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**Modeling Tropical Deforestation: A Survival Analysis Linking Satellite and
Household Survey Data**

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Introduction

Tropical deforestation plays a central role in many of the most acute environmental threats of our time, including global climate change, habitat degradation, and unprecedented species extinction. Scientific and public concerns about these and other potentially massive ecological disruptions have incited a growing number of studies that aim to quantify the social and biophysical determinants of deforestation processes, as well as their interactions over time and space. An emerging methodological approach to these issues combines high-resolution satellite imagery of the surface of the earth, geographic information systems (GIS), and socioeconomic and geophysical data to model the human-environment interactions that drive land-use change (*e.g.* Liverman *et al.*, eds, 1998). While much of this research in tropical deforestation using spatial data has focused on identifying the socioeconomic forces that explain the spatial patterns of landscape development, less attention has been given to also capturing the temporal dynamics from which these patterns emerge. To the extent that both the location and timing of forest clearance matter for assessing environmental outcomes, this de-coupling of spatial and temporal dimensions compromises the implementation of appropriate policy responses to deforestation. Accordingly, the purpose of the present paper is to advance an empirical methodology that supports analysis of how, over time and space, individual land-managers respond to changing economic and ecological conditions.

Our study focuses on land-use change in an agricultural frontier spanning the southern Mexican states of Campeche and Quintana Roo, a region that contains one of the largest and oldest expanses of tropical forests in the America's outside of Amazonia.

Over the past 30 years, these forests have been under sustained assault following the construction of a highway in 1967 that opened the frontier to settlement. The road was part of a larger development effort to promote agricultural colonization and has contributed to a prolonged period of land transformation that has been captured by Thematic Mapper (TM) satellite imagery. We model these landscape dynamics by exploiting a spatial database that links three TM images spanning the years 1986-1996 with a random sample of farm households whose agricultural plots were geo-referenced using a global positioning system (GPS).

Following a brief overview of the study region, our analysis takes as its point of departure a simple utility-maximizing model that suggests many possible determinants of forest clearance in an economic environment characterized by missing or thin markets, as typifies frontier regions in the nascent stages of economic development. We subsequently test the significance of these determinants using survival analysis, a statistical technique that estimates the instantaneous probability of a transition between two states – in this case land-use states – conditional on the time elapsed until the occurrence of the transition. The paper concludes with suggestions for future research.

The Region

The southern Yucatán peninsular region occupies about 22,000 km² of southwestern Quintana Roo and southeastern Campeche, north of the Mexican-Guatemala border. A rolling karstic terrain of semi-deciduous tropical forests covers the landscape, with elevations in the center reaching a peak of about 250 to 300 meters. The

zone corresponds to what was once a portion of the Maya lowlands, and was nearly completely deforested one thousand years ago during the Classic Period of Lowland Maya domination (A. D. 100-900) (Turner, 1983). Following the collapse of Maya civilization in A. D. 800-1000, the region experienced a period largely free of settlement that, continuing past the birth of the Mexican nation-state in 1821, allowed the return of the forests. By the first half of the 20th century, human intervention here re-emerged but was primarily limited to the selective logging of tropical woods, particularly mahogany (*Swietenia macrophylla*) and cedar (*Cedrela odorata*), as well as the extraction of chicle, a tree resin (from *Manilkara zapota*) used in the production of chewing gum.

More extensive deforestation followed with the construction of a two-lane highway across the center of the region in 1967, which opened the frontier to agricultural colonization via the extension of communally-managed *ejido* land grants from the federal government. This colonization was heightened by the inflow of petro-dollars associated with the oil boom of the 1980s, used to fund various large-scale projects in cattle production and mechanized rice cultivation. More recently, the Calakmul Biosphere Reserve (723,185 ha) was established in 1989 in the middle of the region, partly in response to extensive deforestation along the highway and associated international pressures to impede further clearance. Various land-uses surround the reserve, predominately: *ejidos*, on which slash-and-burn subsistence production has prevailed but increasingly is giving way to commodity production; *ejidos* coupled with NGO-sponsored agricultural and forest projects; and private lands largely devoted to livestock production. Cumulatively, these activities have earned the region a designation as a “hot-

spot” of forest and bio-diversity loss by various sources (Achard et al., 1998). Whether this prognosis is supported by future trends will depend in large part on current plans surrounding the *Mundo Maya*, an international development scheme to create an ecotourism-archaeological tourist economy stretching across portions of southern Mexico, Belize, Guatemala, El Salvador and Honduras. This plan has led to recent hotel and road expansion in the region.

Tourist sector development notwithstanding, the region retains many of the features of an agricultural frontier. Population density is low, infrastructure is poorly developed, ties to outside markets remain limited, and the social relations of production are, by and large, organized around the family farm. These features motivate the theoretical and empirical approach taken in this paper, which emphasize the importance of household-specific characteristics, particularly demographic composition, in explaining land-use decision making.

