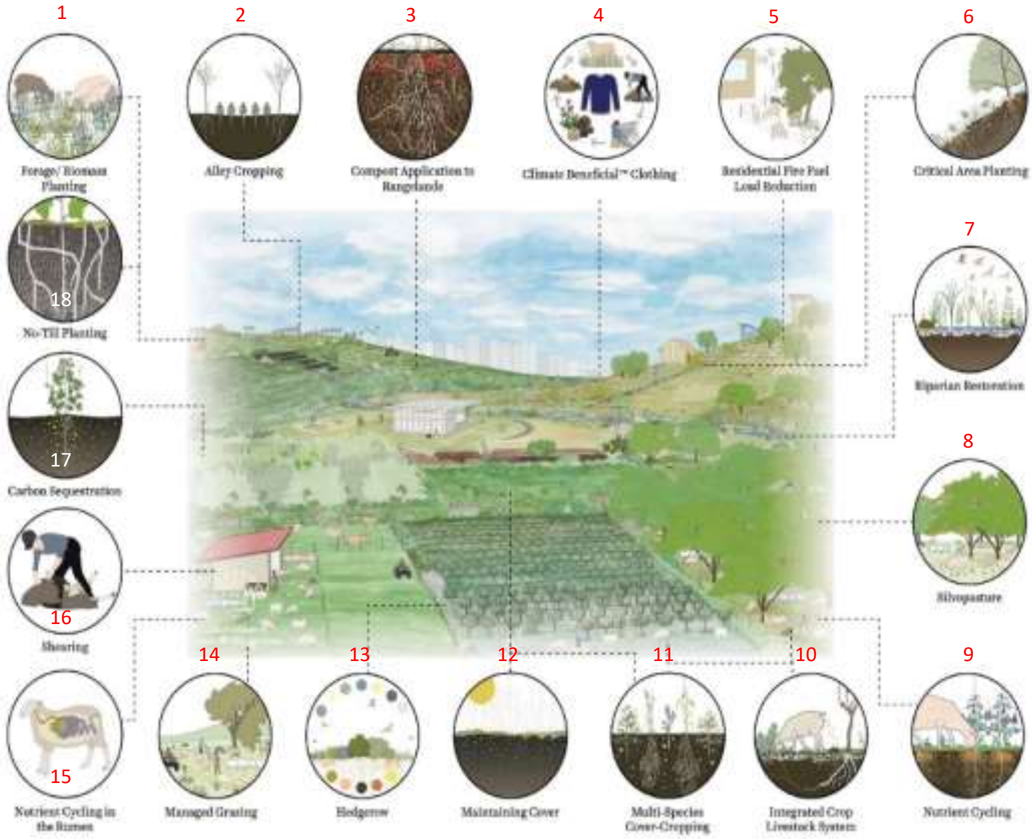

FIGURE 2: Various carbon sequestration options (adopted from [3])

2.2.1 Alley cropping

Alley cropping includes planting of trees or shrubs that are generally implanted in a single or multiple-row with traditional crops like small grain in between [6]. In the Mekabo irrigation scheme all vegetable crops, cereals, and pulses could be cultivated under the mango and papaya fruit trees, which in turn can add to the rate of carbon sequestration. There is no solid research information in the literature for carbon sequestration by agricultural crops in Ethiopia [7], [8]. Nair et.al. [9] reports the rate of crop carbon sequestration in Mali and the West African Sahel at about 1.09 tons/ha/year. In the absence of similar information for Ethiopia, the average rate of 1.0 ton/ha/year carbon sequestration has been used for estimation in the Mekabo irrigation scheme. Also, there is no confirmed CCX price for Ethiopia in the literature [10]; therefore, an equivalent value of $US 10 has been extracted [2] and has been used as an average CCX price for calculating additional benefits in the Mekabo irrigation scheme.

2.2.2 Multi-species cover cropping

Multi-species cover cropping involves the cultivation of two or more species on the same piece of land where the growth cycles of different species overlap at least for part of their growing duration [11], [12]. In the case of the Mekabo irrigation scheme, it may take the form of inter-cropping where mango and papaya trees are inter-planted with annual species such as beans, peas, and lentils. The previous studies in water-limited environments estimated the carbon sequestration for cover crops between

2.37 ± 2.3 tons/ha/year [13]. In the absence of a valid information for Ethiopia, an average rate of 2.0 tons/ha/year has been adopted for carbon sequestration and an equivalent of $US 10 per carbon credit is used for the calculation of economic benefits of multi-species cover cropping in this study [2].

