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Determination of optimum crop mix for crop cultivation in Bangladesh

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The productivity of the agriculture sector in Bangladesh has yet to reach an acceptable level. In this paper the possibility of increasing the contribution of this sector through proper crop planning is sought. Various factors such as land types, alternative crops/crop combinations, crop patterns, input requirement, investment, output, etc. influence the crop cultivation. The choice of the right crop(s) for the right type of land is the key problem that maximizes the overall contribution having satisfied the food demand, land availability, and capital constraints. In this context a linear programming model has been developed to determine the area to be used for different crops for maximum contribution. The results reveal that an annual contribution can be increased by 15,945.10 million Taka (US $1.00 = 41.00 Taka approximately) through proper planning.

Keywords: crop planning, linear programming, optimum crop mix

1. Introduction

Bangladesh is yet to be a self-sufficient country in food. About 80% of the people are engaged in agriculture, yet the country has to import food every year. Along with various other factors responsible for low agricultural output such as unscientific methods of cropping and natural calamities the absence of a proper nationwide crop-planning program has been identified as a significant factor.

Crop planning is related to many factors such as the types of lands, yield rates, weather conditions, availability of the agricultural inputs, food demand, capital availability, and the cost of production. Some of these factors are measurable and can be quantified. However factors like rainfall, weather conditions, floods, cyclones, and other natural calamities are difficult to predict. However if the available information can be utilized properly, it may give valuable suggestions despite the exclusion of nonquantifiable factors. The country grows a wide variety of crops in different seasons (Summer [April–September], locally known as *kharif* season, and Winter [November–March], locally known as *rabi* season), and it has different types of lands. The yield rate, the cost of production, and the contribution are functions of soil characteristics (fertility, etc.), region, the crop being produced, cropping pattern, and method (crops being produced and their sequence, irrigation, nonirrigation, etc.). For a single-cropped land there are a number of alternative crops from which the crop to be cultivated in a year may be chosen. Similarly there are many different combinations of crops for double- and triple-cropped lands. Different alternatives or combinations give different outputs. The utilization of land for necessary/appropriate crops is the key problem for crop planning in Bangladesh. Therefore a linear programming model has been developed and solved to provide an annual crop production plan that determines the

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area to be used for different crops for the maximum possible contribution and self-sufficiency in food having satisfied the constraints arising out of food demand, capital, and land.

A survey of existing literature on the use of LP in agricultural planning revealed several cases similar to the current problem. Butterworth[1] discusses the Bedfordshire mixed cropping model for the selection of crops, particularly vegetables, and livestock heads, which use the resource of land, labor, and machinery to make maximum farm profits. The problem area was a 500-acre farm, which is half on heavy land and half on light. The light land, being irrigated, is suitable for a wide range of crops. The planning team first listed all of the available resources (land, buildings, machinery, labor, and capital) that became the main constraints of the model. The possible enterprises that the farm could invest in were then listed. There were 15 different crop/crop groups possible for the heavy land and 25 for the light land. For livestock farming there were six alternatives. Apart from the main constraints of the limitation of the resources some additional constraints due to the rotational cultivation of some crops and the physical limitations of the machinery, building capacity, livestock feed requirements, etc. were also imposed. Upon solution of the problem the new farming scheme showed an increase of the total gross margin by 38,000 pound-sterling.

Thomas and Euan[2] describe a quantitative whole-farm model to optimize the farm profits by selection of the crop rotation, marketing methods, livestock quantity, level of livestock nutrition, utilization of pastures, and types of livestock feed.

Glen[3] developed an LP model to maximize the profits of an integrated crop- and beef-producing enterprise. The variables of the model relate to the activities of animal feeding, animal buying, animal selling, crop production, and crop selling. The constraints were on feed stuff availability, availability of animals to be sold, farm size, and initial and final conditions of the planning horizon. Bandyopadhyay and Datta[4] developed an LP model to evaluate alternative strategies of water availability for command areas under different cropping patterns and to specify the economic and social effects in India.

Zuo et al.[5] addressed a production-planning problem for a large seed corn production company operated in North America. The company has five divisions, and each division is responsible for its own production plan. It is observed that the average yield of each hybrid varies considerably among different production facilities. It appears that the total cost could be minimized by allocating the production of corn hybrids to the geographical areas that provide maximum yields and then transporting them to the sales regions where they are needed. A series of mathematical programming models is developed to achieve the objectives of the study. A linear programming package and a mixed-integer programming package are combined by a designed heuristic program to solve the problem.

The use of mathematical programming in other areas of the agricultural sector is also a common practice. The interested reader can find some applications in Bari[6] Yates and Rehman[7] and Lara and Romero.[8] However the application of LP for a nationwide crop-planning problem has not been observed in the literature.

The present model differs from the above models in that it seeks to optimize the contribution from the agricultural sector of Bangladesh by determining the allocation of different land types for cultivation, land availability and suitability, capital, and import bounds.

Following this introduction the formulation of the linear programming model for the present problem is presented. The computational experience, the results, and the sensitivity analysis are then briefly discussed. Finally the conclusions are drawn.

2. Model formulation

The model is developed for a planning horizon of 1 crop year (cycle of 12 months). Multiperiod cropping pattern (patterns that take more than 1 crop year), mixed cropping[9] (secondary crops are mixed with the primary crop, for example, gram mixed with wheat)/inter cropping (secondary crops are produced within the rows of the primary crop, for example, potato intercropped with sugarcane), and the shifting of sowing/harvesting periods (sowing and/or harvesting periods may be shifted for some time due to lack of timely rain fall, natural hazards, etc.) are not considered.

