TEXTO PARA DISCUSSÃO Nº 265

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Eustáquio J. Reis
Rolando M. Guzmán

JUNHO DE 1992

Instituto de Pesquisa Econômica Aplicada

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Tiragem: 150 exemplares

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SUMMARY

AN ECONOMETRIC MODEL OF AMAZON DEFORESTATION

Eustáquio J. Reis*
Rolando M. Guzmán**

* Senior Economist, Diretoria de Pesquisa do IPEA.
** Research Assistant, project UNDP/IPEA - BRA 89/008.

This paper was financed by project GESEP (loan BIRD 2347-BR) and elaborated with the support of project UNDP/IPEA BRA 89/008.

INTRODUCTION

Based upon cross section data at municipal level, this paper specifies, estimates, and simulates an econometric model of Brazilian Amazon deforestation and its contribution to CO_2 emissions. The model consists of three blocks of equations: in the first, cleared land - distinguished by vegetation types - is determined by major economic activities; in the second, the relationship between vegetation type and biomass content determines carbon dioxide emissions caused by deforestation; finally, in the third, generating functions for the spatial distribution of population and major economic activities make feasible the simulation of future geographic patterns of deforestation.

The analysis presented here improves Reis and Margulis (1991) in two major aspects. First, the data base was enriched by better information on agricultural output, vegetation cover, transportation conditions, as well as on the spatial characteristics of data like the structure of municipal contiguity. Second, the regression analysis takes into account of the spatial autocorrelation phenomena, thus allowing a better diagnosis and treatment of problems resulting from the omission of variables, measurement errors, and improper specification [Cliff and Ord (1981) and Miron (1984)].

The paper is organized in seven sections. After the introductory remarks on the contribution of Amazon deforestation to CO_2 emissions, the first section surveys early econometric results on tropical deforestation. The second section derives the basic equations of an economic model of Amazon deforestation. The third section discusses estimation issues, with particular attention to spatial autocorrelation. The fourth section describes the data base used and is followed by the presentation of the estimation and simulation results. The concluding section suggests research extensions and further developments of the model.

The climatic and ecological consequences of Brazilian Amazon deforestation are among today's leading global environmental concerns. The main reasons for concern are the contributions of tropical deforestatiion to CO_2 emissions and to the loss of biodiversity. In what follows we address only the first of these issues.

Evidence on the importance of Brazilian Amazon deforestation to CO_2 emissions are presented in Table 1. Figure 1 gives a visual perception of the spatial distribution of deforestation in the region.

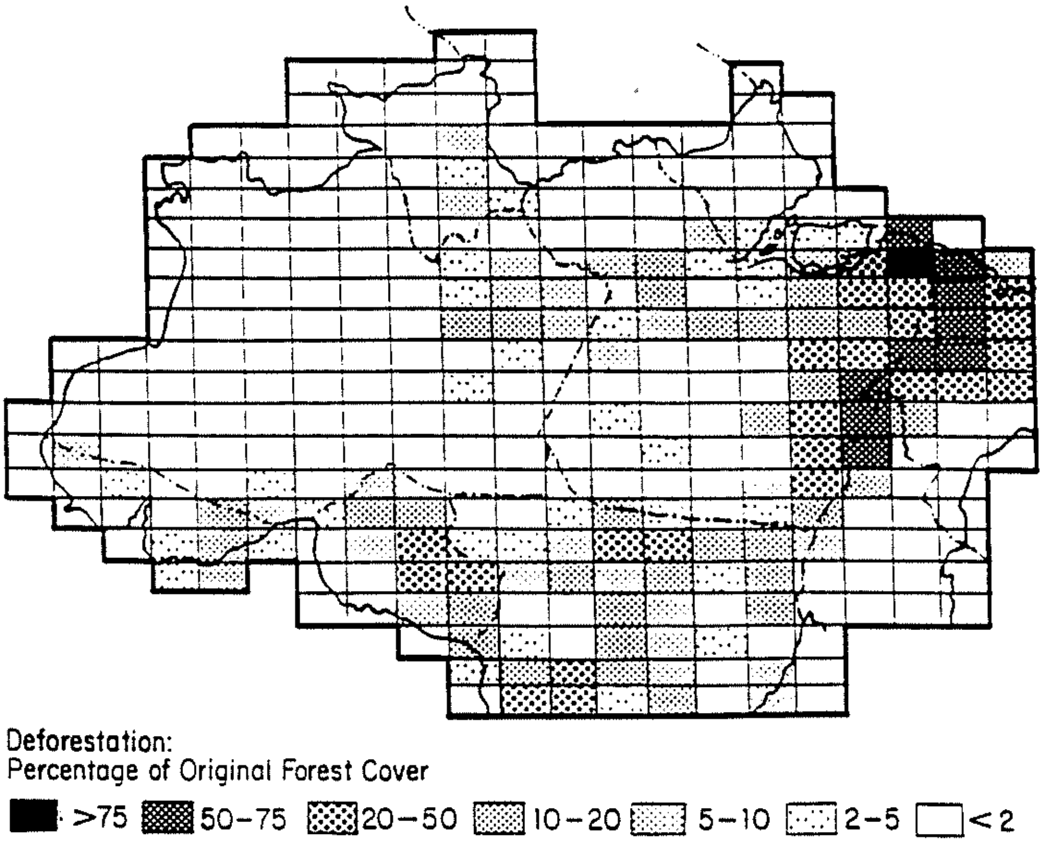
Table 1

Amazon Deforestation and Carbon Dioxide Emissions

Year	Area		Annual increase		Annual CO_2 emissions	
	km2	%	km2	%	in 10^9 t	% of World
1978	152,910	3.1	-	-	-	-
1988	377,633	7.7	22,472	9.5	0.31-0.45	4.4-6.2
1989	401,433	8.2	23,800	6.3	0.33-0.48	4.6-6.6
1990	415,251	8.5	13,818	3.4	0.19-0.27	2.7-3.8
1991	426,351	8.7	11,100	2.7	0.15-0.22	2.2-3.1

Source: INPE; carbon dioxide emissions estimated by the authors.

Figure 1 - Satellite Images of Deforestation in Amazonia, 1989



The contribution of Amazon deforestation to global emissions is specially significant if one considers that agricultural activities in the region represent less than 1 percent of Brazilian GDP. That makes the slowdown of Brazilian Amazon deforestation one of the most cost-effective ways to reduce carbon dioxide emissions [Nordhaus (1991), Hoeller **et alii** (1991), and Mors (1991)], though this kind of estimation tends to understimate the cost of compensate local population for the economic opportunity losses [Reis (1991), and Reis and Margulis (1991)].