2.2.3 No-till Farming

No-till farming is the process of growing crops without disturbing the soil through tillage [14]. No-till farming increases both water absorption and organic matter retention by recycling nutrients back into the soil. According to the existing information in the literature, farmers who convert to no-till practices and start using cover crops may achieve a net carbon gain of one or two tons per hectare each year [1]. In the absence of adequate information for Ethiopia, an average value of 1.0 ton/ha carbon sequestration has been assumed for no-till plantation in the Mekabo irrigation scheme. For estimating the economic benefits [15], an average CCX price of $US 10 has been extracted from Opanda [2] and was used in this paper.

2.3 Using the Simplex Linear Programming (SLP)

The standard form of SLP has the following components [16], which will be discussed as follows:

- Decision variables to be optimized;
- Objective functions that must be maximized and will be subjected to constrains;
- Constraints.

2.3.1 Decision variables

Decision Variables are the combination of mathematical expressions in the objective functions to be optimized by the SLP. The goal is that SLP finds optimized values for the coefficient of decision variables to provide the best rate of the objective functions [16]. For the Mekabo irrigation scheme, the types of selected crops are the decision variables that the percentage of which is to be optimized. The types of crops for the Mekabo irrigation scheme include vegetables (potato, tomato, and cabbage), cereals (corn and barley), pulses (beans, peas, and lentils), fruits (mango, and papaya), and fallow. Accordingly, table 2 shows the list of twelve decision variables X_1, X_2, X_3, $X4$…...... X_{12}, and their coefficients C_1, C_2, C_3, C_4......... C_{12}, for the Mekabo irrigation scheme to be utilized in the SLP.

2.3.2 Objective function

The Objective Function is a mathematical expression that combines the decision variables and their coefficients to maximize farm benefits as follows [16]:

$$Z\ f(C_1X_1, C_2X_2, C_3X_3, C_4X_4 \cdots\cdots\cdots C_nX_n) \quad (1)$$

The maximum farm benefits for the Mekabo irrigation scheme means the combination of secure food produce, adequate farming income, and the highest carbon farming benefits subjected to the agronomic and environmental constraints. The general form of an objective function (Z) could mathematically be expressed as follows [17], [18]:

$$Max\ Z\ \approx \sum_{j=1}^{n} C_j\, X_j\ \ where{:}\ j = 1\ to\ n \quad (2)$$

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

$$Max\ Z\ \approx C_1X_1 + C_2X_2 + C_3X_3 + C_4X_4 + \cdots\cdots\cdots\cdots\cdots C_{12}X_{12} \quad (3)$$

Where Z is the farm gross benefits resulting from growing 11 crops (plus a fallow). The C_1, C_2, C_3, C_4 ....C_{12} are the coefficients of decision variables in the objective function related to Z (the objective function value). Table 2 shows the elements in the objective function.

TABLE 2
THE DECISION VARIABLES AND THE ELEMENTS IN THE OBJECTIVE FUNCTION

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}	$C_{12} * X_{12}$

2.3.3 Constraints

Constraints are the mathematical expressions to represent limits in the linear program related to agronomic, environmental, and carbon farming. The model assesses and identifies possible solutions that respect those limits in order to achieve the optimum objective function [16]. The general form of constraints is expressed as follows:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}\, x_j \leq b_i \tag{4}$$

or

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}\, x_j \geq b_i \;\; where\text{: } j = 1 \; to \; n \; and \; i = 1 \; to \; m \tag{5}$$

Where a_{ij} and b_i are the coefficients and the values for constraints, respectively. Expansion of the above expression for "n" (the number of decision variables or crops) and for "m" (the number of constraints) are presented as follows:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{1n}x_n \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{2n}x_n \leq b_2$$

$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + a_{34}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{3n}x_n \leq b_3$$

$$a_{41}x_1 + a_{42}x_2 + a_{43}x_3 + a_{44}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{4n}x_n \leq b_4$$

$$\vdots\vdots\vdots\vdots\vdots\vdots\vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + a_{m3}x_3 + a_{m4}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{mn}x_n \leq b_m \tag{6}$$

