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Malcolm Mayfield and Serigne Ndiaye

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MODELING FARMING SYSTEMS AND INTERVENTIONS WITH A COMPUTER

Malcolm Mayfield and Serigne Ndiaye
U of A/FSRP/ISAR, Rwerere, Rwanda

INTRODUCTION

This paper describes a method for modeling traditional farming systems on a computer and examining the effects of proposed interventions on each aspect of those systems.

The method uses widely available PC software[1] for linear programming (LP) to solve systems of linear equations. The solution tells the user how a model farm maximizes profits and/or security, or minimizes costs, given certain farm-level constraints (e.g., nutritional requirements, limited land, labor and capital). The model itself requires estimates of inputs (e.g., land, capital, compost), outputs (e.g. yields), prices, resource availabilities and nutritional requirements.

The modeling procedure allows researchers to evaluate technologies holistically in a way that approaches the complex decision-making process of farmers. Like FSR, the modeling process is an iterative one: as agronomic and socio-economic research progresses, more and better estimates (parameters) become available to be plugged into the model, increasing its accuracy and completeness. In this way, recommendations for extension and further research are improved continuously and indefinitely.

Whole-farm planning/modeling can contribute not only to the efficacy of the farming systems research effort, but also to the process of institutionalizing farming systems research: the evolving models, after all, will remain long after the original users have left the scene.

A "SIMPLE" EXAMPLE

A scientist has been working on wheat. Following the results of the diagnostic survey, fungal diseases were identified as a primary cause of low wheat yields, and the scientist experimented with seed treatments of fungicide 'Mycokill' on two types of wheat: local melange and a high-yielding but susceptible variety. The results are presented in Table 1.

The fungicide is estimated to cost 4000 FRw/ha; thus the fungicide appears profitable for both melange and susceptible types. However, the susceptible + fungicide combination is more profitable, so it is tentatively recommended. Rejecting the melange + fungicide option, the two alternatives to compare are then:

1) melange, no fungicide yield = 900
2) susceptible, w/fungicide yield = 1200

We need to compare these two alternatives in light of their costs, benefits, farmers' constraints and changes in other farm activities. Basically, the fungicide technology (alternative 2) must be compared to the traditional practice (alternative 1) in terms of both feasibility and profitability.

First, we examine the traditional systems in which wheat is grown. For simplicity, we start with a "typical" system, described in Table 2.

Each activity in this simple farm requires inputs of land, labor and capital, shown in Table 3.

Thus 1 ha of wheat, for example, requires 1 ha of land, 600 hrs of labor and 100 Francs of capital to get the 900 kg/ha of wheat in Table 2.

For simplicity again, assume the typical farmer's objective is to maximize total value minus costs (profits) from the 1.1 ha of land available, ignoring other objectives like nutritional adequacy, security

[1]One popular LP software package is DHLLP, which is menu driven and easy to use. A program diequette and additional information on using this package are available at the FSRP/ISAR station office at Rwerere.

and leisure time. All that is required now is to combine the information in Tables 1 through 3 in a summary table, called a tableau, as shown in Fig. 1.

Notice that the capital required/ha was subtracted from the value/ha to give profit/ha. We are now ready to see what effect the intervention has on profit and land allocation.

After entering the above tableau into the computer and running the LP software, we obtained the results presented below:

Total Profits = 31,952.5 FRw

Activity	Amount
Melange	0.6275 ha
Sus.+ Fung.	0.4725 ha

Limiting Resources	Shadow Price
land	26,775 FRw/ha
capital	1.25 FRw/FRw

Non-limiting Resource	Excess
labor	492.75 hrs

The computer output suggests that the farmer spends most of the available capital on fungicide to grow the susceptible wheat with fungicide on .4725 ha. Some capital is also used to grow .6275 ha of the traditional melange wheat without fungicide. If the farmer spent every available franc on wheat with fungicide, only about 0.5 ha of land would be cropped, and the rest would be idle. By spending slightly less on fungicide, enough capital becomes available to grow traditional wheat on the remainder.

Profit following adoption of the intervention increases to 31,952.5 FRw, a gain of 12,375.5 FRw. However, the farmer no longer produces peas or corn, so nutrition and taste objectives were compromised (actually, they were ignored). These objectives could be inserted into the model as constraints to see, for example, how much income the typical farmer sacrifices in order to grow enough peas (protein) for home consumption.