1. EARLY ECONOMETRIC RESULTS ON TROPICAL DEFORESTATION

Despite the importance of tropical deforestation to the greenhouse effect, econometric analysis of demographic and economic factors are remarkably lacking. Projections are usually based upon naive extrapolations of past trends, often leading to significant overestimates [INPE (1990) and Schneider (1990)]. As a consequence, considerable uncertainty exists with regards to both future rates of deforestation and the costs of halting it.

To take an authoritative example, in the IPCC (1991) the driving mechanism of the projection model is the simple assumption of a unit elasticity of deforestation in relation to population (lagged by 20 years). Moreover, the distribution of deforestation between closed broadleaf and other kind of forests is made in proportion to the area convered by each kind of forest. In both cases, it is only the lack of knowledge concerning relevant parameters that justify the simplistic assumptions adopted.

Econometric results on elasticities of deforestation are scanty. Table 2 provides an incomplete survey of them, which shows major differences of specification, sample, variables, geographic aggregation, and measuremente of data. Furthermore, in most cases, parameters were not derived from theoretical models, thus making comparisons even more difficult. Note also that equations are underidentified. Thus, population elasticities reflect both effects of the supply of labor and of the demand for output.

Despite the aforementioned problems, results seem reasonable at first sight. Thus, comparing Latin America and Southeast Asia, population growth and logging exert greater pressure on deforestation in the latter, while road elasticities are bigger in the former. The impact of agriculture is practically the same in both regions, if cattle raising elasticity is not taken into account.

Table 2

Survey of econometric results for elasticities of deforestation in relation to major economic activities

Autor	Panoyotu	Southgate	Kummer	Kummer	Reis et alli
Region.	Thailand	Lat. Amer.	Phillip	Phillip	Braz.Amaz.
Depen.var.	Deforest.	Agric.area	Deforest.	Deforest.	Deforest.
Geog.unit	Municipio	Country	Provin.	Provin.	Municipio
Period	1973-82	1970-80	1970-80	1970	1985
Data	Panel	Panel	Crossec	Panel	Crossec
Method	OLS	OLS	OLS	OLS	OLS
Specific.	Log-Log	Grow.rates	FirstDiff	Log-Log	Logistic
Variable	Elasticity estimates ("t" values in parenthesis)				
Population	1.51	0.25		0.54	0.30
	(9.7)	(3.8)		(n.a.)	(2.7)
Roads	0.11		0.23	0.28	0.28
	(1.4)		(2.4)	(n.a.)	(4.7)
Agriculture	0.32*		0.41		0.40
	(1.7)		(4.2)		(3.6)
Logging	0.41*		0.32		0.04
	(4.1)		(3.2)		(1.0)
Productivity	-0.38	-0.20			
	(1.9)	(6.0)			
Cattle herd					0.11
					(1.83)
R^2	0.80	0.67	0.49	0.58	0.84
D.F.	55	18	64	66	165

Obs.: *Assuming a supply price elasticity equal to 1.

These differences can be justified by the lower population densities and the more recent settlement of tropical forests of Latin America. As a caveat, however, note that the larger geographical unities of Latin American samples tend to weaken the relationship between population and deforestation, introducing a downward bias in elasticities.

The results surveyed suggest that the IPCC (1991) assumption of a unit elasticity of deforestation in relation to population is probably a bit exaggerated. Indeed, most of the remaining tropical forests are in Latin America, where population elasticities seems to be significantly lower than unit.

In any case, the lesson to be derived from this brief survey points out to the precarious state of art of the economics of tropical deforestation, and to the contribution which could be brought by econometrics. In this way, it indicates the urgent need for further research efforts on data gathering, model specification and estimation techniques.

2. THE MODEL OF AMAZON DEFORESTATION

Three blocks of equations compound the model. The first one relates deforestation to economic activity; the second block links deforestation to vegetation cover and to CO_2 emissions; and the third one specify generating functions for the spatial growth of population and economic activities.

The first block is based upon an aggregate production function for major agricultural activities - supposedly, the main source of deforestation in Brazilian Amazon. the derived demand for cleared land in agricutlure is determined by profit maximization. Output prices are considered exogenous to the model; wages are determined by demand and supply of labor, and land prices by clearing costs. A logistic function relates deforestation to land cleared in agriculture and to the land requirements of other economic activities.

A Cobb-Douglas production function relates agricultural output (Q) to the inputs of labor (L) and cleared land (C). Profit maximization - given output prices, wages (w), and clearing costs (k) - leads to the following derived demand for cleared land (C_d) and labor (L_d), respectively:

$$C_d = ((1 - a)/a)^a \, . w^a \, . \, k^{-a} \, . \, Q, \qquad (1)$$

$$L_d = (k \, . \, a/(1 - a) \, . \, w)^{1-a} \, . \, Q \qquad (2)$$

where $0 < a < 1$.

Output (Q) is a long run concept defined as a composite index of cattle herd (H) and trend output for temporary and permanent crops (Y) as follows:

$$Q = H^h \, . \, y^{1-h} \qquad \text{where } 0 < h < 1 \qquad (3)$$

The supply of labor (L_s) is assumed to increase with population (N) and wages, and to decrease with transport costs proxyed by a vector of variables-specified as spatial discount factors-which includes the distances to local and national (M) markets, and the networks of roads and rivers (R):

$$L_s = w^b \, . \, N^g \, . \, \exp\,(e_1 \, . \, R - m_1 \, . \, M)$$

$$\text{with } b, g, e_1, m_1 > 0 \qquad (4)$$

Equilibrium in the labor markets leads to:

$$w = (k \,.\, a/(1 - a))^{j \,.\, (1 - a)} \,.\, Q^{j} \,.\, N^{-j.g} \,.$$

$$\exp \,.\, \{-j\ (e_1 \,.\, E - m_1 \,.\, M)\}, \tag{5}$$

where $j = 1/(1+b-a)$

Furthermore, the free availability of land in the region makes it legitimate to assume that deforestation decisions are short sighted [Panayotou and Sungsuwan (1989)]. Accordingly, land prices are assumed to depend solely on clearing cost which, in turn, are assumed to depend only on the vegetation cover as proxied by the density of forest (F/A), and transport cost-which is specified in the same way as in (4):

$$k = \exp\ (f \,.\, (F/A) + m_2.M - e_2 \,.\, R),$$

$$\text{where } f,\ e_2,\ m_2 > 0 \tag{6}$$

where A = geographic area of municipalities.