Since there are 22 constraints and 12 decision variables in this study; therefore, m=22 and n=12 will be substituted in the above expressions and the mathematical expression would be expanded as follows:

$$a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{112}x_{12} \leq b_1$$

$$a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + a_{24}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{212}x_{12} \leq b_2$$

$$a_{31}x_1 + a_{32}x_2 + a_{33}x_3 + a_{34}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{312}x_{12} \leq b_3$$

$$a_{41}x_1 + a_{42}x_2 + a_{43}x_3 + a_{44}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{412}x_{12} \leq b_4$$

$$\vdots\vdots\vdots\vdots\vdots\vdots\vdots$$

$$a_{221}x_1 + a_{222}x_2 + a_{223}x_3 + a_{224}x_4 + \cdots\cdots\cdots\cdots\cdots\cdots + a_{2212}x_{12} \leq b_{22} \quad (7)$$

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

$$X_j \geq 0 \quad (8)$$

Therefore, the above-mentioned equation develops to:

$$X_1 \geq 0;\ X_2 \geq 0;\ X_3 \geq 0;\ X_4 \geq 0; \cdots\cdots\cdots\cdots\cdots X_{12} \geq 0 \quad (9)$$

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

2.3.4 Setting the constraints limits

Twenty-two constraints are defined in the design of the cropping pattern for the Mekabo irrigation scheme. The constraints 1 to 9 reflect the cropping pattern's agro-ecological conditions that include crop water consumption, nutrition values, disease resistance, pest resistance, market demand, fertilizer input, labor requirement, capital expenses, and post-harvest processing demand. The constraint number 10 constitutes the total desired cropping intensity in each scenario. The significance of constraints 1 to 9 is ranked according to the crop performance ranking index (CPR) and is presented in table 3 [17].

TABLE 3
THE CPR INDEX 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

The constraints 11 to 22 would only include the minimum desired cropping area for each scenario, which is presented in table 4. For water consumption, fertilizer input, labor requirement, capital expenses, and post-harvesting demand (constraints 1, 6, and 7 to 9), the "≤" sign was used as a desired condition for analysis in the SLP. However, to maximize the advantage of nutritious crops, disease resistance, pest resistance, and market demand (constraints 2 to 5) the "≥" sign was adopted.

TABLE 4
THE INITIALLY DEFINED CROPPING AREAS FOR EACH SCENARIO

Crops		Constraints	Condition	Scenarios (ha)							Rationale
				1	2	3	4	5	6	7	
Vegetables	Potato	Constraint 11	≥	0.00	0.02	0.00	0.00	0.00	0.05	0.05	To improve nutrition level in the farmer's diet, to generate some income, and to allow carbon farming
	Tomato	Constraint 12	≥	0.00	0.01	0.00	0.00	0.00	0.02	0.05	
	Cabbage	Constraint 13	≥	0.00	0.01	0.00	0.00	0.00	0.00	0.02	
Cereals	Corn	Constraint 14	≥	0.00	0.15	0.00	0.00	0.10	0.10	0.10	To improve fiber level in the farmer's diet and to produce forage for livestock
	Barley	Constraint 15	≥	0.00	0.10	0.00	0.00	015	0.20	0.10	
Pulses	Beans	Constraint 16	≥	0.00	0.05	0.20	0.20	0.05	0/05	0.07	To improve nourishment in the farmer's diet and to allow carbon farming
	Peas	Constraint 17	≥	0.00	0.05	0.00	0.00	0.01	0/00	0.00	
	Lentils	Constraint 18	≥	0.00	0.05	0.15	0.15	0.15	0/15	0.10	
Cash crops	W/rmelon	Constraint 19	≥	0.00	0.01	0.00	0.00	0.00	0/00	0.00	To improve farmer's income
Fruits	Mango	Constraint 20	≥	0.00	0.10	0.20	0.15	0.10	0/10	0.10	To improve nutrition in the farmer's diet, to generate income, to allow carbon farming
	Papaya	Constraint 21	≥	0.00	0.10	0.00	0.20	0.10	0/10	0.10	
Fallow	No crop	Constraint 22	=	0.10	0.10	0.10	0.10	0.10	0.10	0.10	To improve soil health
Total initially defined cropping area (ha)			=	0.10	0.75	0.65	0.80	0.76	0.87	0.79	-

Table 5 shows the matrix of all twenty-two constraints, the sum of the product of each constraint with cropping pattern area, analysis condition, and the minimum or maximum limit for each constraint to be used by SLP.