Three types of lands, namely, single-, double-, and triple-cropped lands, are identified according to the cropping pattern.[10,11] In a single-cropped land we have a number of alternative crops from which we can cultivate one crop in a year. Similarly we have many combinations of crops for double- and triple-cropped lands. The number of crop combinations selected for these three land types are $n1$, $n2$, and $n3$, respectively. From the above considerations the following variables, coefficients, and data can be identified and defined.

2.1 Variables

X_{ijk} = The area (acre) of land to be cultivated for crop i of crop combination j in land type k.

I_i = The amount (metric tons) of crop i that should be imported.

2.2 Coefficients

A_{ijk} = Yield-rate coefficient that is the amount of production (metric tons) per acre of crop i of crop combination j in land type k.

C_{ijk} = Cost coefficient that is the cost (Taka) of production per acre of crop i of crop combination j in land type k.

B_{ijk} = Contribution coefficient that is the benefit (Taka) that can be obtained per acre of land from crop i of crop combination j in land type k.
$= P_i^* A_{ijk} - C_{ijk}$

P_i = the market price (Taka) of crop i per metric ton.

IC_i = Contribution in Taka per ton from import of crop i.
= (Market revenue − Import cost) in Taka per ton of crop i.

2.3 Data

D_i =Yearly demand (Metric tons) of crop i.
L_k =Available acreage of land type k.
C_a =Capital available (Taka); this indicates the total amount of money that can be invested for cropping.

The linear programming model for crop planning then can be presented as follows.

Objective function.—The objective function of the model is to maximize the contribution that can be obtained from cropping in a single-crop year plus imported crops.

$$\text{Maximize } Z = \sum_i \sum_j \sum_k B_{ijk} \cdot X_{ijk} \sum_i IC_i \cdot I_i$$

where

$$i = 1, n1$$

$$j = \begin{cases} 1, n1 & \text{for single cropped land } (k = 1) \\ 1, n2 & \text{for double cropped land } (k = 2) \\ 1, n3 & \text{for triple cropped land } (k = 3) \end{cases}$$

where

$$k = 1, 2, \text{ and } 3$$

2.4 Constraints

1. **Food demand constraint**: This constraint represents that the sum of local production and the import quantity of crop i in a single-crop year must be greater than or equal to the total requirements in the country. The constraint may be of two kinds:

$$\sum_j \sum_k A_{ijk} \cdot X_{ijk} + I_i \geqslant D_i \quad (1)$$

$$\sum_j \sum_k A_{ijk} \cdot X_{ijk} \geqslant D_i \quad (2)$$

In the first kind there would be no restriction for import of any crop (/crop groups). All the crops are free to be imported. In this case only equation (1) is required. In the second kind the import may not be permitted for some crops (/crop groups). In that case both the types of equations (1) and (2) are needed, where equation (1) presents the set of crops having import permission and equation (2) has no such permission.

2. **Land constraint**: The sum of lands used for a given type of land must be less than or equal to the total available land of that type.

$$\sum_i \sum_j T_k \cdot X_{ijk} \leqslant L_k \quad (3)$$

where

T_k = Land type coefficient;
$T_1 = 1$ for single-cropped land, because no area is shared with other crops;
$T_2 = 1/2$ because the same land is being used by two consecutive crops in a year on double-cropped land; and
$T_3 = 1/3$ because the same land is being used by three consecutive crops in a crop year in triple-cropped land.

3. **Capital constraint**: The total amount of money that can be spent for crop production must be less than or equal to the capital available/budget.

$$\sum_i \sum_j \sum_k C_{ijk} \cdot X_{ijk} \leqslant C_a \quad (4)$$

4. **Contingent constraint**: The areas used for any crop under a crop combination for double- or triple-cropped land must be equal for every crop.

(a) Double-cropped land: The area used for two crops belonging to any crop combination of double-cropped land must be equal.

$$X_{(i1 \epsilon j)jk} - X_{(i2 \epsilon j)jk} = 0 \quad (5)$$

where

$i1$ = first crop of combination j for $k = 2$
$i2$ = second crop of combination j for $k = 2$

Here $k = 2$ means double-cropped land. For a given crop combination j there are only two crops: $i1$ and $i2$. For example the crop combination $j = 3$ contains: Aus rice, which is denoted by $i1$, and wheat, denoted by $i2$ in the equation. Both Aus rice and wheat use the same double cropped land. Aus rice is cultivated during the first half of the year, and wheat is cultivated just after harvesting Aus rice in the second half of the year.

(b) Triple cropped land: The area used for three crops belonging to any crop combination of triple-cropped land must be equal.

$$X_{(i1 \epsilon j)jk} - X_{(i2 \epsilon j)jk} = 0 \quad (6)$$

$$X_{(i2 \epsilon j)jk} - X_{(i3 \epsilon j)jk} = 0 \quad (7)$$

where

$i1$ = the first crop of combination j for $k = 3$
$i2$ = the second crop of combination j for $k = 3$
$i3$ = the third crop of combination j for $k = 3$

5. **Area and import bound constraint**: Sometimes the amount of area to be used for certain crops is restricted. As for example we cannot use an infinite amount of land for fruits because of the unsuitability of some lands for fruit cultivation. Similarly the quantity of import and/or export also has some bounds. We cannot import or export any crop as we like.

