Working Papers in
AGRICULTURAL ECONOMICS

June 1993 93-7

A Spatial Model of Forest Conversion

Using a Geographic Information System

by

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PART I: CONCEPTUAL OUTLINE

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June, 1993

Abstract

Rapid gains in computing hardware and remote-sensing capacity have thrust geographical information systems (GIS) into the forefront of new tools available to ecologists, natural resource managers, biologists, and the like. Economists however have been slow to adopt this new technology. This paper outlines a simple spatial and dynamic model of forest conversion in the tropics that uses the analytic capacity of GRASS 4.0, a raster-based GIS. By developing the rudiments of the model and explaining how map algebra works, the paper serves both as an introduction to GIS, and also as a basis for further testing and refinement.

Key words: GIS, economic model, forest conversion, spatial.

Preface

The inspiration for this paper came from a recent trip (September 1992 - January 1993) to the humid forest region of Cameroon, in Central Africa. Support from Cornell's International Institute of Food and Agricultural Development (CIIFAD) is gratefully acknowledged. Professor Randolph Barker was instrumental in arranging for logistic support in Cameroon through the International Institute of Tropical Agriculture (IITA). The author would like to thank him and the staff of IITA in Cameroon for their support.

I. Overview

Once dominated by Nature, humans have reached a stage in their evolution where they are capable of quickly destroying their own habitat. In the process of converting natural resources into consumable form, we have extended our reach to the most remote regions of the earth. Further, rates of resource conversion are accelerating as changes in technology, demographic pressure, and poverty bear down or give sway to human needs (Lele and Stone, 1989). In the case of the equatorial rainforest, conversion to agricultural use, once accomplished, can have irreversible effects on soil quality and biological diversity (Lal, 1986; Wilson, 1992).

The objective of this paper is to develop an economic model of forest conversion in the tropics that can make use of the vast and growing analytic capabilities of geographic information systems (GIS). To date, most economic models (including those of forest conversion) have ignored spatial detail. This is a shame since most economic behavior implicitly carries a spatial dimension that is often reduced for reasons of simplicity, "elegance," or mathematical tractability.

A second and overriding goal of this paper is to develop the model in such a way as to give it some usefulness in the formulation of policy. Rather than being normative -- which begs the question of what is to be maximized or minimized -- the model attempts to depict actual conditions. This includes pushing the limits of accuracy on predicting rates of forest conversion, where it is likely to happen, and what factors may influence the process.

It should be noted that the focus of this paper is conceptual. For the purposes of developing the model, data values are assumed. This allowed the author to focus on modelling the conceptual issues of tying the model to GIS, without the need for time-consuming runs to de-bug the programming macros. In Part II, the model will be tested using empirical data. The software used in this exercise is GRASS 4.0, a raster- (or grid, as opposed to polygon or vector-) based software.

When fully estimated, the model can be used to simulate various policy scenarios to give a visual reading of possible outcomes. The merits of this approach should be obvious: information can be assimilated much more rapidly and in much greater quantity visually than through the reading of text.

II. Review of Literature

Given the broad array of spatial models in other disciplines, it is a wonder why there are so few in economics.[1] Of those that exist, virtually none use GIS. Rapidly evolving computing technology and remote-sensing capacity means more power to process and monitor data that, ultimately, stems from economic behavior. We are on the cusp of breaking open the myths of "missing markets" and "hidden" externalities -- but not until models are developed that can handle the geographic content of these phenomena.

The textbook microeconomic models that explicitly include a spatial dimension are generally treated under monopolistic competition. The standard model poses the question, "where should the monopolist locate her firm to maximize profits?" (Salop, 1979, cited in Varian, 1984). The model is used analogously to solve for optimal product diversification, the analogy being where to "locate" the product in relation to consumers' tastes (Dixit and Stiglitz, 1977). Location models have matured into a variety of applications (e.g. Chakrauorty and Ramousset, 1991; Goodwin and Schroeder, 1991) but so far without tapping into the potential of computer-aided mapping.