TABLE 5
THE CONSTRAINTS USED FOR THE ANALYSIS BY THE SLP

CONSTRAINTS	Potato	Tomato	Cabbage	Corn	Barley	Beans	Peas	Lentils	W/melon	Mango	Papaya	Fallow	Sum of product of constraint and cropping pattern area	Required	
	a_{i1} x_1 +	a_{i2} 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}		Condition	Limit
Constraint 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}	Sum of product of constraint 1 and cropping area	≤	50
Constraint 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}	'Sum of product of constraint 2 and cropping area	≥	70
Constraint 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}	'Sum of product of constraint 3 and cropping area	≥	60
Constraint 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}	'Sum of product of constraint 4 and cropping area	≥	60
Constraint 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}	'Sum of product of constraint 5 and cropping area	≥	50
Constraint 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}	'Sum of product of constraint 6 and cropping area	≤	70
Constraint 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}	'Sum of product of constraint 7 and cropping area	≤	50
Constraint 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}	'Sum of product of constraint 8 and cropping area	≤	50
Constraint 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}	'Sum of product of constraint 9 and cropping area	≤	50
Constraint 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}	Sum of cropping area (ha)	=	1.0 or 1.2 or 1.35 ha
Constraint 11	a_{111} x_1												Area for potato (ha)	≥	according to scenario (ha)
Constraint 12		a_{122} x_2											Area for tomato (ha)	≥	according to scenario (ha)
Constraint 13			a_{133} x_3										Area for cabbage (ha)	≥	according to scenario (ha)
Constraint 14				a_{144} x_4									Area for corn (ha)	≥	according to scenario (ha)
Constraint 15					a_{155} x_5								Area for barly (ha)	≥	according to scenario (ha)
Constraint 16						a_{166} x_6							Area for beans (ha)	≥	according to scenario (ha)
Constraint 17							a_{177} x_7						Area for peas (ha)	≥	according to scenario (ha)
Constraint 18								a_{188} x_8					Area for lentils (ha)	≥	according to scenario (ha)
Constraint 19									a_{199} x_9				Area for watermelon (ha)	≥	according to scenario (ha)
Constraint 20										a_{2010} x_{10}			Area for mango tree (ha)	≥	according to scenario (ha)
Constraint 21											a_{2111} x_{11}		Area for papaya tree (ha)	≥	according to scenario (ha)
Constraint 22												a_{2212} x_{12}	Area for fallow (ha)	=	according to scenario (ha)

2.4 Application of the SLP

The "Add-Ins" choice in the Microsoft "Excel Options" [19], [20], [21] was activated and the "Solver" tool from the "Data" menu was utilized. The "Solver" tool needed inputs from the average crop production rates as well as the farm-gate prices for eleven selected crops, which was adopted by Jebelli et al., [17] with some adjustment in the prices (table 6). To run the "Solver", the crop production rates and the farm-gate prices were administered in two separate adjacent row cells in the Excel sheet. The "Solver" also required a third-row cells be allocated for the twelve optimized cropping areas calculated by the "Solver" (changing variable cells). For the "Solver" to inscribe the calculated maximum value (Max Z in ETBirr/ha), a single cell had also been allocated in the Excel sheet adjacent to the other three rows. The argument embedded in this single Excel cell would calculate the "SUMPRODUCT" of the three previously described sets of rows and then would pick the maximum value to inscribe it in the single cell.

When the "Solver" button in the Excel menu was clicked, it prompted a screen titled "Solver Parameters" as demonstrated in fig 3. The address of a single Excel cell for maximizing benefits (Max Z) was entered in the empty space for "Set Objective". The addresses of the row cells to receive the twelve optimized cropping areas were entered for "By Changing Variable Cells" and the addresses of the row cells containing the sum of products and the conditions of the twenty-two constraints were added one by one in the "Subject to the Constraints" sub-window [21]. After entering all the required data, the "Max" button on the Solver screen was checked. The process of optimization started when the "Solve" button was activated.