Area bound:

$$\sum_{i \in L1} X_{ijk} \leqslant a \tag{8}$$

where

$L1$ = the set of crops (/crop groups) having area limitation; and

a = area suitable and available for crop i with $k = 1$.

Import bound:

$$\sum_{i \in L2} I_i \leqslant b \tag{9}$$

where

b = limit of total crop import; and

$L2$ = the set of crops (/crop groups) having import limitation.

5. **Nonnegativity constraint**: The decision variables must be greater than or equal to zero, i.e.,

$$X_{ijk} \geqslant 0 \text{ and } I_i \geqslant 0$$

3. Computational experience

The formulated model was incorporated with the data collected from the Bangladesh Bureau of Statistics,[12] the Ministry of Food,[13] and from different publications in the Bangladesh Institute for Development Studies (BIDS), the Bangladesh Agricultural Research Council (BARC), and the Bangladesh University of Engineering and Technology (BUET) library.[9–11,14–16] There are more than 100 different crops cultivated in the country. A full-scale model, considering all these crops, would consist of more than 350 constraints and 150 variables. Though this is not a big problem the decision makers are interested only in the major crops and aggregate information of other crops. Thus all the crops are divided into 10 major groups. The major crops such as rice, jute, and wheat were grouped independently, and the minor crops were grouped according to their sowing and harvesting periods.

The minor crops, normally sown around November and harvested around March, are grouped together as *Rabi* crops (from their local name). Minor crops, sown around April and harvested around September, are grouped as *Kharif* crops. Fruits, sugarcane, and some other whole-year crops are grouped together as fruit and juice. Drugs, narcotics, and some spices and condiments are also whole-year crops, and they are grouped as drugs and narcotics. Appendix I shows all of the 10 crop groups and their member crops. With this grouping the number of crop combinations (see Appendix II) identified for single-, double-, and triple-cropped lands are 10, 17, and 6, respectively, according to the present cropping pattern. Any of the 10 major groups/crops can be produced in a crop year in the single-cropped land. There are 17 pairs of crops that can be produced (one after another of the pairs) in a crop year in double-cropped lands, while there are 6 combinations (3 crops in each group, one after another in a year) in triple-cropped lands. The data for each crop member are then aggregated to get the data for a crop group. The present model consists of 68 variables and 45 constraints.

The model was first solved without import and area restrictions. The result, although indicating high contribution, was not a realistic one. It suggested low production and high import of cereals and high production of fruits, drugs, and narcotics. This is because of the low import costs of cereals and the high contribution of fruits, drugs, and narcotics. The import cost of cereals is lower because the Government of Bangladesh receives around 2.0 million metric tons of cereals every year, at different rates as part of different aid packages. The model considers the subsidized import rates and thus encourages greater import of cereals. The country imposes major restrictions on the import of cereals (to achieve self-sufficiency in food). Moreover there is limited land suitable for the cultivation of fruit, drugs, and narcotics. Thus it is necessary to modify the model by introducing import and area restrictions for these crops. The modified model is then solved permitting the import of 0, 0.5, 1.0, 1.5, and 2.0 million tons of cereals, and their results are compared. The model is solved on a PC using a package program (Quantitative Software for Operations Management, QSOM). The data are given in Appendix III, and a sample LP formulation is shown in Appendix IV.

4. Results and findings

The model maximizes the contribution from cropping. It provides the amount of land that should be used for each crop of a particular crop combination in each of the three land types. The total contribution from cropping is calculated for both the existing cropping pattern and the crop plan suggested by the mathematical programming model. The maximum contribution that can be obtained from existing cropping method and pattern is calculated manually (Taka 142,219.3 million). The contributions suggested by the model under different cereal import conditions are presented in *Table 1*.

The table shows that Taka 15945.10 million more can be earned annually with no cereal imports, and that this amount increases with an increase of cereal imports. This is because, as explained earlier, the import costs of cereals are lower than the local production cost, and fruits are more contributive. Thus if the cereal import quantity is increased, more area may be used for fruit, resulting in high contribution. Due to the limited local market and almost no foreign market, the excess production of fruit is not feasible. Moreover the land type suitable for fruit cultivation is also limited. Since fruits are perishable goods and there exists no proper preserving technology in the country, the storage of surplus fruit production over the local demand is thus not possible and will provide no revenue. On the other hand, due to socioeconomic reasons, it is not possible to import greater quantities of cereals. Presently the cereal is imported at a subsidized rate as part of aid packages, and higher levels of import would incur much higher costs. Moreover a large import

Table 1. Contribution with cereal imports

Problem number	Upper limit of cereal imports (million MT)	Objective function value (million Taka)	Improvement over existing system (million Taka)
1	0.0	158,164.40	15,945.10
2	0.5	177,803.90	35,585.00
3	1.0	184,134.80	41,915.00
4	1.5	188,763.70	46,544.00
5	2.0	193,392.60	51,173.00

of cereals would result in unutilized land and unemployment in the agricultural sector. So self-sufficiency is to be achieved at the same time profit should be maximized with available resources.

With zero cereal import the model suggests that land be used in producing the crops (/crop groups) according to *Table 2*. The model recommends importation of about 1 million metric tons of Rabi crops, while a surplus of more than 10 million metric tons of fruit can be produced for export or storage. The solutions of the model indicate that no importation of other crops is required.