The limiting resources are land and capital. Some labor is leftover (492.75 hrs). The value of excess family labor could be realistically included in the objective, along with profit, as leisure. The model could also include the option of working on neighbors' farms for, say, 10 FRw/hr.

The "shadow prices" of land and capital give the value, in terms of increased profit, if one more unit of land (1 ha) or capital (1 FRw) were available to use in production. Thus the farmer may choose to rent land from the commune if the rent is below 26,000 FRw/ha/season. Similarly, money might be borrowed from the Banque Populaire if the cost is below 1.25 FRw/FRw (i.e., 25% interest). These decisions will depend on such factors as how much the farm family values its leisure, risk preferences, etc.

This typical farm, its resources and the crop coefficients used are fictional. The output based on these numbers, however, is the actual computer output. Though the model is simple in the extreme, the analysis of such a simple model is not. The allocation of resources that maximizes profits cannot be seen by simply looking at the initial values. Prior to solving the tableau, researchers and extension personnel would be at a loss if asked whether our typical farmer should borrow money to buy fungicide.

One point requires added emphasis: The analysis and results are only as good as the estimates that go into it (the coefficients or parameters). As the saying goes, garbage in --> garbage out. The GIGO principle extends to the completeness of the model as well as to the accuracy of the numbers in it. The task of researchers in an FSR modeling effort is to describe as many key components of as many major farming systems with as much accuracy as possible given limited research time and dollars. Obtaining this information is an ongoing and cooperative enterprise involving biological and social scientists. For the FSRP, much useful data has already been produced, especially on tested interventions. As was noted in the TDY report of Drs. Parsch and Wailes in July, 1988, the project is but one year away from having the capability (information) to model FSRP-area farming systems and to analyze the effects of interventions developed or in the pipeline on those systems. Filling in the larger gaps in the existing knowledge

base will require some further study of the traditional systems, the inputs and outputs by major crop, farm resource availabilities, prices, etc..

The modeling/planning process described above makes explicit one of the central tenets of the farming systems perspective: Everything is interconnected. An intervention, any intervention, typically causes a redistribution of resources, whether or not it requires any change in total resource use. Also typically, one and only one such redistribution out of the infinite number possible maximizes a farmer's set of objectives.

The process is iterative and continuous as is FSR itself, progressing and improving as research progresses and farmers' conditions evolve. Establishing this process, demonstrating its logic and usefulness and accumulating experience in its use by FSRP/ISAR can contribute directly to the goal of institutionalizing FSR in Rwanda. This contribution will increase as researchers and extension clients expand their knowledge of farmer problems, constraints and potential solutions and how these are interrelated in complex ways.

OUTLINE OF STEPS IN THE MODELING PROCESS[2]

Modeling Existing Farming Systems[3]

1. Cataloguing Activities and Constraints

A. Activities. The first step is to list all the major activities in the major farming systems of the project area. What constitutes major activities and farming systems depends on the criteria used to rank activities (e.g., market value, role in nutrition, etc.) and differentiate between farming systems (agro-ecological conditions, dominant cultures, resource availabilities, etc.). One useful breakdown of farm units is according to resources. High-, medium- and low-resource farms, in terms of land area/person, differ markedly in both on- and off-farm activities (MINAGRI/SESA, 1987). Land area can be weighted by many factors (slope, pH, etc.), and persons can be weighted by age and sex to define farming systems more accurately. Statistically valid criteria should be used to define both farming systems and the activities in them whenever possible. The Diagnostic Survey and SESA sources may be used as guides, but the former lacks statistical validity, and the latter are neither very representative nor detailed. A carefully planned and executed survey is needed to provide representative information of sufficient reliability and detail for use in the modeling effort.

When this information becomes available, the farming systems are defined and activities listed and ranked. Finally, the major activities are chosen for inclusion in the models (one model for each major farming system). Activities can include growing crops for home consumption, growing for sale, producing/drinking/selling beer, selling labor, hiring labor, renting land, buying food and many others. Selling and buying activities, where significant, must be included because these have direct impacts on resource flows and other major activities. Visiting cabarets should also be included when and where the time and money for that activity are significant.