Substituting (5), (6) and (3) in (1), the reduced form of the derived demand for cleared land in agriculture is:

$$C = (a/1-a)^{a.(j.(1-a)-1)Qj.(a+1)} \,.\, N^{-j.a.g}.$$

$$.\ \exp\ \{j.(e_2.(1-a)-e_1).E+j.(m_1+m_2.(1-a)).M\}\ .$$

$$.\ \exp\ \{a \,.\, (j.(1 - a) - 1) \,.\, f(F/A)\} \tag{7}$$

or

$$C = B_0.Q^{B}{}_1.N^{B}{}_2.\exp(B_3.(F/A)+B_4.R+B_5.M), \tag{7'}$$

where:

$$B0 = ((1 - a)/a)^{ab/(1+b-a)} > 0$$

$$B1 = (b + 1)/(b - a + 1) > 0$$

$$B2 = -a \,.\, g/(b - a + 1) < 0$$

$$B3 = -a \,.\, b \,.\, f/(b - a + 1) < 0$$

$$B4 = a\ [be_2 - e_1]/(1 + b - a) > 0 \text{ se } be_2 > e,$$

$$B5 = -a\ [bm_2 - m_1]/(1 + b - a) > 0 \text{ se } bm_2 > m,$$

Taking logarithms, we obtain an relation with the form:

$$C = A_0 + A_1q + A_2n + A_3(F/A) + A_4R + A_5M \tag{7"}$$

where small letters refer to logarithm.

Finally, the extent of deforestation (D) is determined by land clearing in agriculture, logging activities (L) for timber and firewood production, and by all kind of urban activities as proxyed by urban population (U) [Panayotou and Sungsuwan (1989)]. The specification adopted is a logistic function relating density of deforestation (d), defined as the relation between deforested area and total geographic area, to the economic activities described above:

$$\log\ (d/(1-d)) = B_0 + B_1.c + B_2.u + B_3. \quad + B_5.a \qquad (8)$$

where, as before, small letters refer to logarithms.

The logistic is used to describe deforestation as a process which tends toward saturation within a given geographic area. In other words, during early stages of settlement and deforestation is high. As the remaining forest area dwindles, the impact of economic activities on deforestation diminishes, eventually dying out in totally deforested areas.

According to the model derived in the above equations, Amazon deforestation is the result of profit maximizing behavior in a static framework. Dynamic considerations related to the role of land as an asset, to land price speculation and to wealth maximization were completely ruled out by the assumptions embodied in equation (4).

Institutional considerations related to the open access to land and to the weakness of government institutions in Amazonia are also ruled out from the model. These motivations make deforestation a mean to secure property rights in land, and as consequence, cleared land tends to exceed land requirement for agricultural purposes, specially in areas where land conflicts are pervasive [Sawyer **et alli** (1990) and Southgate (1989)]. And **ad hoc** test to the institutional hypothesis would be to include proxies for tenure conditions like population of squatter farmers (S) and land area in public domain (V), as additional variables in equation (8).

The second block of equations uses an identical logistic specification to estimate the distribution of deforested areas by major types of vegetation. Thus:

$$\log\ (d_j/1-d_j) = D_0 + D_1.q + D_2.n + D_3.R + D_4.M + \\ +\Sigma_j(D_{5j}.F_j) + D_6.D \qquad (9)$$

for j = 1, 2, ..., 6;

where:

d_j = deforested share in vegetation type *j*.

Based upon the biomass content of each major type of vegetation, CO_2 emissions are determined, as follows:

$$CO_2 = \Sigma_j \; q_j * c_j * (b_j - b_0) * D_j \qquad (10)$$

where:

CO_2 = CO_2 emissions (in tons),

q_{ji} = percent of biomass which is burnt in vegetation *j*,

b_j = biomass content (t/ha) of vegetation *j*,

b_0 = biomass (t/ha) content in deforested areas (converted or abandoned),

c_j = percent of CO_2 in vegetation *j*.

Estimates of the biomass content in major types of vegetation cover of Brazilian Amazon are presented in Table 3. For estimation and simulation purposes, they were aggregated in two types: forests (which includes dense, open and ecological transition) and savannas (including campinarana and wetlands). Insid each of these two types, deforestation was distributed in proportion to areas of each type of vegetation in the municipality. Finally, for all kinds of vegetation it is assumed that the biomass is completely burnt, that is:

$$q_j = 1 \text{ for all } j \qquad (11)$$

The third block of equations consists of the generating functions for the spatial distribution of major economic activities. For population, crop output, cattle stock, logging, and roads, the assumption is that rates of growth in municipality *i* and time *t* depends only on the spatial density of the respective activity at time t-1. Thus:

$$x_{ki,t} = C_{0k} + C_{1k} \, . \, \log \, (x_{ki,t-1}) \qquad (12)$$

where k = population, agriculture, cattle, and logging, x is growth rate, and x is the spatial density, that is, the relation between activity level and geographic area.

Equations (12) describe the patterns of spatial concentration of economic activities over time. An activity k will show increasing spatial concentration if C_{1i} is greater than zero and will show spatial dispertion if C_{1i} is less than zero.

Table 3

Estimates of above ground and total biomass (t/ha) for major types of vegetation covers of Amazonia

Vegetation Type	Area %	Aboveground		Roots(1)		Total	
		Min	Max	Min	Max	Min	Max
Dense rain forests	69,53	188	300	54	100	242	400
Open forests	3,03	112	186	37	62	160	247
Ecological transition(2)	5,11	75	112	25	37	100	148
Savanna	13,97	6	75	6	32	12	107
Campinarana	6,34	6	120	6	45	12	165
Wetlands	2,01	6	115	6	38	12	153
Average(3)	100,00	139	240			180	322

Source: Author estimates for areas and various sources for biomass.

Obs.: (1) Assumed to be 1/3 of aboveground biomass.

(2) Biomass content assumed to be between the maximum for savannas and open forests.

(3) Weighted by area.

3. ESTIMATION ISSUES: SPATIAL AUTOCORRELATION (SAC) AND SEEMINGLY UNRELATED REGRESSION (SURE)

The model is designed to make secular projections and simulations of the ecological and climatic consequences of tropical deforestation. Reliable estimates of long-run elasticities of deforestation in relation to major economic activities are crucial for this purpose. A major obstacle, however, is the lack of time series sufficiently long to characterize long run equilibrium solutions. This is particularly true for deforestation data.

Fortunately, cross section data for Brazilian Amazonia are especially suited to estimate long run elasticities. The sample includes more than 300 municipalities in very diverse stages of demographic and economic settlement, thus encompassing a wide range of configurations concerning the geographic densities of deforestation, population, and economic activities. Metaphorically speaking, the data mimics long run equilibria situations where differences between municipalities represent decades or centuries [Pindyck (1979)]. On top of that, the availability of panel data for major economic and demographic variables allows more rigorous dynamic analysis.

Deforestation, population settlement and economic activities are simultaneous processes taking place in the same geographic space. This brings the possibility of two major econometric problems, namely residual covariance across different equations and spatial autocorrelation of residuals in each equation - both of them deserve careful consideration since, othwerwise, estimates of long run elasticities are likely to be biased and inconsistent.