The Theoretical Model

As a predominately agrarian economy, land is an input in virtually all of the economic activities within the *ejido* sector of the southern Yucatán peninsular region. Some of these activities, such as bee-keeping, agro-forestry, and hunting, rely on land under forest, while others, such as agricultural production and animal husbandry, require that the land be cleared of trees for use. Whether or not a farmer decides to clear a given tract of land depends on a complex multiplicity of factors, including the market value of

output from the land in alternative uses, the availability of labor, and the farmer's perception of the potential future benefits derivable from the land.

We abstract from many of these complications in the theoretical approach taken in this paper. The model used here follows the recent trend in environmental economics of models of land use change that focus on both the location and timing of land use change. The approach has been used very recently in tropical deforestation (Kerr, Pfaff, and Sanchez, 2001), U. S. agriculture (Lubowski, Plantinga, and Stavins, 2001) and urban fringe development (Irwin and Bockstael, 2001; Geoghegan and Bockstael, 2000). Older literature in this area focused exclusively on the location of deforestation and not the temporal dimension (Chomitz and Gray (1996); Nelson and Hellerstein (1997), Pfaff, 1999). These newer models posit that a particular land use change will occur if the present discounted benefits of doing so are greater than the net present discounted benefits of leaving the land in its current use, with the second condition that there are no additional benefits in waiting past this time.

Following these newer models, we model the decision of the farmer to clear land for agricultural use. Let $A(i, t)$ be the net benefits to agricultural use for each time period after pixel i is cleared in time period T . Let $F(i, t)$ be the net benefits to the farmer for leaving pixel i in forestry use in each time period, and let $C(i, T)$ be the one-time clearing costs associated with clearing the pixel in time period T and δ is the discount rate. Then the benefits to the farmer of clearing pixel i in period T are:

$$\sum_{t=0}^{\infty} A(i, T+t)\delta^{T+t} - \sum_{t=0}^{\infty} F(i, T+t)\delta^{T+t} - C(i, T) \quad (1)$$

For T to be the optimal time period for clearing, the following two conditions must hold:

$$\sum_{t=0}^{\infty} A(i, T+t)\delta^{T+t} - \sum_{t=0}^{\infty} F(i, T+t)\delta^{T+t} - C(i, T) > 0 \quad (2a)$$

$$\begin{aligned} \sum_{t=0}^{\infty} A(i, T+t)\delta^{T+t} - \sum_{t=0}^{\infty} F(i, T+t)\delta^{T+t} - C(i, T) > \\ \sum_{t=1}^{\infty} A(i, T+1)\delta^{T+t} - \sum_{t=1}^{\infty} F(i, T+1)\delta^{T+t} - \delta C(i, T+1) \end{aligned} \quad (2b)$$

The first condition is that net benefits to clearing are positive. The second condition considers that although clearing may yield net positive benefits at time T , there may still be benefits to waiting because of the potential for even higher benefits at some future date. Such a circumstance could arise, for example, in anticipation of improved technologies that reduce clearing costs. This very simple model ignores fallow cycle dynamics and assumes that the deforestation process is irreversible, clearly a limitation of the current theoretical framework.

Let the characteristics of pixel i be $X(i)$. The optimal time for clearing this pixel then is the first time period in which the following holds:

$$A(X(i), T) - F(X(i), T) - \delta C(X(i), T + 1) \geq 0 \quad (3)$$

Given this theoretical framework, our empirical model aims to explain why certain pixels, in certain locations, under certain land managers, become deforested.

The Empirical Model

We add an error term to Equation 3 to account for unobservable characteristics:

$$A(X(i), T) - F(X(i), T) - \delta C(X(i), T + 1) - \varepsilon(i) \geq 0 \quad (4)$$

The probability that pixel i will be deforested in period T is the hazard rate for period T :

$$h(i, T) = \frac{G[W(i, T + 1)] - G[W(i, T)]}{1 - G[W(i, T)]} \quad (5)$$

where G is the cumulative distribution function for the error term, and

$$W(i, T) = A(X(i), T) - F(X(i), T) - \delta C(X(i), T + 1) \quad (6a)$$

$$W(i, T + 1) = A(X(i), T + 1) - F(X(i), T + 1) - \delta C(X(i), T + 2) \quad (6b)$$

As $h(i, T)$ is a hazard rate, we use a hazard model to estimate the parameters in $X(i)$ to test hypotheses concerning the explanatory variables. For example, we can

hypothesize that the benefits to agricultural land use of pixel i at time t could be influenced by such factors as the ecological traits of the pixel, the market price of its output, or the contribution of its output to the household's subsistence requirements.