B. Constraints. If activities represent one side of the farming system equation, constraints represent the other. Availability of land, labor, capital and compost are obvious constraints, information about which can be collected in the survey mentioned above. Other constraints include dietary needs and preferences. For these, information about current consumption levels of all foods is needed in addition to information about the nutritional value of each food product, whether purchased or not. Data from SESA can be used here in combination with survey data. Calorie and protein needs are, of course, most important to include in the model. Land, labor and capital availabilities can and should be further divided. Land can be divided into high- and low-fertility/erodibility classes, while labor and capital availabilities can be put on a monthly basis.

Some constraints can be relaxed over time: Taste preferences, male labor participation and

[2]For a detailed exposition, see M. Collinson, *Farm Management in Peasant Agriculture*, chapters 16-19 (Boulder, 1983).
[3]The term farming system is used here to indicate any large group or subgroup of farm units that have certain important characteristics in common.

desired alcohol consumption are a few examples. Changes in these can later be examined for their impact on the systems.

It is important to remember that increasing the number of real activities and constraints in the model and improving their accuracy is a long-term process. But the more you can include and the more accurate the numbers used to quantify them, the more accurate, realistic and hence meaningful the model becomes.

2. Putting Activities and Constraints Together

A. Create a Tableau. The next step is to build a tableau similar in form to the one in Fig. 1. Activities are listed across the top and constraints down the left side. Begin by numbering each activity $X_1, X_2, ..., X_n$, noting beside each activity the units in which it is measured. For instance, a wheat-growing activity would be put on a 1-ha basis so that 1 unit = 1 ha. A wheat-selling activity could be in 1-kg or 1-ha units. Since wheat-growing and wheat-selling activities are necessarily linked, it is convenient to use the same units for both. When activities are linked as this, a "transfer row" is used to establish the linkage (see Box, p. 5)..

The list of activities, X_1 through X_n, is often called a "vector of activities" and is designated X_j (j = 1, 2, ..., n). The rows are also labeled, from 1 to m. The intersection of columns and rows forms a matrix of n columns and m rows, and its dimensions are thus m x n (matrix dimensions are written as no. of rows by no. of columns). This matrix is designated Aij, and each cell or location in it is an a_{ij}.

To fill in the A_{ij}, put the amount of each resource used to produce one unit of the activity in a column. For example, if a wheat-growing activity is in column 2 (i.e, wheat-growing = X_2) and land, labor and capital are rows 1, 2 and 3, respectively, a_{12} is the amount of land, a_{22} is the amount of labor, and a_{32} is the amount of capital required to produce 1 ha of wheat. Amounts of labor and capital will vary depending on which farming system is being modeled. In a model of a low-intensity system, labor might be 200 hrs/ha, while in a high-intensity model, it could be 900 hrs/ha. These parameters must be obtained from the detailed survey and other sources.

Other elements in the A_{ij} matrix are filled in the same way, but for a row (constraint) that defines a dietary or other requirement, each number in the row represents the amount that one unit of each activity contributes towards meeting the requirement. If rows 4 and 5 are calories and protein, for instance, and column 3 is wheat-eating (in kgs), then a_{43} and a_{53} are the calories and grams of protein in 1 kg of wheat.

B. The Right-Hand Side (RHS). To complete the rows of constraints, the total quantities of resources available and outputs required are put in a final column on the right-hand side of the tableau. This vector is called the RHS and is designated b_i (i = 1, 2, ..., m). If the average farm size for the farming system being modeled is 1.1 ha, put this number in the land constraint row under the RHS column. If the total protein requirement for the average farm in the system is 18,000 g, put that number in the protein constraint row under the RHS column.

It is also necessary to specify whether a constraint is a greater than, less than or equals to constraint. Resource constraints are always less than, requirements are always greater than, and transfer rows are normally equal to constraints (see Box, page 5).

C. Objective Function Values. To complete the columns of activities, one last row must be added at the bottom of the tableau to indicate the amount or value one unit of each activity contributes to the objective that farmers are trying to maximize (the so-called "objective function"). This objective can be net income which, since land is likely to be the limiting factor for most farmers, amounts to maximizing returns to land. Under a "tobacco-grow/sell" column, the net return per unit grown/sold is put in the bottom row under that column. This row is thus made up of the "values of activities in the objective function" and is designated C_j (j = 1, 2, ..., n). Many activities do not contribute directly to the objective function--wheat-grow, for instance. Under these activities, put a zero in the C_j row. This row is not a constraint, so no value is put in the RHS for this row.