The simultaneity and interdependence of economic decisions give rise to Seemingly Unrelated Regression problems. Thus, equations describing population settlement, forest clearing, cropping, cattle raising, and logging are likely to show stochastic dependence, and therefore, residual covariance across them. The stochastic dependence can result from common generating mechanisms, latent variables and/or adding up restrictions not explicitly recognized in the model. Techniques to deal with these problems are well known [Zellner (1962)].

In its turn, spatial or geographic contiguity give rise to phenomena like contagion and/or spatial inertia across observations (neighboring municipalities in this case) which can lead to the presence spatial autocorrelation of residuals in each equation. Figure 3 shows the lattice of municipalities of Brazilian Amazonia in 1986.

Spatial autocorrelation is usually a signal of missing variables, improper structural form, or measurement error. Therefore, its diagnosis can be a strong tool for improving model specification. Its identification requires a contiguity matrix, and usually, its corretion is made by the use of Generalized Least Square (GLS) or Maximum Likelihood (ML) methods [Miron (1984), and Cliff and Ord (1973, 1981)].

Moran (1950) and Geary (1954) coefficients are the usual statistics to test the presence of spatial autocorrelation. For a variable X, with normal deviates z, the Moran coefficient (M) is:

$$M = (n/1 \, . \, W \, . \, 1) \, . \, (Z' . \, W. \, Z/Z'Z) \qquad (13)$$

and the Geary coefficient (G) is:

$$G = ((n - 1)/2 \, (1' \, . \, W \, . \, 1)) \, . \, (\Sigma w_i \, . \, p_i/Z'Z) \qquad (14)$$

where

n = number of observations (muncipalities in this case),

W = contiguity matrix (nxn) with elements w_{ij} equal to 1 if i and j are spatially contiguous observations, and equal to zero otherwise,

1 = column-vector with all elements equal to 1,

Z = column-vector (n x 1) with elements $z_i = (x_i - \overline{x})$,

p_i = i^{th} line of matriz P (nxn) where $p_{ij} = (x_i - x_j)^2$,

w_i = i^{th} line of matriz W.

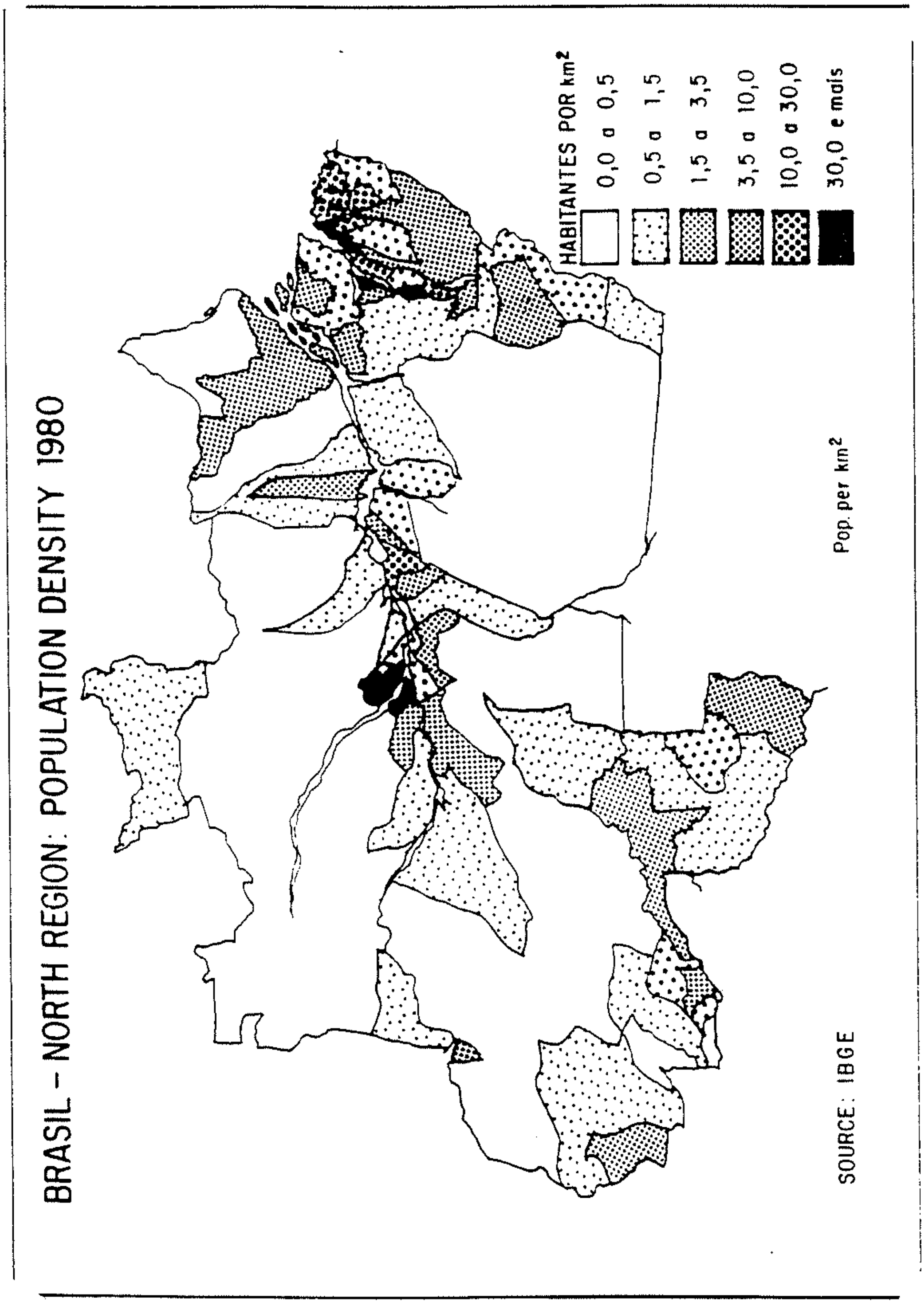
It is possible to demonstrate that both M and G are asymptotically normal under weak assumptions [Cliff and Ord (1981)]. Both coefficients can also be used to test residual autocorrelation in regression equations.

Table 4 presents both the Moran and Geary coefficients for the main variables of the model. Standard errors were calculated under the normality assumption. Spatial autocorrelation for the logarithms of densities of deforestation, population and major economic activities are about the same and significantly higher than the coefficients obtained for growth rates. Figures 1 and 2 give an intuitive perception of the presence of spatial autocorelation for the spatial distribution of the density of deforestation and population.