Another genre of spatial modelling used in the discipline is linear programming. A normative model, it may be employed to find least-cost routing paths for distribution or travel, or to allocate a resource among a set of activities (Dykstra, 1984; Hazell and Norton, 1986). In general, spatial features are subsumed within constraints and are not explicit in the models.

Economic models of forest conversion have mostly been non-spatial. Dvorak (1992) outlines a simple model of the cost-minimizing farmer who is clearing and producing subject to a subsistence constraint. Labor input, time to fallow, and area to clear are the decision variables. Southgate (1990), followed by Larson (1991), models the farmer as maximizing the present value of future cultivation with area under repeated cultivation and area newly cleared as the decision variables. Ehui and Hertel (1989) developed an optimal control model of deforestation to yield an optimal forest stock for the Cote D'Ivoire, but without dealing with its spatial distribution.

The spatially sophisticated models that incorporate economic analysis, on the other hand, have tended to be simplistic. Baskent and Jordan (1991) derive a wood harvesting model using GIS, but it is based on accounting rather than economic principles. Rossiter and VanWambeke (1992) developed a spatial model of land evaluation, but without making use of opportunity cost to determine optimal land allocation. Pardey and Wood (1991) have attempted to use GIS to model spill-over effects of agricultural research -- but GIS was used for land classification only. Parks (1990) uses an econometric model to predict land-use changes in the Georgia peidmont regions. Given the wide breadth for innovation in this field, there is room for much more work of this nature.

Ironically, some of the earliest work in geography used economic concepts that can serve as a spring-board for more elaborate economic models. Von Thünen developed a model of land use based on transport costs; the farther from market, the lower the net economic value of production (Parks, 1990). When net economic value goes to zero, as Parks puts it, "wilderness begins."

III. The Model

The model is based on the premise that humans respond to economic incentives. Deforestation is a rational response of individuals struggling to survive in the equatorial rainforest. It is assumed that individuals gravitate to areas of highest economic potential to clear and cultivate those areas first, leaving plots of little or zero economic profit undisturbed unless so forced by population pressure.

Briefly, the model works as follows: first, specific attribute data are entered in maps (or grids) covering the area to be modelled. These maps are nothing more than layers of data with each cell value corresponding to specific geographical (longitudinal, latitudinal) coordinate. For example, the cost of transporting 1 kg. of a given commodity across a particular cell is entered in a COST map (see Figure 1). The spatial dimension enters explicitly as transportation costs reflect physical infrastructure, geography, and means of transport that prevail. The more difficult as passage, the higher the cost of moving the commodity out of the area.[2]

Price data (per kg. of agricultural commodity) are entered in a PRICE map (see Figure 2). As with the COST map, the price data are tied to specific geographical locations; they could be thought of as corresponding to the price available at a purchasing depot, a local market, or at the farmgate. Where there are no buyers (no market), cells take on a zero value.

With the COST and the PRICE maps, one can use GIS to do some simple "map algebra." In this case, we want to find the cumulative cost of transporting 1 kg of the commodity from each cell to demand location # 1, in the north-west corner of the region. The operation is accomplished using a command in GRASS that finds the least-cost path to the specified coordinate (see Figure 3). Repeating this step for each demand location, all the cumulative cost maps (COST1, COST2, etc.) are created.

The same type of algebra used above can be repeated in all forms -- including using logical operators -- to create a variety of other maps. For instance, the COST1 map can be subtracted from a layer of homogeneous price values, i.e. the price available at demand location #1, to yield a map (PRICE1) with cell values containing the price per kg. available at each cell, net of transportation costs. This operation can be repeated for each COST# map (COST2, COST3) for their respective demand locations to yield a series of PRICE# maps (see Figure 4).

Using the maximum operator, the layer with highest price per kg. for each location is selected to yield a maximum net price (NETPRICE) map. The command forces GRASS to compare values in each layer for one particular cell and to select the highest value for that coordinate. The result is the best possible price available to the farmer, given his marketing options. Were the model to incorporate other crops, a similar macro could be developed to find the maximum potential rent -- or opportunity cost -- of devoting land to another use.