The results suggest an increase in the usage of area for cereals and fruit because of the need for self-sufficiency and higher contribution. It also recommends the decrease of area usage for jute, rabi crops, kharif crops, and drugs and narcotics. The *Table 2* shows the proposed area usage for different crops along with the existing and suggested production quantity, the food demand, and the import quantity.

As mentioned earlier the multiperiod cropping, mixed/intercropping, and the shifting of sowing/harvesting periods is not discussed, in detail, in this paper. For multiperiod cropping the input data are prepared as the ratio of the length of the planning horizon to the sowing to the harvesting period length. For example if the length of the sowing to the harvesting period for sugarcane is n years, then the total costs and yield data must be divided by n to fit into the 1-year model. It is expected that the other two patterns will have a negligible effect on the solutions, because the mathematical model is solved with the aggregate information, as discussed in an earlier section, and because these practices do not involve the major crops with remarkable quantity.

5. Sensitivity analysis

Sensitivity analysis of the tight constraints with positive shadow prices shows that the contribution can be increased by increasing single-, double-, and triple-cropped land, the area for fruit, juice, drugs, and narcotics, and cereal import quantity. The increases in the objective function due to the increase in the right-hand side of these constraints are shown in *Figure 1*. The analysis shows that contribution can be increased greatly by increasing triple-cropped land (an increase of about Taka 600,000 for an increase of 1 acre of triple-cropped land area). However, in practice, an increase in the triple-cropped land area may not be possible, because of unsuitable land type, farmer preferences, lack of proper technology, lack of demand in the local market, etc. The sensitivity analysis also shows that the objective function increases by about Taka 200,000 for an increase of 1,000 tons of the import restriction bound for cereals. However, as discussed earlier, the importation of a larger tonnage of cereals will not be at the subsidized rate, and much higher import costs would be incurred.

Table 2. Area, production and import quantity of different crop (or crop groups)

Name crop	Present area[a]	Area used in model[a]	Present production[b]	Model sol. /production[b]	Food demand	Import quantity
Aus	4.735	4.944	2.179	2.274	2.274	0
B. Aman	2.072	2.176	0.855	0.892	0.892	0
T. Aman	11.995	12.550	8.416	8.785	8.785	0
Boro	6.443	6.726	6.804	7.102	7.102	0
Wheat	1.419	1.574	1.066	1.181	1.181	0
Jute	1.453	0.436	0.956	0.287	0.287	0
Rabi	4.166	3.294	3.839	3.034	4.074	1.041
Kharif	0.511	0.446	0.477	0.417	0.417	0
Fruit and juice	0.979	1.695	9.262	16.027	5.942	−10.085[c]
Drugs and narcotics	0.333	0.273	0.169	0.138	0.138	0

[a] Area in millions of acres.
[b] Production in millions of metric tons.
[c] Negative sign indicates the excess quantity.

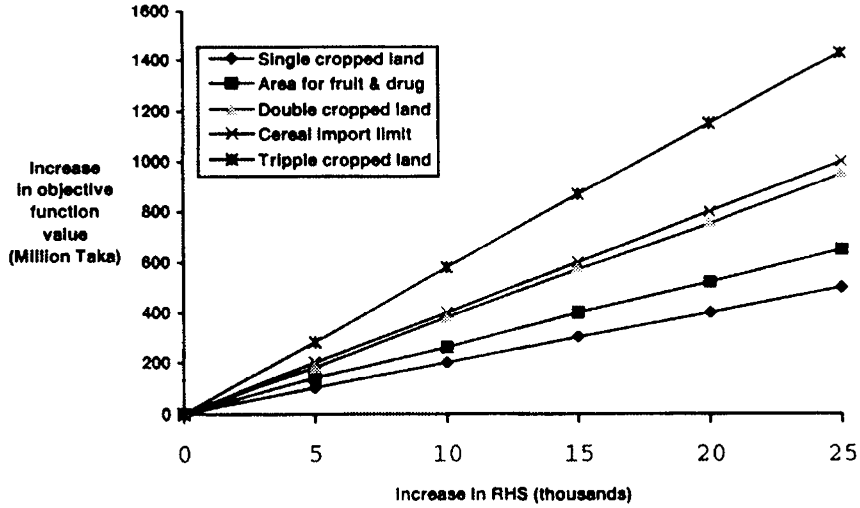

Figure 1. Increase of objective function values with increase of RHS.

6. Conclusions

Agriculture is a broad economic sector of the country, and almost 80% of the workers are involved in this profession. The per capita income of the country is the world's lowest. So the overall prosperity of the nation is impossible without the improvement of the socioeconomic condition of the agricultural people. It cannot be improved unless the proper return from their investment is ensured. This can be done by improving productivity through removing various production constraints, ensuring proper and stable market prices, and by proper production planning.

The results indicate that the crop-planning program devised through linear programming in the present work would generate a greater contribution (Taka 15,945.10 million) than the existing cropping scheme. During the formulation and solution of the problem every aspect of planning is considered and included as much as possible. However some inevitable limitations still remain in the model that can be overcome in future work. In spite of the limitations if the findings of the research are properly implemented, it will definately provide a higher contribution to the national economy and improve the socioeconomic condition of the agricultural people.