For estimation purposes, the analysis of spatial autocorrelation as well as of residual covariance across equations was restricted to equations (12) where the problem is likely to be specially severe. The reason for that is the parsimonious and naive specifications used for the generating functions of spatial distribution of population, agriculture, cattle raising, and logging.

For equations (7")-(10), specifications are supposed to be theoretically more rigorous and to include a good number of the relevant spatial factors. To that extent, the damages caused by improper specification or omitted variables are smaller. Moreover, since the specification of deforestation and deforestation by vegetation type are practically the same, SURE techniques are not likely to make significant improvements compared to OLS results. Therefore, in these cases, it is fair to neglect the problems posed by spatial autocorrelation and residual covariance across equations.

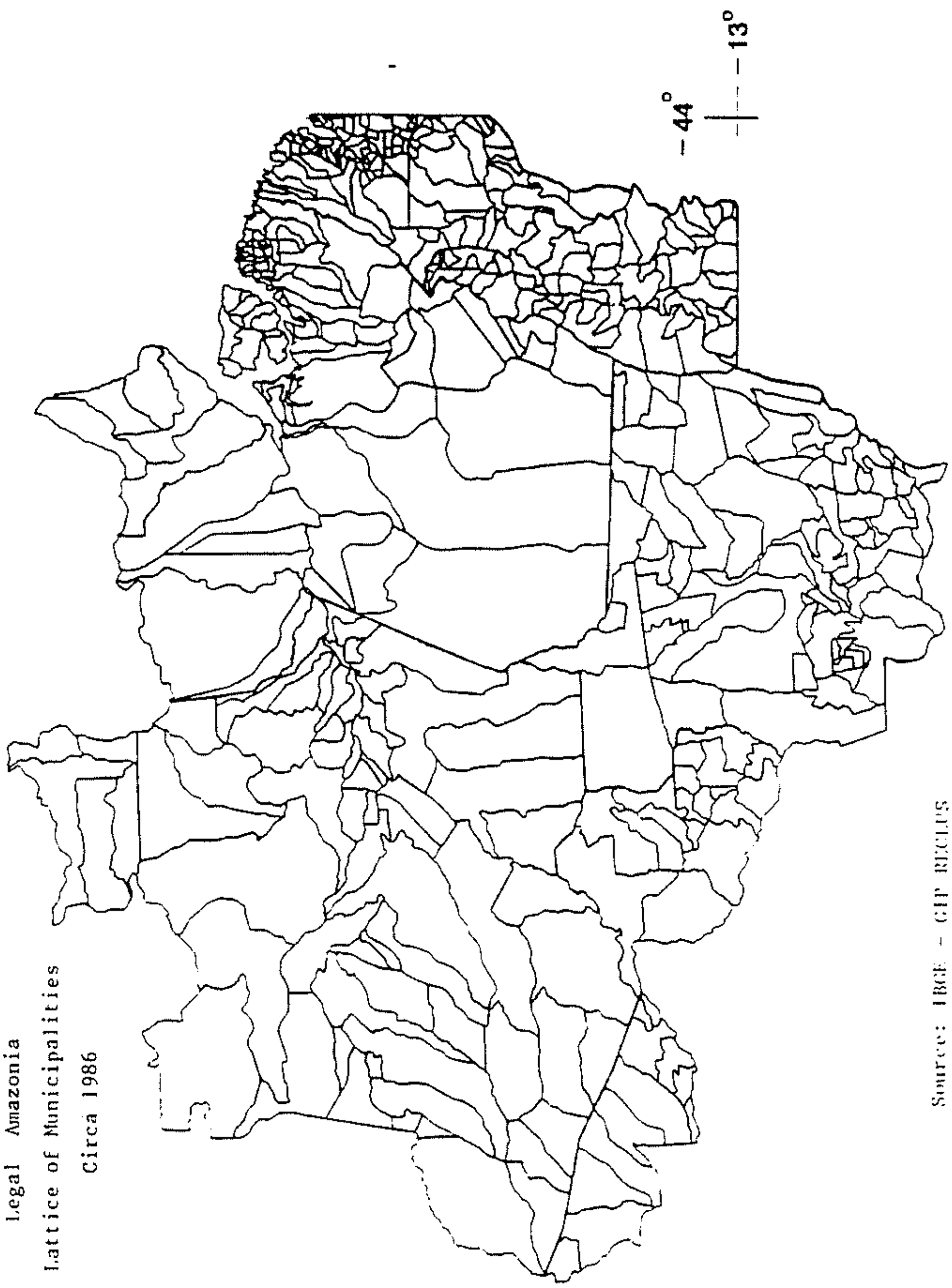
Figure 2



BRASIL - NORTH REGION: POPULATION DENSITY 1980

SOURCE: IBGE

Figure 3



Legal Amazonia
Lattice of Municipalities
Circa 1986

Source: IBGE - GIP RECLUS

Table 4
Spatial Autocorrelation for Logarithms of Geographic Densities of Main Variables

	Moran		Geary		Sample Size
	Value	St.er.	Value	St.er.	
log(dt-1)	0.717	0.049	0.266	0.070	153
log(ct-1)	0.740	0.032	0.226	0.048	336
log(nt-1)	0.700	0.033	0.267	0.048	336
log(ht-1)	0.706	0.032	0.289	0.048	336
log(qt-1)	0.724	0.032	0.259	0.048	335
log(wt-1)	0.487	0.032	0.432	0.048	335
log(nt/nt-1)	0.400	0.033	0.658	0.048	336
log(ht/ht-1)	0.079	0.033	0.886	0.048	336
log(qt/qt-1)	0.350	0.033	0.718	0.048	335
log(wt/wt-1)	0.282	0.035	0.705	0.052	295

Obs.: (1) St. er: standard error asuming a normal distribution.
(2) Small letter refer to geographic densities: d = deforestation, c = agricultural land, n = population, h = herd, q = crop output, w = logging.
(3) Period t is 1985 and t-1, 1980, except for logging, where they refer to 1982 and 1987, respectively.

A general specification for the presence of spatial autocorrelation in a model is [Case (1991)]:

$$Y = p . W . Y + Z . B + u \qquad (15)$$

$$u = r . W . e + e$$

where

Y = vector (nx1) of dependent variable,

Z = a matrix (nxk) of explanatory variables,

B = a vector (kx1) of coefficients,

u = vector (nx1) of residuals,

e = vector (nx1) of residuals,

p = intensity of spatial autocorrelation in the dependent variable,

r = intensity of spatial autocorrelation in the residuals.