Clearing costs enter the model as a one-time, fixed cost. They enter as a linear function of forest cover; a scalar is entered and multiplied times the indexed values representing the degree of forest cover density (given in the COVER map). Subtracting these costs from the NETPRICE map, we arrive at a new NNETPRICE map that contains all costs except wages. Note that in this formulation, the shadow price of land is assumed to be zero; there is no rent accruing to unused land.

The behavioral response to economic incentives is modelled using a simple, static profit-maximization problem iterated for each period. Given that farmers are more concerned with survival today than planning for tomorrow -- in the lexicon of economics, have high rates of marginal time preference -- the static approach seems reasonable. The alternative is to model the farmers behavior as maximizing the present value of future clearing and cultivation.

Using a Cobb-Douglas production function with a fixed land input (i.e. the area available per cell) and labor (L_i) as the only variable input, the objective function is to:

(1)

$$\begin{gathered} Max\ P_i \gamma L_i^{\beta_i} - w_i L_i \\ s.t.\ 0 \leq L_i \leq \tilde{L} \end{gathered}$$

where gamma is a scalar, w_i is the wage, $ß_i$ is the elasticity of production, L tilde is the total population, and P_i is the value from NNETPRICE described above. In this formulation, $ß_i$ is being treated as a proxy for land quality.[3] The more productive a unit of land, the higher the value of $ß_i$. As an elasticity, it tells us how great a percentage increase in production to expect from a 1% increase in labor allocated to that cell. Since paid labor is a rare phenomenon in the rainforest, w_i should be thought of as the shadow price of labor. Note that these values fluctuate throughout the year, and will be lower in the dry season (when land is typically cleared) and higher just before the rains when planting occurs and during harvest periods.

Differentiating (1) with respect to L_i, first-order necessary conditions imply:

(2)

$$P_i \gamma \beta_i L_i^{\beta_i - 1} = w_i$$

By concavity, this condition will be sufficient for a global maximum as long as $0<\beta_i<1$.

Equation (2) can be solved for the derived demand for labor, $L_i^*(P_i, w_i)$:

(3)

$$L_i^* = \left[\frac{w_i}{P_i \gamma \beta_i}\right]^{\left(\frac{1}{\beta_i - 1}\right)}$$

Using the same map algebra outlined above, equation (3) can be used (along with NNETPRICE, BETA, and WAGE maps) to create a derived demand for labor surface (DEMAND). The surface contains spikes where labor demand is highest, and troughs where it is lowest.

Once the labor demand surface is derived, labor is allocated to those areas of highest potential profit. However, instead of peaks where labor demand is highest, we want to create depressions so that individuals migrate, or quite literally, gravitate, to areas of highest potential. This operation is achieved by subtracting the DEMAND surface from a layer containing the maximum value in DEMAND (see Figure 5). The cell with the highest demand for labor goes to zero; areas of low demand become peaks.

Migration is modelled using a "flooding" macro whereby the depressions are slowly filled using the available labor supply. Modelling human migration in this way assumes individuals have perfect information about economic opportunities and perfect mobility -- restrictions that could be relaxed in subsequent revisions of the model.

When all labor is allocated, resulting values of L_i are recorded in a LABOR# surface, and plugged back into the production and profit functions to yield PRODUCTION# and PROFIT# maps. The model then begins to iterate the process over again for a pre-specified amount of time units.

After each clearing and cultivation cycle, changes occur in soil fertility (through BETA#) and forest cover (COVER#). Specifically, the phenomenon of rapid loss in soil nutrients and land productivity after cultivation in the tropics (Lal, 1986) is modelled by a large decrease in β_i. Obviously, forest cover on cultivated land goes to zero. If left fallow, β_i increases slightly and forest cover increases. Ideally, these processes should be modelled using as concave functions, but for present purposes linear approximations are used.