TABLE 6
THE MAXIMIZED BENEFITS AND THE OPTIMIZED CROPPING PATTERN FOR EACH SCENARIO

Crops		Crop production (kg/ha)	Farm-gate price (ETB/kg)	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6		Scenario 7	
				Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)	Cropping area (ha)	Max Z (ETB/ha)
Vegetables	Potato	9,500	18	0.00	347,300	0.02	176,974	0.00	229,552	0.00	250,976	0.00	244,884	0.05	177,411	0.05	244,228
	Tomato	12,000	28	0.00		0.01		0.00		0.00		0.00		0.02		0.05	
	Cabbage	20,000	12	0.00		0.01		0.00		0.00		0.00		0.00		0.02	
Cereals	Corn	5,000	12	0.00		0.15		0.00		0.00		0.10		0.10		0.10	
	Barley	2,000	18	0.10		0.10		0.40		0.40		0.63		0.20		0.42	
Pulses	Beans	2,100	39	0.00		0.05		0.20		0.20		0.05		0/05		0.07	
	Peas	1,400	41	0.00		0.05		0.00		0.00		0.01		0/00		0.00	
	Lentils	1,000	83	0.40		0.29		0.15		0.15		0.15		0/27		0.10	
Cash crops	W/melon	10,000	21	0.00		0.01		0.00		0.00		0.00		0/00		0.00	
Fruits	Mango	12,600	28	0.00		0.10		0.20		0.15		0.10		0/10		0.10	
	Papaya	22,500	35	0.40		0.11		0.15		0.20		0.21		0/11		0.19	
Fallow	No crop	0	0	0.10		0.10		0.10		0.10		0.10		0.10		0.10	
Total desired cropping intensity (Input for constraint 10 in SLP)				1.00	-	1.00	-	1.20	-	1.20	-	1.35	-	1.00	-	1.20	-

Accordingly, the Solver estimated the optimized percentage for the twelve proposed crops as well as calculated the Max benefit (Z) and displayed it in the previously allocated single cells in the Excel sheet.

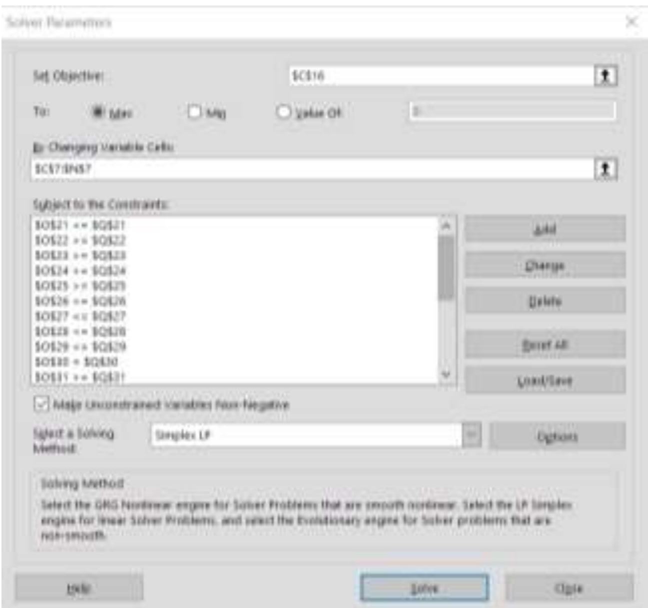

FIGURE 3. The snapshot of the "Solver Parameters" screen

III. RESULTS AND DISCUSSION

Accounting for all twenty-two constraints, the SLP has maximized the benefits while in the meantime optimizing the percentage of crops in the cropping pattern for each scenario. In each successful run, a message reading "Solver found a solution" followed by "All constraints and optimality conditions are satisfied" demonstrated the successful end of the optimization process. Table 7 shows the results of maximized benefits and the optimized percentages of cropping pattern for all scenarios. As demonstrated in table 7, the introduced Carbon farming would generate some extra financial benefits from selling the carbon credit in the CCX trade market. The total financial benefits of CCX and the selling crops are presented in table 8. The rate of additional carbon sequestered in each scenario as a result of additional carbon farming is also presented in table 8. Fig 4 compares the Max Benefits (Z) and the optimized cropping areas for all scenarios. The SLP has maximized the farmer's income in scenario one without considering the farmer's food security demand and carbon farming. In this case, the farmer can earn 347,300 ETBirr/ha/year if all its farm products are sold at the market.