The three possible cases of spatial autocorrelation and their respective implications are: (i) if p 0 and r = 0, spatial autocorrelation occurs in the dependent variable but not in the residuals; thus, least square estimators will be biased and inconsistent; (ii) If p = 0 and r 0, spatial autocorrelation occurs in occurs the residuals but not in the dependent variable; thus, OLS estimator of B will be unbiased but inefficient; and (iii) if p 0 and r 0, spatial autocorrelation occurs both in the dependent variable and in the residuals; in this case, maximum likelihood methods are suggested for estimation.

When spatial autocorrelation in residuals combines with seemingly unrelated regresion, the specification of equation (15) becomes:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_m \end{bmatrix} = \begin{bmatrix} Z_1 & 0 & \dots & 0 \\ 0 & Z_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & Z_m \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_m \end{bmatrix} + \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix}$$

$$\begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix} = \begin{bmatrix} p_1 I & 0 & \dots & 0 \\ 0 & p_2 I & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & & p_m I \end{bmatrix} \begin{bmatrix} W & 0 & \dots & 0 \\ 0 & W & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & W \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_m \end{bmatrix} + \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_m \end{bmatrix} \qquad (16')$$

where $E(e_i e_j) \neq 0$.

This can be written in the form:

$$\begin{aligned} Y_{(mnx1)} &= Z_{(mnxmk)} B_{(mkx1)} + U_{(mnx1)} \\ \underset{(mnx1)}{U} &= (\underset{(mxm)}{p} \otimes I)\underset{(mnxmn)}{W}\ \underset{(mnx1)}{U} + \underset{(mnx1)}{E} \qquad (16) \\ E(E) &= 0; \qquad E(EE') = \psi_{(mnxmn)} \end{aligned}$$

where subscripts in parenthesis indicates the dimensions of respective matrices, O is the kronecker product, and

m = number of dependent variables or equations in the model,

n = number of observations,

k = number of independent variables or coefficients,

p = diagonal matrix with elements p_i $(i = 1,2,...,m)$.

4. THE DATA

Deforestation (D) data were derived from the Landsat satellite images plotted at municipal level. They are available for a reduced sample of municipalities, and in a single point in time. The images are from 1983 for some observations, 1985 for others, and 1987 for the remaining. Dummies variables for 1983 (DU83) and 1987 (DU87) were included in regressions to reduce bias introduced by these measurement errors.

Geographical areas of major types of vegetation cover (V_j) - closed forest, open forest, savanna, wetlands, campinarana, and ecological transition - as well the extent of deforestation in each of them (D_j) come from estimates of IBDF-IBGE also based upon Landsat images.

Cleared land and output in agriculture come, respectively, from the 1985 Agricultural Census, and the Annual Agriculture Production Municipal Surveys available from 1977 to 1987. Cleared land (C) is a stock variable, the area alocated to various economic uses (excluding natural pastures) at Census data. For cattle raising, output (H) is also measured by a stock variable: the size of herds at Census date. Since temporary and permanent crop outputs are annual flows, to make time dimensions less disparate, the variable used in the estimations was trend output (Q), defined as the average quantities produced in the five-year periods centered on Census years. This concept smoothens the yearly fluctuations in crop output, and accounts for leads of deforestation in relations to output, particularly relevant for permanent crops.

Rural (R_u) and urban (U) population come from the 1980 and the 1991 (preliminary data) Demographic Census. Figures for 1985 are geometric interpolation assuming the same rural/urban composition as in 1980. Urban population is used as a proxy variable for all kinds of urban activities.

Logging (L) for timber, charcoal and firewood comes from the Extractive Production Country Surveys available from 1982 to 1987. In equation (8), the variable used is aggregate cumulative production flows from 1982 to 1987 for timber and charcoal. In equation (12), rates of growth of logging refer to the 1982/87 period.

Access and transportation conditions are described by the distance to state capitals and to Brasilia - as proxies to local and national markets - an by the extension of major roads and rivers in each municipality. Roads (federal and state, paved and non paved) and rivers (deeper than 2.10 m in 90% of time) come from maps and are available only for 1985/86. For the purposes of the model, it is reasonable to neglect feeder roads since they are simulataneously determined with deforestation and population settlement.

5. ESTIMATION RESULTS

Table 5 reports estimation results for equations (7), and (8). Column 2 shows ordinary least squares (OLS) estimation for the double logarithm specification of the equation (7) on cleared land in agriculture; columns 3 and 4 show OLS and maximum likelihood estimates (ML), respectively, of eq. (8) which explains deforestation density as a logistic function of agriculture clearing and urban activities; columns 4 and 6 present OLS and ML results for a reduced form of the model which describes deforestation density as logistic function of all the exogenous variables.

However, "one should not be surprised to find large wage differences from one district or village to another and apparent disequilibrium in frontier labor markets - especially if one must reside on one's land to retain ownership." [Kazmer (1977:432)]. In a context of land abundance, high real wages in a given municipality could simply mean relatively enlarged possibilities for establishing an independent farm and, therefore, reduced supply of labor. On the other hand, low real wages "may indicate only that new settlers arrive to claim land faster than they can be absorbed into employment." [Kazmer (1977:432)].

The above arguments show that the model is underidentified and point the need of more careful specification of the dynamics of labor supply and land settlement. For the time being, however, results wil be accepted as they are based upon the assumption that labor will continue to be the binding factor for the expansion of the Amazon agricultural frontier.

Table 5 - Estimates for agricultural clearing and deforestation

Eq. Number	(7)	(8)	(8)	(8′)	(8′)
Dependent	Ag. Cle.	Def. den.	Def. den.	Def. den.	Def. den.
Specif.	Log-Log	Logistic	Logistic	Logistic	Logistic
Method	OLS	OLS	OLS	OLS	ML
N. Obs	305	151	151	151	151
D. F.	290	145	144	132	132
R2 adj.	0.99	0.72		0.81	
RMSE	0.55	0.36	0.34	1.77	0.62
Moran resid.	0.23	0.30	0.14	0.21	0.11
Rho resid.	0.61	0.80	0.38	0.72	0.30
Variable	Coefficient (standard errors in parenthesis)				
Intercept	-	9.05	6.48	-	-
		(1.60)	(0.98)		
Agric. Clearing	-	1.13	0.97	-	-
		(0.13)	(0.09)		
Rural pop.	0.23			0.52	0.60
	(0.06)			(0.29)	(0.33)
Urban pop.		0.11	0.04	-0.10	-0.14
		(0.12)	(0.07)	(0.16)	(0.19)
Crop output	0.32			0.64	0.34
	(0.03)			(0.14)	(0.16)
Cattle herd	0.41			0.20	0.22
	(0.03)			(0.10)	(0.14)
Logging		-0.44	-0.12	-0.49	-0.20
		(0.12)	(0.08)	(0.13)	(0.17)
Geog. area	0.06	-1.65	-1.61	-1.76	-1.97
	(0.03)	(0.09)	(0.10)	(0.14)	(1.52)
Paved road	-0.28			1.76	2.77
	(0.39)			(1.57)	(2.46)
Nonpaved road	0.33			1.27	0.63
	(0.12)			(0.50)	(0.62)
Rivers	-0.53			0.37	-3.89
	(0.37)			(1.31)	(3.36)
Dist. state	0.19			-0.26	0.13
	(0.12)			(0.65)	(1.06)
Dist. federal	-0.23			-0.92	-0.92
	(0.06)			(0.24)	(0.63)
Rain forest	-3.20			6.13	2.84
	(0.48)			(2.76)	(3.68)
Open forest	-3.09			6.66	3.81
	(0.48)			(2.99)	(3.20)
Savanna	-3.20			5.52	2.23
	(0.44)			(2.37)	(2.93)
Ecol. Trans.	-3.12			6.12	2.98
	(0.49)			(2.78)	(2.97)
Wetlands	-4.80			2.97	0.90
	(0.49)			(2.68)	(3.69)
Campinarana	-3.06			5.19	2.06
	(0.62)			(3.05)	(14.8)