For each time period, copies of DEMAND#, LABOR#, PRODUCTION#, PROFIT#, BETA# and COVER# maps are stored for further analysis, or for rapid display of prediction results. A useful display technique is overlaying changes in forest cover on political boundary maps, to show who will be affected by changes in rates of forest conversion.

IV. Results

To demonstrate uses of the model, a simulation exercise was carried out on a 10x10 grid. Each cell in this scenario corresponds to 10 km^2; obviously greater resolution is available from satellite imagery, and would be used to test the model empirically.

Data on costs and prices were obtained for a cash crop grown in the humid forest region of Central Africa. For reasons of data availability, cacao is used as the generic agricultural commodity. Data used are presented in Table 1. The unit of currency, the CFA, is tied to the French Franc at 50:1; so the shadow price of labor for a season is roughly $220 dollars or $3 to $4 a day. In the model, w_i is a seasonal wage; it varies from 30,000 CFA/season to 50,000 CFA/season. Similarly, price varies across space, between 400 and 360 CFA/kg.

The model was run several times to determine its sensitivity to key variables. Specifically, total population and gamma, the scaling parameter on the production function, are varied in a set of different scenarios laid out in Table 2. In terms of the maps, gamma can be thought of as regulating the "depth" of the demand troughs; the greater gamma, the more labor each parcel of land can support.

In the first scenario, with a total population of 1000 and a low value for gamma, all land was forced into production by the second period as population flooded into unprofitable areas. All land was exhausted by the fourth season -- e.g. $ß_i < 0$ for all i. Increasing the value of gamma in the second scenario delayed the process of deforestation and mitigated against land exhaustion.

Still, all land was forced into use by the 5th season in this scenario.

The outcomes of third and fourth scenarios closely paralleled the results of the first two. Even though total population was cut in half, all land came into use by the third season in run # three, with $ß_i < 0$ for all i by the eigth period. Doubling gamma slowed deforestation and soil depletion. Even so, the system never achieved a "steady-state" where profitable (in Von Thünen’s sense) land was abundant enough to allow for a stable rotation between cultivation and fallow.

Two important points emerge from this simulation exercise. First, reinforcing a point made by Lele and Stone (1989), increases in productivity in economically profitable areas are a good means of conserving resources in areas of lower productivity. Second, population is the driving force behind changes in land use; increases in efficiency, price subsidies, or road-building may alter the flow or distribution but cannot change its magnitude. That is the domain of family planning.

V. Conclusion

This paper has endeavored to show the tremendous analytic capacity of GIS for economics. In particular, it applies GIS to the problem of modelling the spatial dynamics of forest conversion. Although simplistic, the model represents a first step towards the goal of bringing spatial detail, that so far has remained outside of conventional economic analysis, into the picture.

Further refinements of the model should include: the interaction between farmers and commercial loggers (effectively bringing the cost of clearing down to zero in a given year and significantly reducing transportation costs); the effect of uncertain land tenure rules on forest clearing; speculation on land prices and its effects on land use; and how labor-saving innovations in cultivation, clearing, and soil fertility maintenance affect forest cover.

Macros for the model were developed using a simple 10x10 grid. In Part II of this series, it will be tested using the vast amounts of data being collected over the Amazon. More data means better resolution for the maps, and more information that can be made available to the public and the to leaders who represent them.

With the recent gains in hardware development and data collection, GIS is becoming a more accessible and more powerful tool for economists. Given the rapid changes in the earth's biosphere, it may become indispensable for assessing the changes brought about by humans -- and tell us more about how to channel them for the common good.