Such a crop-mix plan should be determined by the Agriculture Ministry or the Bangladesh Agricultural Development Corporation, and implemented by Agricultural Development Corporation. Lands are owned by the farmers. The individual farmer thinks about his own gain based on his vision. He never thinks about the policy for the entire country. The Agricultural Development Corporation is successful in increasing the production of major crops, taking a number of measures like providing instructions for higher productivity, providing loans, tractors, water pumps, and fertilisers, ensuring higher prices, etc. The corporation has some control on the cultivation of major crops. The corporation can make a nationwide program to encourage the farmers to cultivate the most attractive crops on their lands that is consistent with the national crop-mix plan. This is not an easy program, and this may take a few years to reach to an equilibrium or an accepted crop mix.

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APPENDIX I : Crop groups

The crop groups along with their group members are shown below :

1. Aus Rice 1) Local 2) HYV 3) Pajam	**2. Broadcast Amon Rice**
3. Transplanted Amon Rice 1) Local 2) HYV 3) Pajam	**4. Boro Rice** 1) Local 2) HYV 3) Pajam
5. Wheat 1) Local 2) HYV	**6. Jute** 1) White 2) Tossa 3) Other varieties
7. Rabi Crops 1) Barley 2) Rabi Jower 3) Rabi Maize 4) Cheena & Kaown 5) Other Rabi Cereals 6) Gram 7) Arhar (Pigeon Pea) 8) Masur (Lentil) 9) Motor (Pea) 10) Mung (Green gram) 11) Mashkalai (Black Gram) 12) Khesari 13) Other Rabi Pulses 14) Winter Til (Seasame) 15) Rape & Mustard 16) Rabi Groundnut 17) Linseed 18) Castor 19) Other Oil Seeds 20) Rabi Chilies 21) Onion 22) Garlic 23) Turmeric 24) Gari Kalai 25) Corriander Seeds 26) Rabi Cotton 27) Other Rabi Fibres 28) Rabi Sunhemp	**8. Kharif Crops** 1) Bhadoi Jower 2) Bhadoi Bajra 3) Bhadoi Maize 4) Other Bhadoi Cereals 5) Ginger 6) Other Kharif Pulses 7) Kharif Til 8) Kharif Groundnut 9) Kharif Chilies 10) Kharif Cotton 11) Kharif Sunhemp 12) Kharif Brinjal 13) Patal 14) Kharif Pumpkin 15) Lady's finger 16) Jhinga 17) Karala 18) Arum 19) Chalkumra (White gourd) 20) Cucumber 21) Barbati 22) Puisak (Indian Spinach) 23) Chichinga 24) Danta (Amaranths) 25) Other Kharif Vegetables 26) Bhadoi fodder 27) Mulberry 28) Mesta

Continued

29) Rabi Brinjal 30) Cauliflower 31) Cabbage 32) Water Gourd 33) Rabi Pumpkin 34) Tomato 35) Radish 36) Palong sak (Spinach) 37) Beans 38) Other Winter Vegetables 39) Potato 40) Sweet Potato 41) Rabi Fodder	
9. **Fruits & Juice** 1) Banana 2) Mango 3) Pine apple 4) Jackfruit 5) Papaya 6) Melon & Water melon 7) Litchi 8) Guava 9) Ber 10) orange 11) Pomelo 12) Lime & Lemon 13) Other Fruits 14) Other Citrus Fruits 15) Cocoanut 16) Sugarcane 17) Date Palm 18) Palmyra Palm	10. **Drugs & Narcotics** 1) Tea 2) Tobacco 3) Betel nut 4) Betel leaves 5) Narcotics 6) Some Condiments & Spices

APPENDIX II: Crop combinations

Single cropped land: Any one of the following crops (/groups) can be selected for this type of land.

Combination no.	Crop (/crop group)
1	Aus Rice
2	Broadcast Amon Rice
3	Transplant Amon Rice
4	Boro Rice
5	Wheat
6	Jute
7	Rabi Crops
8	Kharif Crops
9	Fruits and Juice
10	Drugs and Narcotics

Continued

Double cropped land: Any combination of the following crops (/groups) can be selected for this type of land.

Combination no.	Members of the combination Crop-1	Crop-2
1	Aus Rice	Transplant Amon Rice
2	Aus Rice	Boro Rice
3	Aus Rice	Wheat
4	Aus Rice	Rabi Crop
5	Broadcast Amon Rice	Boro Rice
6	Broadcast Amon Rice	Wheat
7	Broadcast Amon Rice	Rabi Crops
8	Transplant Amon Rice	Boro Rice
9	Transplant Amon Rice	Wheat
10	Transplant Amon Rice	Jute
11	Transplant Amon Rice	Rabi Crops
12	Boro Rice	Jute
13	Boro Rice	Kharif Crop
14	Wheat	Jute
15	Wheat	Kharif Crop
16	Jute	Rabi Crops
17	Rabi Crop	Kharif Crop

Triple cropped land: Any combination of the following crops (/groups) can be selected for this type of land.