TABLE 7
THE SUM OF TOTAL FINANCIAL BENEFITS IN EACH SCENARIO

Scenario	Optimized Cropping Intensity (ha)	Alley Cropping			Multi-species-cover Cropping			No-till Planting			Maximized Benefits by SLP (ETBirr/ha/year)	Sum of Total Benefits (ETBirr/ha/year)
		Match for Alley Cropping (ha)	(1)Unit CCX ($US)	(2)Total Price (ETBirr/ha)	Multi-species Cropping (ha)	(3)Unit CCX ($US)	Total Price (ETBirr/ha)	No-till Cropping (ha)	(4)Unit CCX ($US)	Total Price (ETBirr/ha)		
1	1.0	0	-	0	0	-	0	0	-	0	347,300	347,300
2	1.0	0	-	0	0	-	0	0	-	0	176,974	176,974
3	1.20 (0.2 ha extra allowed for carbon farming)	0.35 (beans under mango and lentils under papaya tree)	10	179	0	-	0	0.65 (no-till cropping for all available fields)	10	332	229,552	230,062
4	1.20 (0.2 ha extra allowed for carbon farming)	0.35 (beans under papaya and lentils under mango tree)	10	179	0	-	0	0.65 (no-till cropping for all available fields)	10	332	250,976	251,486
5	1.35 (0.35 ha extra allowed for carbon farming)	0.31 (beans+peas+ lentils under papaya and corn under mango)	10	158	0	-	0	0.69 (no-till cropping for all available fields)	10	352	244,884	245,394
6	1.0	0	-	0	0	-	0	0	-	0	177,411	177,411
7	1.20 (0.2 ha extra allowed for carbon farming)	0.29 (potato+tomato+cabbage+ beans under papaya & lentils under mango tree)	10	148	0.10 (corn and barley)	10	51	0.71 (no-till cropping for all available fields)	10	362	244,228	244,789

(1) The unit CCX price for alley cropping is estimated to be $US 10 [2].
(2) The $US conversion rate assumed to be 1$US= 51 ETBirr.
(3) The unit CCX price for multi-species-cover cropping is estimated to be $US 10 [2].
(4) The unit CCX price for no-till cropping is estimated to be $US 10 [2].

The lowest financial benefits are produced in scenario two because the SLP has maximized the farmer's food security benefits; therefore, the farm income and the carbon farming benefits are compromised.

TABLE 8
THE SUM OF ADDITIONAL CARBON SEQUESTRATION IN EACH SCENARIO

Scenario	Optimized Cropping Intensity (ha)	Alley Cropping			Multi-species-cover Cropping			No-till Planting			Sum of Total Carbon Sequestration (Ton/ha/year)
		Match for Alley Cropping (ha)	(1)Carbon Sequestration (Ton/ha/year)	Total Sequestration (Ton/ha/year)	Multi-species Cropping (ha)	(2)Carbon Sequestration (Ton/ha/year)	Total Sequestration (Ton/ha/year)	No-till Cropping (ha)	(3)Carbon Sequestration (Ton/ha/year)	Total Sequestration (Ton/ha/year)	
1	1.0	0	-	0	0	-	0	0	-	0	0
2	1.0	0	-	0	0	-	0	0	-	0	0
3	1.20 (0.2 ha extra allowed for carbon farming)	0.35 (beans under mango and lentils under papaya tree)	1.0	0.35	0	-	0	0.65 (no-till cropping for all available fields)	1.0	0.65	1.0
4	1.20 (0.2 ha extra allowed for carbon farming)	0.35 (beans under papaya and lentils under mango tree)	1.0	0.35	0	-	0	0.65 (no-till cropping for all available fields)	1.0	0.65	1.0
5	1.35 (0.35 ha extra allowed for carbon farming)	0.31 (beans+peas+ lentils under papaya and corn under mango)	1.0	0.31	0	-	0	0.69 (no-till cropping for all available fields)	1.0	0.69	1.0
6	1.0	0	-	0	0	-	0	0	-	0	0
7	1.20 (0.2 ha extra allowed for carbon farming)	0.29 (potato+tomato+cabbage+ beans under papaya & lentils under mango tree)	1.0	0.29	0.10 (corn and barley)	2.0	0.20	0.71 (no-till cropping for all available fields)	1.0	0.71	1.20