Against theory and intuition, the coefficient of logging came out negative and, in OLS estimations, significantly different from zero. The problem seems to be rooted in the use of annual flows of logging to measure the cumulative impact of logging on deforestation. This leads to problems of dynamic specification, since logging flows are at the same time cause and consequence of forest clearing. Thus, they tend to be large in relatively unsettled regions where the agricultural frontier is expanding fast. The suggestion to eliminate this negative bias is to specify panel data and to specify a system of equations where logging flows are simultaneously determined with changes in land clearing.

The values of coefficients in equation (7) show that the importance of cattle raising and cropping as sources of land clearing in agriculture is practically the same. Different results, however, appear in equations (8) and (8'). Thus, though coefficients in these equations are not straight elasticities, their values show that cropping and rural population are, by far, the most important sources of deforestation. This an important corroboration of results of Reis and Margulis (1991), mainly because cropping is now measured by the output of crops and not by crop area as was done earlier.

Table 6 report results for the equation (9) which determines the share of deforestation which takes place in forest areas (including dense forests, open forests, and ecological transition) as opposed to areas covered by other kind of vegetation (savannas, wetlands, and campinaranas). The same specification as in equation (8) is used in this case, except for the substitution of deforested area for geographic area.

Table 7 report estimation results for the generating functions of spatial distribution described by equation (12). The specification used is too simple to explain the variances in growth rates of population and economic activities, thus resulting in extremely low correlatioin coefficients. However, all the activities, except perhaps for logging, show small standard errors for the slope coefficients which quantify the relation between its geographic density and subsequent growth rate. Comparing different estimation methods, it is possible to see that OLS result are significantly different from the estimates obtained in the models assuming spatial autocorrelation in residuals (SACR), especialy when it is combined with seemingly unrelated regressions (SURE + SACR). In the equation for population growth, however, differences are not significant.

Table 6

Estimates for the share of deforested areas in forests

Eq. number	(9)	(9)
Dependent	Clearing in forest	Clearing in forest
Specifi.	Logistic	Logistic
Method	OLS	ML
N. Obs.	70	151
D. F.	51	132
R2 adj.	0.89	
Rmse	0.52	4.55
Rho	-0.09	0.79
Moran	-0.00	0.31
Dependent	Coefficient (standard erros in parenthesis)	
Rural pop.	-3.01	-0.05
	(1.74)	(2.51)
Urban pop.	1.59	0.16
	(0.96)	(1.23)
Crop output	0.54	0.37
	(0.88)	(1.15)
Cattle herd	1.84	-0.18
	(0.61)	(0.80)
Logging vol.	0.89	-0.42
	(0.81)	(0.99)
Defor. area	-4.08	0.30
	(0.03)	(2.26)
Paved road	0.01	0.001
	(0.02)	(0.02)
Nonpaved road	-0.003	-0.0002
	(0.005)	(0.006)
Rivers	-0.04	-0.01
	(0.01)	(0.02)
Dist. state	-0.009	-0.005
	(0.005)	(0.01)
Dist. federal	0.016	-0.001
	(0.003)	(0.005)
Rain forest	-9.72	-0.45
	(16.9)	(26.5)
Open forest	6.87	4.06
	(15.2)	(22.3)
Savanna	-15.7	-1.67
	(13.2)	(19.2)
Ecol. tension	-7.98	2.76
	(13.9)	(20.3)
Wetlands	-23.9	-1.01
	(22.8)	(26.6)
Campinarana	-1.43	-11.3
	(0.63)	(123)

Table 7

Estimates for the generating functions of the spatial distribution of population, crop output, herd and logging

Model	OLS	SURE	SACD	SACR	SURE + SACR
Dependent: Population growth, 1980/85					
C_{10}	3.412	3.397	1.585	3.218	1.48
	(0.264)	(0.232)	(0.292)	(0.207)	(3.52)
C_{11}	-0.722	-0.752	-0.420	-0.699	-0.625
	(0.111)	(0.100)	(0.114)	(0.101)	(0.16)
Rho/Tau			0.55	0.55	0.95
			(0.059)	(0.059)	
R2/Lm	0.123	0.15	-254.2	-252.4	
RMSE	0.030		0.001	0.001	
N. Obs	293	326	336	336	326
Dependent: Cattle herd growth, 1980/85					
C_{20}	9.245	8.498	7.583	8.427	11.3
	(0.798)	(0.714)	(0.965)	(0.691)	(2.29)
C_{21}	-2.516	-2.341	-1.973	-2.444	-4.47
	(0.332)	(0.282)	(0.356)	(0.306)	(0.45)
Rho/Tau			0.05	0.25	0.74
			(0.083)	(0.076)	
R2/Lm	0.161	0.15	-716.2	-712.5	
RMSE	0.100		0.013	0.012	
N. Obs	294	326	335	335	326
Dependent: Crop output growth, 1980/85					
C_{30}	1.396	1.700	0.902	1.073	1.58
	(0.655)	(0.651)	(0.627)	(0.606)	(1.70)
C_{31}	-3.462	-3.786	-2.532	-3.600	-4.46
	(0.315)	(0.307)	(0.440)	(0.330)	(0.47)
Rho/Tau			0.35	0.45	0.70
			(0.077)	(0.066)	
R2/Lm	0.268	0.15	-681.9	-677.4	
RMSE	0.106		0.099	0.097	
N. Obs	326	326	335	335	326
Dependent: Logging growth, 1982/87					
C_{40}	-4.325	-4.467	4.277	9.306	15.8
	(2.963)	(2.939)	(2.900)	(2.727)	(19.2)
C_{41}	-0.614	-0.557	-2.334	-5.721	-6.94
	(0.988)	(0.976)	(1.072)	(0.982)	(0.96)
Rho/Tau			0.70	0.75	0.94
			(0.046)	(0.041)	
R2/Lm	-0.002	0.15	-942.8	-932.7	
RMSE	0.295		0.049	0.045	
N. Obs	326	326	328	328	326

Obs.: Rho and Tau refers to spatial autocorrelation of residuals and dependent variables, obtained in ML estimation.