Combination no.	Members of the combination Crop 1	crop 2	Crop 3
1	Aus Rice	Transplant Amon	Boro Rice
2	Aus Rice	Transplant Amon	Wheat
3	Aus Rice	Transplant Amon	Rabi Crops
4	Transplant Amon	Boro Rice	Jute
5	Transplant Amon	Wheat	Jute
6	Jute	Transplant Amon	Rabi Crop

APPENDIX III: Variables and their coefficients

Sl. no.	Variable X_{ijk}	A_{ijk} M.ton/acre	C_{ijk} Taka/acre	Return Taka/acre	B_{ijk} Taka/acre
1	X_1_1_1	0.46	4313	5447	1134
2	X_2_2_1	0.41	3450	3566	116
3	X_3_3_1	0.70	4702	7475	2773
4	X_4_4_1	1.056	7557	9752	2195
5	X_5_5_1	0.75	4518	4809	291
6	X_6_6_1	0.658	5233	4531	-702
7	X_7_7_1	0.921	2090	10251	8125
8	X_8_8_1	0.935	1355	8445	7090
9	X_9_9_1	9.453	1680	49401	47722
10	X_10_10_1	0.506	12486	29247	16761
11	X_1_1_2	0.46	4313	5447	1134
12	X_3_1_2	0.70	4702	7475	2773
13	X_1_2_2	0.46	4313	5447	1134
14	X_4_2_2	1.056	7557	9752	2195
15	X_1_3_2	0.46	4313	5447	1134

Continued

Sl. no.	Variable X_{ik}	A_{ik} M.ton/acre	C_{ik} Taka/acre	Return Taka/acre	B_{ik} Taka/acre
16	X_5_3_2	0.75	4518	4809	291
17	X_1_4_2	0.46	4313	5447	1134
18	X_7_4_2	0.921	2090	10215	8125
19	X_2_5_2	0.41	3450	3566	116
20	X_4_5_2	1.056	7557	9752	2195
21	X_2_6_2	0.41	3450	3566	116
22	X_5_6_2	0.75	4518	4809	291
23	X_2_7_2	0.41	3450	3566	116
24	X_7_7_2	0.921	2090	10215	8125
25	X_3_8_2	0.70	4702	7475	2773
26	X_4_8_2	1.056	7557	9752	2195
27	X_3_9_2	0.70	4702	7475	2773
28	X_5_9_2	0.75	4518	4809	291
29	X_3_10_2	0.70	4702	7475	2773
30	X_6_10_2	0.658	5233	4531	-702
31	X_3_11_2	0.70	4702	7475	2773
32	X_7_11_2	0.921	2090	10215	8125
33	X_4_12_2	1.056	7557	9752	2195
34	X_6_12_2	0.658	5233	4531	-702
35	X_4_13_2	1.056	7557	9752	2195
36	X_8_13_2	0.935	1355	8445	7090
37	X_5_14_2	0.75	4518	4809	291
38	X_6_14_2	0.658	5233	4531	-702
39	X_5_15_2	0.75	4518	4809	291
40	X_8_15_2	0.935	1355	8445	7090
41	X_6_16_2	0.658	5233	4531	-702
42	X_7_16_2	0.921	2090	10215	8125
43	X_7_17_2	0.921	2090	10215	8125
44	X_8_17_2	0.935	1355	8445	7090
45	X_1_1_3	0.46	4313	5447	1134
46	X_3_1_3	0.70	4702	7475	2773
47	X_4_1_3	1.056	7557	9752	2195
48	X_1_2_3	0.46	4313	5447	1134
49	X_3_2_3	0.70	4702	7475	2773
50	X_5_2_3	0.75	4518	4809	291
51	X_1_3_3	0.46	4313	5447	1134
52	X_3_3_3	0.70	4702	7475	2773
53	X_7_3_3	0.921	2090	10215	8125
54	X_3_4_3	0.70	4702	7475	2773
55	X_4_4_3	1.056	7557	9752	2195
56	X_6_4_3	0.658	5233	4531	-702
57	X_3_5_3	0.70	4702	7475	2773
58	X_5_5_3	0.75	4518	4809	291
59	X_6_5_3	0.658	5233	4531	-702
60	X_6_6_3	0.658	5233	4531	-702
61	X_3_6_3	0.70	4702	7475	2773
62	X_7_6_3	0.921	2090	10215	8125

Appendix IV: A sample linear programming formulation

objective function:

Max + 1134 X_1_1_1 + 116 X_2_2_1 + 2773 X_3_3_1 + 2195 X_4_4_1 + 291 X_5_5_1 - 702 X_6_6_1 + 8125 X_7_7_1 + 7090 X_8_8_1 + 47722 X_9_9_1 + 16761 X_10_10_1 + 1134 X_1_1_2 + 2773 X_3_1_2 + 1134 X_1_2_2 + 2195 X_4_2_2 + 1134 X_1_3_2 + 291 X_5_3_2 + 1134 X_1_4_2 + 8225 X_7_4_2 + 116 X_2_5_2 + 2195 X_4_5_2 + 116 X_2_6_2 + 291 X_5_6_2 + 116 X_2_7_2 + 8125 X_7_7_2 + 2773 X_3_8_2 + 2195 X_4_8_2 + 2773 X_3_9_2 + 291 X_5_9_2 + 2773 X_3_10_2 - 702 X_6_10_2 + 2773 X_3_11_2 + 8125 X_7_11_2 + 2195 X_4_12_2 - 702 X_6_12_2 + 2195 X_4_13_2 + 7090 X_8_13_2 + 291 X_5_14_2 - 702 X_6_14_2 + 291 X_5_15_2 + 7090 X_8_15_2 - 702 X_6_16_2 + 8125 X_7_16_2 + 8125 X_7_17_2 + 7090 X_8_17_2 + 1134 X_1_1_3 + 2773 X_3_1_3 + 2195 X_4_1_3 + 1134 X_1_2_3 + 2773 X_3_2_3 + 291 X_5_2_3 + 1134 X_1_3_3 + 2773 X_3_3_3 + 8125 X_7_3_3 + 2773 X_3_4_3 + 2195 X_4_4_3 - 702 X_6_4_3 + 2773 X_3_5_3 + 291 X_5_5_3 - 702 X_6_5_3 - 702 X_6_6_3 + 2773 X_3_6_3 + 8125 X_7_6_3 - 5940 I_1 - 5940 I_2 - 5940 I_3 - 5940 I_4 - 4609 I_5 - 12341 I_7