(1) The carbon sequestration for alley cropping is taken from Nair et.al., [9].
(2) The carbon sequestration for multi-species-cover cropping has been taken from Blanco-Canqui, et al., [13].
(3) The carbon sequestration for no-till cropping has been taken from Barth [1].

Scenario three considers the additional carbon farming as a top priority and the other two profits have less importance. Maximizing the combined benefits of additional carbon farming and farmer's income is reflected in scenario four. In scenario five, the combined benefits of additional carbon farming and farmer's food security is considered a high priority and the farmer's income gets lower importance. There is no carbon farming benefit in scenario six; thus, the combined benefits of farmer's food security and farm income play an important role in the process. The SLP has maximized the combined benefits of farm income, farmer's food security, and additional carbon farming in scenario seven. Figure 4 compares both the financial benefits and the cropping areas for all scenarios.

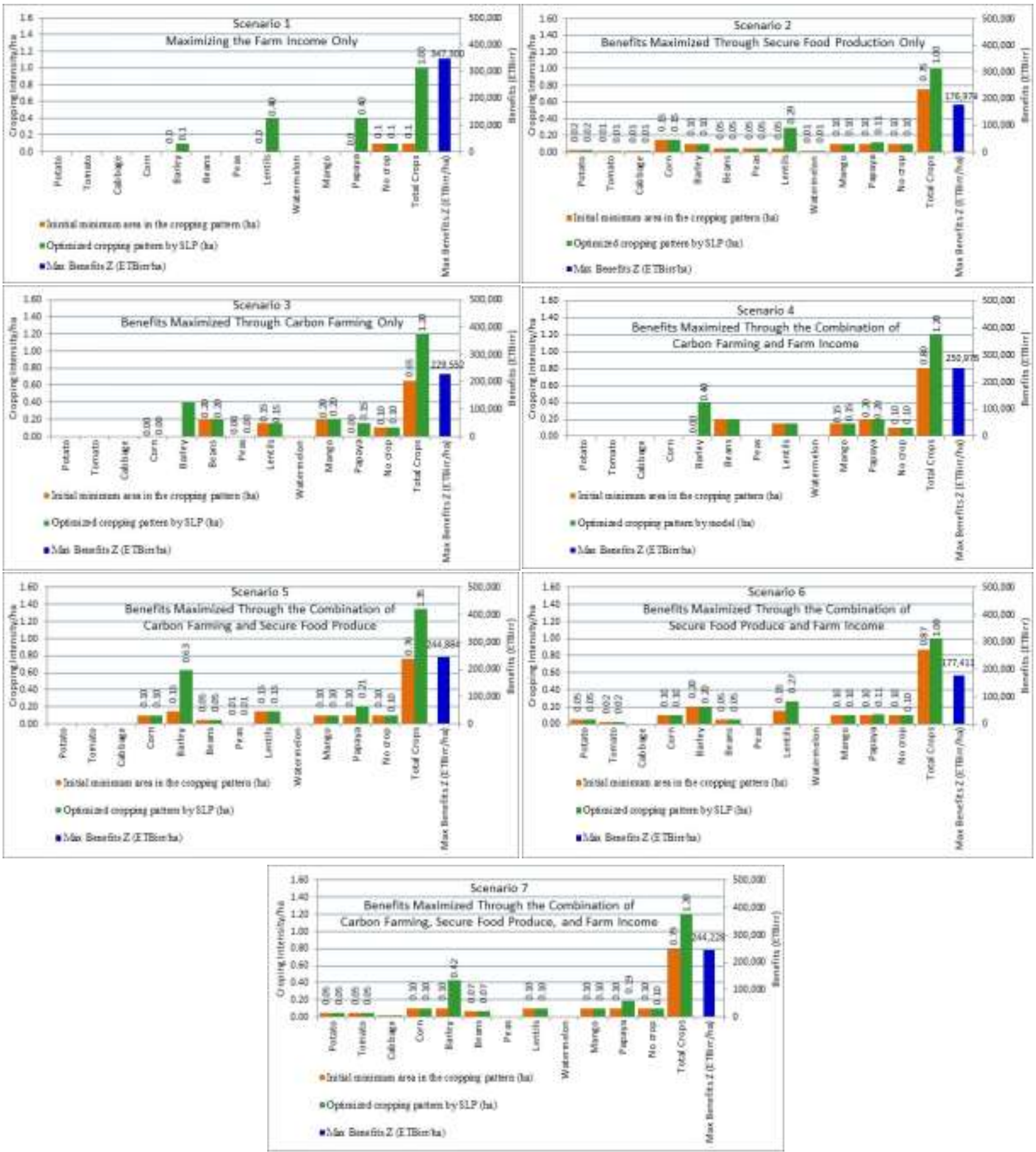

FIGURE 4. Comparing the financial benefits and the percentage of optimized cropping areas

IV. SUMMARY AND CONCLUSIONS

Seven scenarios were developed, and a simplex linear programming (SLP) was utilized to study various options of adopting carbon farming into the cropping pattern while maximizing either the individual or the combined