Results show a spatial dispersion of economic activities typical of frontier areas, with growth rates proving lower in areas of less dense economic activity. According to the estimates of C_{k1} obtained by combining spatial autocorrelation of residual and seemingly unrelated regressions (SACR + SURE), this pattern is stronger for logging, followed by cropping and cattle raising, and much lower for population. This is a reasonable finding if one consider that, in the case of population, centripetal forces related to frontier expansion are offset by agglomeration phenomena such as urbanization and industrialization.

6. SIMULATION RESULTS

Projections and simulations of Brazilian Amazon deforestation used the ML estimations of equations (7-10) and the SACR + SURE estimations for equations (12). Projections and simulations are made for the period 1990/2090. Results and assumptions are presented in Table 8.

The Basic Scenario, presented in column A, assumes a secular slowdown in population growth which declines from an average 3.1% p.a., in 1980/90, to 2.1%, in the 1990/2025, and 1.1%, in the 2025/2090. **Per capita** growth of agricultural GDP (which includes crops, cattle raising and logging) is constant at 3.0% p.a. throughout the whole period 1990/2090. These assumptions are comparable to the ones made in Scenario E of IPCC (1991).

The Basic Scenario also assumes that the per capita growth of paved and non-paved roadas is constant at 1.9% and 0.6%, respectively, reflecting a gradual substitution between them.

Finally, the pattern of spatial dispersion of the economic activities in the next century is assumed to be the same as the one observed for the estimation period, 1980/85. In other words, we keep constant the values of C_{1k}.

From an environmental perspective, projections of the Basic Scenario are far from the catastrophic scenarios usually depicted. The deforested share of Brazilian Amazon is less than 30% by the end of next century. As to their impact on the greenhouse effect, such deforestation growth rates would push cumulative carbon dioxide emissions for 1990 through 2090 to something around 12 billion tons - an additional 3.3% over the current concentration level. Assuming that in the absence of drastic policies carbon dioxide concentration in the atmosphere wil grow at around 0.5%

to 1.0% per annum, the Amazon's cumulative contribution would be somewhere between 1.4% and 2.0% of global emissions.

Table 8

Simulations for Brazilian Amazon Deforestation, 1990/2090

	A Basic Scenar.	B Growth 1% high	C Herds 1% high	D Crops 1% high	E Roads 1% high	F OLS Param.
Asumptions on average annual growth rates for 1990/2090						
Population	1.4	2.5	1.4	1.4	1.4	1.4
Crops	2.9	4.0	2.9	4.0	4.0	2.9
Cattle	6.7	7.8	7.8	6.7	6.7	6.7
Logging	6.8	7.8	6.8	6.8	6.8	6.8
Paved road	3.3	4.4	3.3	3.3	4.4	3.3
N. pav. road	2.0	3.1	2.0	2.0	3.1	2.0
Annual growth rate for deforested area:						
1990/2025	3.7	4.6	3.8	3.9	4.4	3.9
2025/2090	0.2	0.6	0.2	0.2	0.6	0.4
1990/2090	1.4	1.9	1.4	1.5	1.9	1.6
Percentage of geographic area deforested:						
1990	7.1	7.1	7.1	7.1	7.1	7.1
2025	25.2	34.1	26.0	26.7	31.7	26.6
2090	28.3	50.2	29.2	30.0	46.8	34.5
Cumulative carbon dioxide emissions, in 109t:						
1990/2025	10.8	15.8	11.3	11.6	14.4	11.7
2025/2090	1.6	7.6	1.8	1.6	7.3	5.8
1990/2090	12.4	23.4	13.1	13.2	21.7	17.4

Source: Author's estimates.

N.B.: For lack of information, estimates for deforestation and carbon dioxide emissions exclude the geographic area of the state of Maranhão which represents aproximately 6% of Legal Amazônia.

Most of the deforestation takes place in the 1990/2025 period, reflecting, on the one hand, the assumption of slowdown in growth and, on the other hand, the saturation effect in deforestation captured by the logistic functional form.

It could be argued that, even for secular projections, the growth asumptions in the Basic Scenario are probably too low for a frontier region. Thus, column B presents an alternative scenario where secular rates of growth of population, econoic activities, and roads are increased by 1%. From an environmental perspective, the growth rates of deforestation in Scenario B are alarming and could be considered unsustainable.

Comparisons of scenarios A and B show the significant impact of growth on deforestation. The deforested share in 2090 increases by more than 20% as a consequence, and average rates of growth of deforestation in the 1990/2090 period increases by 0.5%. Thus, maintaining growth in output per capita constant, implies an elasticity of deforestation in relation to growth equal to 0.5.

Scenarios C to D show that both cattle raising and cropping have small relative impact on deforestation growth, with partial elasticities close to 0.1. By its turn, Scenario E shows that road expansion is, by far, the most important single factor which determining deforestation, with an elasticity around 0.5. Finally, Scenario F show that estimation method can make significant difference, especially for secular projections.

7. CONCLUDING REMARKS

The model and the simulation presented in the paper are still preliminary, and therefore, should be read carefully. Concluding, it is worth pointing the most critical aspects for research extensions and further developments.

In what concern projections, the negative coefficient of logging is, perhaps, the most disturbing result. As already mentioned, this seems to be rooted in the fact that logging is at the same time cause and consequence of forest clearing. An additional problem is the use of annual logging output, a flow variable, to measure the impact of logging on deforestatioin which, like the measures of the other economic activities, is a stock variable. The suggested solution, therefore, is to use panel data to specify and estimate a dynamic simulataneous equation model where logging flows are simultaneously determined with changes in land clearing.

To make projections more reliable, three other dynamic aspects deserve careful analyses. The first is population growth and the determinants of migratioin and urbanization. The suggestion here is to make more use of demographic techniques instead of econometrics.

The second aspect concerns the long run determinants of technical progress in agricultural activities, and its relation to changes in the geographic densities of population and major economic activities. The suggested solutions, in this case, are, on the one hand, to conduct the analysis at the level of major agricultural activities like catle raising, temporary and permanent crops, as well as reforestation and fallow lands. On the other hand, to use panel data analysis to estimate the parameters related to efficiency and technical progress.

Finally, the third aspect concerns the specification of dynamic relationships between the fate of carbon stocks and land use changes.

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