constraints:

subject to
(1) + 0.46 X_1_1_1 + 0.46 X_1_1_2 + 0.46 X_1_2_2 + 0.46 X_1_3_2 + 0.46 X_1_4_2 + 0.46 X_1_1_3 + 0.46 X_1_2_3 + 0.46 X_1_3_3 + I_1 ≥ 2274566
(2) + 0.41 X_2_2_1 + 0.41 X_2_5_2 + 0.41 X_2_6_2 + 0.41 X_2_7_2 + I_2 ≥ 892498
(3) + 0.7 X_3_3_1 + 0.7 X_3_1_2 + 0.7 X_3_8_2 + 0.7 X_3_9_2 + 0.7 X_3_10_2 + 0.7 X_3_11_2 + 0.7 X_3_1_3 + 0.7 X_3_2_3 + 0.7 X_3_3_3 + 0.7 X_3_4_3 + 0.7 X_3_5_3 + 0.7 X_3_6_3 + I_3 ≥ 8785105
(4) + 1.056 X_4_4_1 + 1.056 X_4_2_2 + 1.056 X_4_5_2 + 1.056 X_4_8_2 + 1.056 X_4_12_2 + 1.056 X_4_13_2 + 1.056 X_4_1_3 + 1.056 X_4_4_3 + I_4 ≥ 7102647
(5) + 0.75 X_5_5_1 + 0.75 X_5_3_2 + 0.75 X_5_6_2 + 0.75 X_5_9_2 + 0.75 X_5_14_2 + 0.75 X_5_15_2 + 0.75 X_5_2_3 + 0.75 X_5_5_3 + I_5 ≥ 1180728
(6) + 0.658 X_6_6_1 + 0.658 X_6_10_2 + 0.658 X_6_12_2 + 0.658 X_6_14_2 + 0.658 X_6_16_2 + 0.658 X_6_4_3 + 0.658 X_6_5_3 + 0.658 X_6_6_3 ≥ 287016
(7) + 0.921 X_7_7_1 + 0.921 X_7_4_2 + 0.921 X_7_7_2 + 0.921 X_7_11_2 + 0.921 X_7_16_2 + 0.921 X_7_17_2 + 0.921 X_7_3_3 + 0.921 X_7_6_3 + I_7 ≥ 4074360
(8) + 0.935 X_8_8_1 + 0.935 X_8_13_2 + 0.935 X_8_15_2 + 0.935 X_8_17_2 ≥ 417513
(9) + 9.453 X_9_9_1 ≥ 5942200
(10) + 0.506 X_10_10_1 ≥ 138600
(11) + X_1_1_1 + X_2_2_1 + X_3_3_1 + X_4_4_1 + X_5_5_1 + X_6_6_1 + X_7_7_1 + X_8_8_1 + X_9_9_1 + X_10_10_1 ≤ 7727000
(12) 0.5 X_1_1_2 + 0.5 X_3_1_2 + 0.5 X_1_2_2 + 0.5 X_4_2_2 + 0.5 X_1_3_2 + 0.5 X_5_3_2 + 0.5 X_1_4_2 + 0.5 X_7_4_2 + 0.5 X_2_5_2 + 0.5 X_4_5_2 + 0.5 X_2_6_2 + 0.5 X_5_6_2 + 0.5 X_2_7_2 + 0.5 X_7_7_2 + 0.5 X_3_8_2 + 0.5 X_4_8_2 + 0.5 X_3_9_2 + 0.5 X_5_9_2 + 0.5 X_3_10_2 + 0.5 X_6_10_2 + 0.5 X_3_11_2 + 0.5 X_7_11_2 + 0.5 X_4_12_2 + 0.5 X_6_12_2 + 0.5 X_4_13_2 + 0.5 X_8_13_2 + 0.5 X_5_14_2 + 0.5 X_6_14_2 + 0.5 X_5_15_2 + 0.5 X_8_15_2 + 0.5 X_6_16_2 + 0.5 X_7_16_2 + 0.5 X_7_17_2 ≤ 9615000
(13) + 0.333333 X_1_1_3 + 0.333333 X_3_1_3 + 0.333333 X_4_1_3 + 0.333333 X_1_2_3 + 0.333333 X_3_2_3 + 0.333333 X_5_2_3 + 0.333333 X_1_3_3 + 0.333333 X_3_3_3 + 0.333333 X_7_3_3 + 0.333333 X_3_4_3 + 0.333333 X_4_4_3 + 0.333333 X_6_4_3 + 0.333333 X_3_5_3 + 0.333333 X_5_5_3 + 0.333333 X_6_5_3 + 0.333333 X_6_6_3 + 0.333333 X_3_6_3 + 0.333333 X_7_6_3 ≤ 2387000