benefits of farm income, farmer's food security, and additional carbon sequestration in the Mekabo irrigation scheme. The Solver tool from Microsoft Excel program was used to run the SLP. The results show that additional carbon farming increased the amount of carbon sequestration and created the potential for extra financial benefits from selling carbon credits. Figure 5 compares the total financial benefits and the rate of additional carbon sequestered in all scenarios. Among the scenarios, there is no additional carbon sequestration in scenarios 1, 2, and 6. However, among the remaining scenarios, scenario 7 has the highest rate of additional carbon sequestration (1.2 ton/ha/year). Because there are no meaningful financial benefit differences among scenarios 3, 4, 5, and 7; therefore, it could be concluded that scenario 7 is the most beneficial scenario because it has the highest rate of additional carbon sequestration while satisfies the benefit of farmer's food security and still generates relatively a good farming income. Alley cropping, multi-species-cover cropping, and no-till planting in scenario 7 could encourage the highest rate of additional carbon sequestration so it could have a better role in the alleviation of global warming.

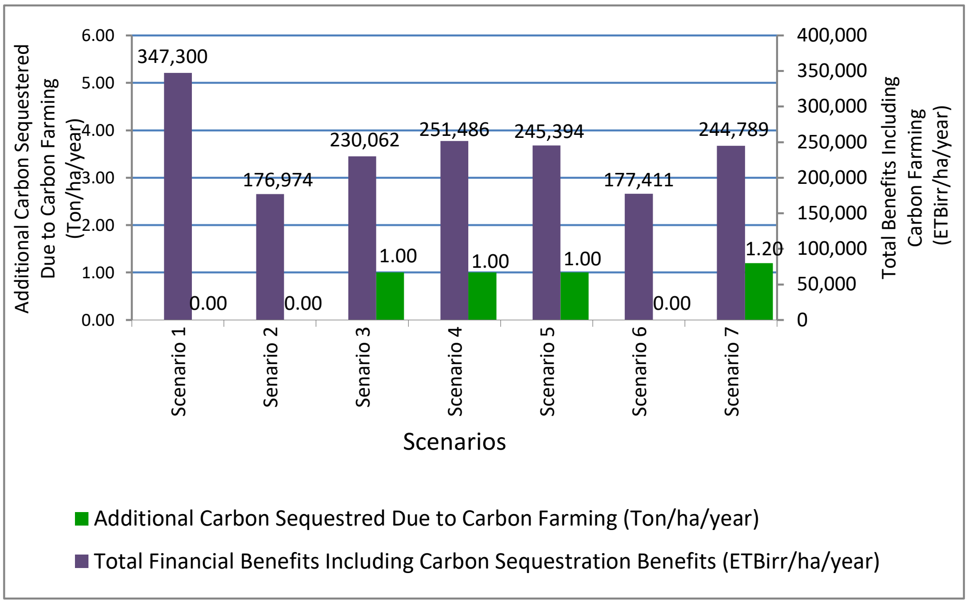

FIGURE 5. Comparison of total financial benefits and the additional carbon sequestration

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