1	2	2	2	3	3	3	3	2	1
2	1	1	1	2	2	2	2	1	1
2	2	2	1	1	1	1	1	2	2
3	3	2	2	1	1	2	2	3	3
4	4	3	2	1	1	2	2	3	3
5	4	3	2	1	1	1	1	2	2
5	4	3	2	1	1	2	2	1	1
5	4	3	2	1	2	3	3	2	1
5	4	3	2	1	2	3	4	3	2
5	4	3	2	2	2	3	4	4	3

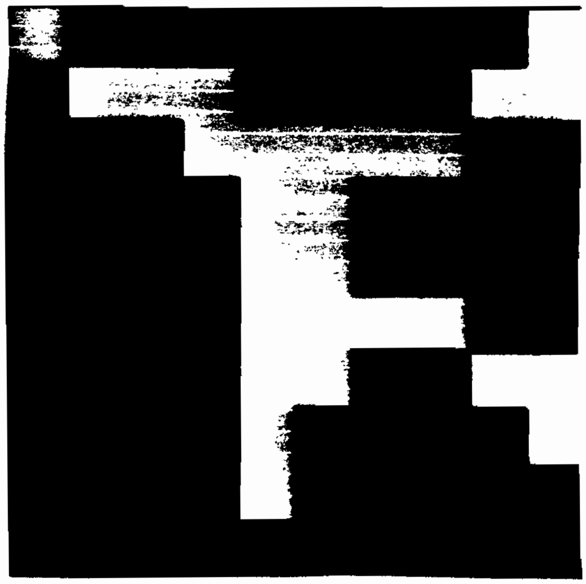

Figure 1: Digital and Display Format of COST Map.

400	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	380	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	360	0	0	0	0
0	0	0	0	0	0	0	0	0	0
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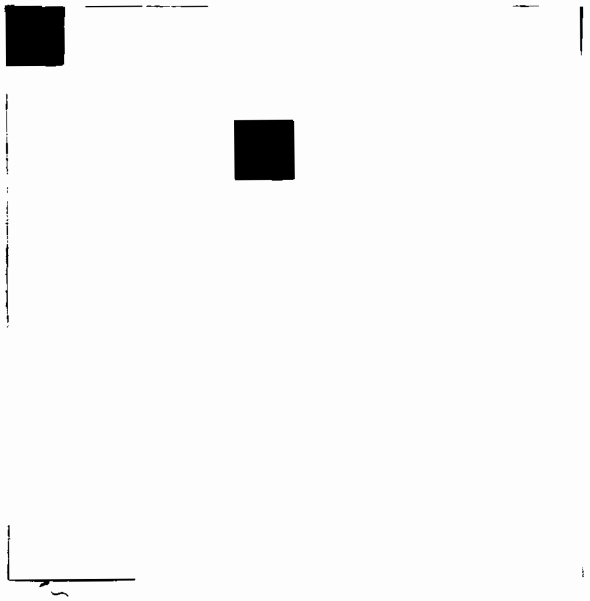

Figure 2: Digital and Display Format of PRICE Map

0	2	4	5	7	9	11	12	11	10
2	1	2	3	5	7	8	9	9	10
4	3	4	3	4	5	6	7	9	11
7	6	6	5	5	6	8	9	12	14
11	10	9	7	6	6	8	10	13	15
16	14	12	9	7	7	8	9	11	13
21	17	13	10	8	8	10	10	10	11
23	18	14	11	9	10	12	13	12	11
24	19	15	12	10	12	14	17	15	13
25	20	16	13	12	13	16	20	19	16