Continued

(14) + 4313 X_1_1_1 + 3450 X_2_2_1 + 4702 X_3_3_1 + 7557 X_4_4_1 + 4518 X_5_5_1 + 5233 X_6_6_1 + 2090 X_7_7_1 + 1355 X_8_8_1 + 1680 X_9_9_1 + 12486 X_10_10_1 + 4313 X_1_1_2 + 4702 X_3_1_2 + 4313 X_1_2_2 + 7557 X_4_2_2 + 4313 X_1_3_2 + 4518 X_5_3_2 + 4313 X_1_4_2 + 2090 X_7_4_2 + 3450 X_2_5_2 + 7557 X_4_5_2 + 3450 X_2_6_2 + 4518 X_5_6_2 + 3450 X_2_7_2 + 2090 X_7_7_2 + 4702 X_3_8_2 + 7557 X_4_8_2 + 4702 X_3_9_2 + 4518 X_5_9_2 + 4702 X_3_10_2 + 5233 X_6_10_2 + 4702 X_3_11_2 + 2090 X_7_11_2 + 7557 X_4_12_2 + 5233 X_6_12_2 + 7557 X_4_13_2 + 1355 X_8_13_2 + 4518 X_5_14_2 + 5233 X_6_14_2 + 4518 X_5_15_2 + 1355 X_8_15_2 + 5233 X_6_16_2 + 2090 X_7_16_2 + 2090 X_7_17_2 + 1355 X_8_17_2 + 4313 X_1_1_3 + 4702 X_3_1_3 + 7557 X_4_1_3 + 4313 X_1_2_3 + 4702 X_3_2_3 + 4518 X_5_2_3 + 4313 X_1_3_3 + 4702 X_3_3_3 + 2090 X_7_3_3 + 4702 X_3_4_3 + 7557 X_4_4_3 5233 X_6_4_3 + 4702 X_3_5_3 + 4518 X_5_5_3 + 5233 X_6_5_3 + 5233 X_6_6_3 + 4702 X_3_6_3 + 2090 X_7_6_3 ≤ 1.7E+11

(15) X_1_1_2 - X_3_1_2 = 0
(16) X_1_2_2 - X_4_2_2 = 0
(17) X_1_3_2 - X_5_3_2 = 0
(18) X_1_4_2 - X_7_4_2 = 0
(19) X_2_5_2 - X_4_5_2 = 0
(20) X_2_6_2 - X_5_6_2 = 0
(21) X_2_7_2 - X_7_7_2 = 0
(22) X_3_8_2 - X_4_8_2 = 0
(23) X_3_9_2 - X_5_9_2 = 0
(24) X_3_10_2 - X_6_10_2 = 0
(25) X_3_11_2 - X_7_11_2 = 0
(26) X_4_12_2 - X_6_12_2 = 0
(27) X_4_13_2 - X_8_13_2 = 0
(28) X_5_14_2 - X_6_14_2 = 0
(29) X_5_15_2 - X_8_15_2 = 0
(30) X_6_16_2 - X_7_16_2 = 0
(31) X_7_17_2 - X_8_17_2 = 0
(32) X_1_1_3 - X_3_1_3 = 0
(33) X_3_1_3 - X_4_1_3 = 0
(34) X_1_2_3 - X_3_2_3 = 0
(35) X_3_2_3 - X_5_2_3 = 0
(36) X_1_3_3 - X_3_3_3 = 0
(37) X_3_3_3 - X_7_3_3 = 0
(38) X_3_4_3 - X_4_4_3 = 0
(39) X_4_4_3 - X_6_4_3 = 0
(40) X_3_5_3 - X_5_5_3 = 0
(41) X_5_5_3 - X_6_5_3 = 0
(42) X_6_6_3 - X_3_6_3 = 0
(43) X_3_6_3 - X_7_6_3 = 0
(44) I_1 + I_2 + I_3 + I_4 + I_5 ≤ 0
(45) X_9_9_1 + X_10_10_1 ≤ 1969350

The country produces jute, kharif crops, fruits & juice and drugs & narcotics more than their demand. Import is restricted for them. It is permitted only for cereals (rice and wheat) and rabi crops due to their shortage. This is why, I1, I2, I3, I4, I5 and I7 are inserted while the other omitted.

In constraint 12, the land for each crop (/ crop group) is divided by 2 (alternately, total double cropped land is multiplied by 2) because these lands are used two times in a year by two crops (/ crop groups) of any combination of double cropped land.

In constraint 13, the land for each crop (/ crop group) is divided by 3 (alternately, total triple cropped land is multiplied by 3) because these lands are used three times in a year by three crops (/ crop groups) of any combination of triple cropped land.

The area to be used for fruits & juice and drugs & narcotics is limited. All of the single cropped land is not available and suitable for these crops (/ crop groups). The area available and suitable for them is assumed to be 150% higher than the presently used area.

The coefficients of the variables in the objective function are contributions that can be obtained from different crops (/ crop groups). The coefficients in the constraints from 1 to 10 are the yield rate of each crop (/ crop group) while it is the cost of production in constraint 14.

Since our objective is to achieve self-sufficiency in food, therefore, import of foods has to be minimized. In this model, it is assumed that no cereal will be imported and hence constraint 44 is set to be equal or less than zero.