Transfer Rows.

Transfer rows are used to link dependent activities such as wheat-growing with wheat-selling and wheat-eating. Obviously, to sell or eat wheat (without buying it), one must grow wheat. The link can best be described with an equation:

$$1WS + 1WE = 1WG,$$

where WS = the quantity of wheat sold, WE = the quantity of wheat eaten, and WG = the quantity of wheat grown. For convenience, it is best to put related activities in the same units, such as hectares of wheat grown, sold and eaten. If not, factors of conversion would have to appear in the equation replacing one or more of the ones. Subtracting 1WG from both sides results in

$$-1WG + 1WS + 1WE = 0.$$

If WG, WS and WE are X_1, X_2 and X_3, the transfer row is formed following the above equation:

	X_1	X_2	X_3	X_4	...	...	X_n	RHS
Wheat Transfer Row	-1	1	1	0	...	...	0	= 0

All other elements of the transfer row are zero, the RHS is zero, and the transfer row is an "equals to" constraint.

The objective function is what the computer program tries to maximize. An example might be,

$$MAX(NR) = 0X_1 + 26{,}900X_2 + 0X_3 + \ldots + C_nX_n,$$

where NR = net revenue, and X_1, X_2 and X_3 are wheat-grow, sell and eat (unit = 1 ha). The coefficient for X_2 is 26,900 FRw (C_2 = 26,900), indicating that selling the output of 1 ha of wheat yields net revenue of 26,900 FRw. This value is obtained by multiplying the yield/ha times the harvest sale price and subtracting 100 FRw (capital used) from the result, as in the "simple" example used earlier.

Notice that each column in the table describes a sort of "production function." Staying with the wheat example, the X_1 or wheat-grow column says that 1 ha of land, Y hrs of labor, and Z FRws of capital are used to produce 1 ha of wheat (at a specified yield level!). A production function can be written as, Y = f(X, Y, Z), and the function can be linear, quadratic, cubic, 'Cobb-Douglas', etc.. Unfortunately, linear programming, as its name implies, only deals with linear production functions. That is, all the columns in the tableau describe linear relationships. Fortunately, the actual parameters (a_{ij}, b_i and C_j) are all "point estimates" that can come from any type of function mentioned above. Modeling wheat production at different levels of nitrogen, when the relationship between nitrogen and yield is not linear, requires taking the estimated yield at different points on the yield response curve and creating a separate column for each nitrogen level. In practice, dealing with non-linear relationships is not as difficult as it might seem.

3. Notation

To summarize the model mathematically, the objective function is given below, followed by the constraints.

$$MAX(NR) = C_1X_1 + C_2X_2 + C_3X_3 + \ldots + C_nX_n$$

Subject to:

$$\begin{array}{l}
a_{11}X_1 + a_{12}X_2 + a_{13}X_3 + \ldots + a_{1n}X_n \le b_1 \\
a_{21}X_1 + a_{22}X_2 + a_{23}X_3 + \ldots + a_{2n}X_n \le b_2 \\
a_{31}X_1 + a_{32}X_2 + a_{33}X_3 + \ldots + a_{3n}X_n \le b_3 \\
\quad\vdots \\
a_{m1}X_1 + a_{m2}X_2 + a_{m3}X_3 + \ldots + a_{mn}X_n \le b_m
\end{array}$$

Written in matrix algebra notation, the model reduces to:

$$MAX(NR) = C_jX_j \qquad (j = 1, 2, ..., n)$$

Subject to: $$A_{ij}X_j \leq b_i \quad (i = 1, 2, ..., m).$$

C, X and b are vectors; A is a matrix. This is demonstrably a very concise notation system. It is introduced here for the benefit of those who might wish to consult a linear programming text and because LP software packages use it as well. Once a user knows this notation, using the software to enter the data is straight-forward.

4. Testing the Existing Systems Models

One test of an existing system model is that the model is solvable (if not, the computer program tells you it is not). An unsolvable model indicates that one or more numbers in the model was entered incorrectly or was wrongly estimated. Check the numbers, their locations and whether the less than, greater than and equals to specifications are correct. If there are no mistakes there, check the actual numbers to see if they were properly estimated in the first place.