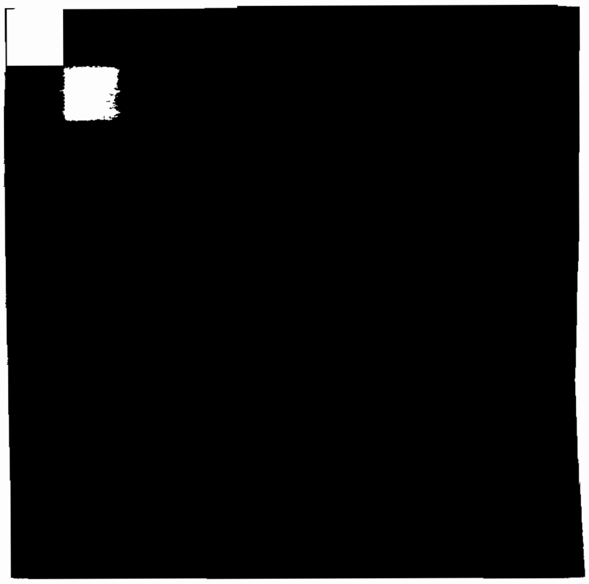

Figure 3: Digital and Display Format of Resulting COST1 Map

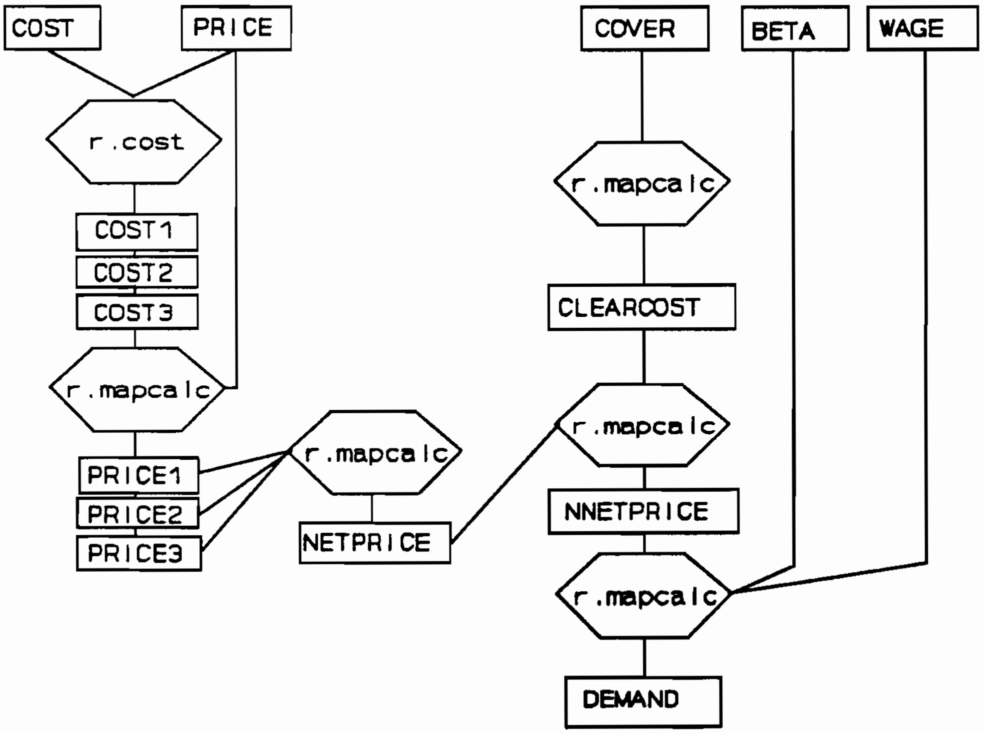

Figure 4: Schematic Diagram of Data Manipulation, Part I

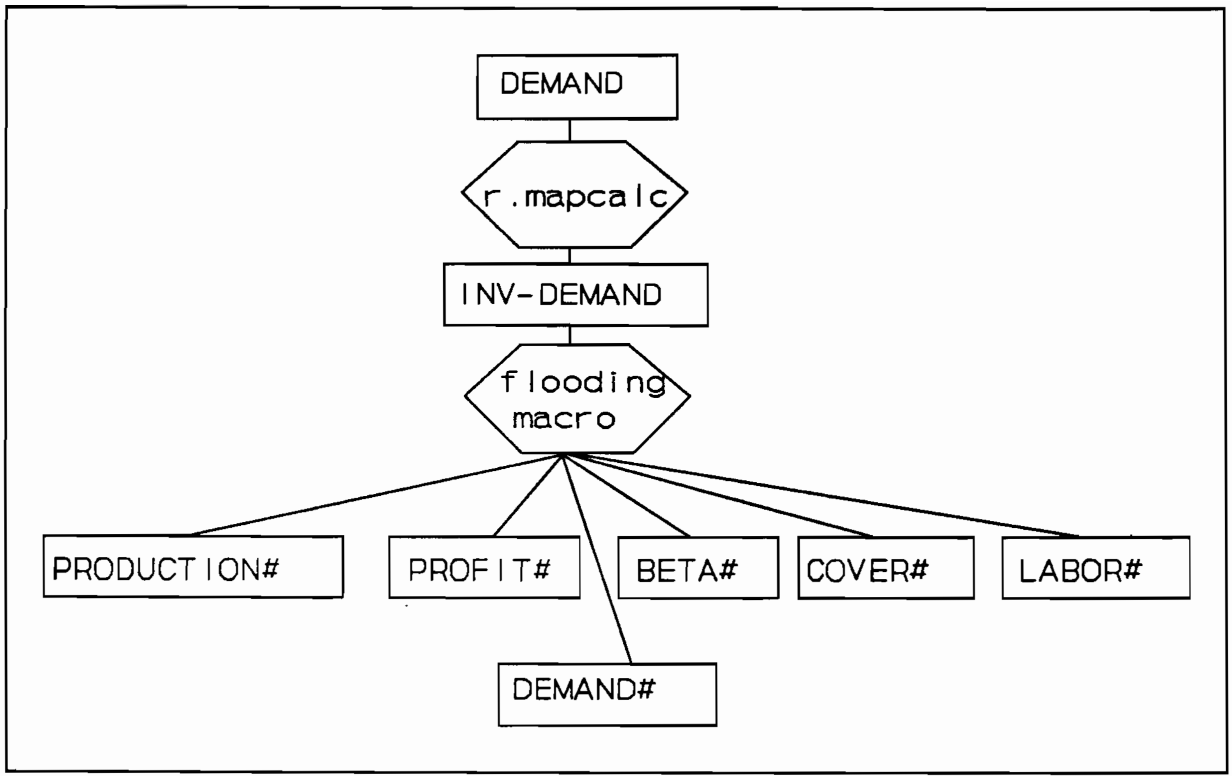

Figure 5: Schematic Diagram of Data Manipulation, Part II.

Table 1: Baseline Data for Model Simulation

Price	420	CFA/kg
Yield	260	kg/ha
Total Revenue	109,200	CFA/ha
Costs	34,000	CFA/ha
Profit	55,200	CFA/ha
Mandays/ha	59	days/ha
Derived Wage	935.6	CFA/manday
Derived Seasonal Wage	55,165	CFA/growing season

Source: World Bank, 1989

Table 2: Parameter values used in simulations[4]

Parameter	Run # 1	Run # 2	Run # 3	Run # 4
Population	1000	1000	500	500
Persons/km^2	10	10	5	5
gamma	1000	2000	1000	2000
clearing cost	93	93	93	93

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End Notes

1. For a review of developments in geography, physics, biology, physics, and ecology, see Sklar and Costanza (1990).

2. Values reflect cost of transporting 1 kg of product across the 10 km cell, in CFA. Thus, the cost of transporting a 100 kg. bag 10 km. ranges from 100 - 500 CFA, or about US$ 0.30 - 2.00.

3. This assumes that the quality of labor is the same across all cells.

4. The initial values for clearing costs and gamma were derived as follows: it is assumed that one person can clear one-tenth of very lightly covered forest regrowth (i.e. after one year) in one day. Since clearing is done in the off (dry) season, the shadow price of labor drops to 9.3 CFA/day. Using these estimates, it will cost roughly 93 CFA to clear 1 km^2. For each additional year of regrowth, that cost is increased by a factor equal to the number of years. A plot with 5 years of regrowth would cost 465 CFA to clear.

Gamma is used as a scaling parameter to bring output to the appropriate magnitude. Since there are no data on estimates, gamma is varied between 1,000 and 2,000. This means that if one person worked 1 km^2, he would produce between 1,000 and 2,000 kg of cacao. Because of concavity, returns drop off as more labor is added to each parcel.

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