Another test of a model is to see if the output is close to what was expected. Is the objective function value (net returns, for example) close to the observed average? Are the "shadow prices" reasonably close to expected levels? For instance, a shadow price for labor of 2000 FRw/hr would not be reasonable, whereas 5 to 15 FRws/hr would be. If part of the output is unreasonable, check the numbers in the model to see if they were entered correctly.

Testing Interventions

Once the basic models are established, interventions can be tested for their acceptability and impact on the existing systems. Key constraints to adoption and recommendations appropriate to specific farming systems can be determined at this stage. Finally, suggestions for future agronomic research can result.

First, researchers must compile a list of interventions for which sufficient data exists to include as new activities in the models. All inputs, as well as timing of inputs, and the outputs of an intervention are the basic data necessary. These numbers should be statistically valid or else the subsequent analysis will be similarly compromised.[4] A yield increase, for example, should be significant at a specified probability level.

An intervention to be tested is added to each model as a new activity (column). This may require linking the intervention activity with directly related activities, in the same way that wheat-grow is linked, via a transfer row, to wheat-eat and wheat-sell. After adding the new column for the intervention, the model is solved again and the results examined. If the new activity is among those "in the solution" then the intervention was adopted by the model.

Supposing an intervention is accepted, then the output will give the level of the intervention activity in the model. This will normally be the area of land devoted to the new activity. The levels of other activities in the model will be changed somewhat as well. The user can compare the results with the existing system to see which activities are decreased and the amount of the decrease. The fact that an intervention is accepted means that the objective function is thereby increased. The change in the objective function value should be determined to estimate the increase in net revenues resulting from the initial adoption of the intervention.

An examination of changes in the shadow prices is also revealing. These show which resources increase in value as a result of the intervention. As in the "simple" example, the shadow price of capital may increase to a level that justifies borrowing money to invest in the production process. Or, if adoption of a technology results in an increase in the shadow price for a requirement (e.g, protein), the suggestion is that research efforts need to concentrate on meeting that requirement more efficiently.

[4] It is often desirable to test some 'what if' questions before an intervention is developed. An example would be: "How large an increase in yields is required from the intervention being studied before it will be adopted by farmers?

The bottom line is the value of the objective function. By testing a series of interventions and comparing the results, interventions can be ranked by their contribution to net revenues at the levels that farmers are expected to adopt them. This will allow researchers to select interventions meriting a high priority in extension programs.

It should be emphasized that, as of September 1988, the FSRP is only a year away from being able to provide all of the analyses and results described in this paper. Some relatively simple models are being investigated at this time, but the level of complexity and precision will increase as knowledge and researchers' skills develop. The methodology is in no way "inappropriate" for an FSR project, any more than scientific reasoning or statistical methods are. Subjective reasoning, guestimating and superficial testing, on the other hand, are seldom appropriate methods where taxpayers' money is being spent. The modeling/planning process offers the means of providing objectively verifiable criteria for evaluating interventions and making the most efficient use of limited resources.

Table 1. Yields of wheat with and without fungicide.

Variety	No fungicide	Fungicide	Yield difference	Value of diff.
	kg/ha			FRw/ha
Melange[1]	900a	1100b	200	6,000
Susceptible[1]	800a	1200b	400	12,000

[1]Means followed by the same letter are not significantly different at the 95% confidence level.

Table 2. Typical wheat-producing farm: crops, areas, yields and values.

Activity	Area (ha)	Mean yield	Price	Value/ha	Total value
Wheat	0.2	900 kg/ha	30 FRw/kg	27,000 FRw	5,400 FRw
Corn	0.6	1250 kg/ha	12 FRw/kg	15,000 FRw	9,000 FRw
Peas	0.3	600 kg/ha	30 FRw/kg	18,000 FRw	5,400 FRw

Table 3. Inputs by crop and total resource availabilities.

Input	Activity			Total resource availability
	Wheat	Corn	Peas	
Land (ha)	1	1	1	1.1
Labor (hrs)	600	2000	700	1,200
Capital (FRw)	100	300	75	2,000

Constraints (rows)	Activities (columns) Melange	Susc.+ fung.	Corn	Peas	Total Resource Available
Land	1	1	1	1	1.1 ha
Labor	600	700	2000	700	1200 hrs
Capital	100	4,100	300	75	2000 FRw
Profit/ha	26,900	31,900	14,700	17,925	

Fig. 1. Tableau of proposed and existing activities in a wheat/corn/peas system.