Hazard models, also known as survival or duration models, focus on the timing of a change in state, such as the onset of an illness, the change in marital status, or as in this paper, the change from forest cover to agricultural land use. Hazard models typically estimate the conditional probability of exiting a state given that the state has been occupied for some length t . The dependent variable, the duration, is the length of time that elapses from the beginning of the state until its end or until measurement is taken and therefore truncates the observation. For this paper, the duration of interest is the length of time that an individual pixel remains in forest before being converted to cropland or pasture.

Hazard models can be either fully parametric models or semi-parametric models, depending upon the assumptions made, such as the process by which the data were generated, the explicit role of time in the model, as well as the distribution of errors for fully parametric models. For this paper, we use a fully parametric model, the complementary log-log model. This specification assumes that the underlying process that generates the data is continuous, but that the data are grouped into discrete time intervals. This assumption is well suited for the particular case of our data. Deforestation is a continuous process across the landscape, but we only observe the event at discrete times, as our temporal resolution is rather coarse, due to the difficulty of

obtaining cloud-free TM data for the tropics. Therefore, we do not know the exact timing of the deforestation event, rather that it occurred during some relatively long time period. In addition, this specification, as opposed to other fully parametric specifications, can easily handle time-varying covariates (Irwin, 1998). Finally, different specifications of time as a variable can be included as a covariate, making it possible to test alternative functional forms of the hazard function. For example, by including the logarithm of time as a covariate, the model corresponds to the Weibull (see Allison 2000 for further discussion).

For the n pixels that are observed to be deforested (that is, these pixels are ‘uncensored’ in hazard modeling terminology), the likelihood function can be written as:

$$\prod_{i=1}^n P_{i,t_i} (1 - P_{i,t_i-1})(1 - P_{i,t_i-2}) \dots \quad (7)$$

where P_{it} is the probability that deforestation occurs to pixel i in interval t , given that the pixel was not deforested any earlier periods and t_i is the time period in which pixel i is deforested. The complementary log-log model specification resulting from this likelihood function is:

$$\log[-\log(1 - P_{it})] = \beta'X(i, T) \quad (8)$$

where

$$X(i, t) = A(X(i), T) - F(X(i), T) - \delta C(X(i), T + 1) \quad (9)$$

That is, the X are the exogenous variables and the β is a vector of parameters to be estimated using maximum likelihood methods, with the assumption that the underlying survival models is distributed as type I extreme value (Irwin, 1998). Previous work (Vance and Geoghegan, 2001) has demonstrated the importance of including data on household demographics in estimating models of land use choices in agricultural frontier regions such as in the Yucatan. We turn next to the discussion of our data.

The Data

The econometric model presented in this paper is estimated using Landsat TM satellite data on land cover for the dependant variable and household survey data and other biophysical spatial data for the independent variables. Here we will briefly describe each of these data sources in turn. The unit of observation for the model is the TM pixel, which is approximately 30 by 30 meters. The satellite images were obtained across four contiguous zones spanning the study region; the dates for each of which are given in Table I. The process of imagery classification included the normal preparatory steps of geo-referencing, haze removal, adding NDVI information, and principal component analysis. These steps were followed by texture analysis, which lead to the creation of a 7-band image for signature development and classification. Signature development was facilitated by a combination of ground truth data derived from GPS assisted field visits and topographic, vegetation and land-use maps. Maximum likelihood supervised classification methods produced six land cover classes. Excluding clouds, shadows and water, these include: mature lowland and upland forest; one stage of upland successional growth between 7 and 15 years of age; agriculture (including pasture); one significant

invasive; and inundated savannas. From these classes we define deforestation as a binary variable: the conversion of upland, lowland, or successional growth to agriculture land use. For further detail on these methods see Geoghegan, et al. (2001) and Turner, et al. (2001).

Table I: Dates of Satellite Imagery

ZONE I	ZONE II & III	ZONE IV
Nov. 11, 1984	Apr. 01, 1987	Jan. 14, 1985
Feb. 21, 1993	Oct. 29, 1994	Nov. 07, 1994
Jan. 31, 1997	Feb. 05, 1996	Jan. 31, 1997

Data for the explanatory variables are from a household survey that was carried out in the region during two separate field seasons during 1997-1999 and were linked to the satellite data, as will be further explained below. Selection of households in the sample proceeded according to a stratified, two-stage cluster sample (Warwick and Lininger, 1975; Deaton, 1997), with *ejidos* as the first stage unit and *ejidatarios* (*ejido* members) as the second stage unit. A standardized questionnaire, administered to the household head, was used to elicit the socio-economic and land use data. The questionnaire was organized into two sections. The first section covered migration history, farm production and inputs, ethnicity, educational attainment, and the demographic composition of the household. By collecting information on the births, deaths, and permanent out-migration of sons and daughters of the head, it was possible to reconstruct the biological household's age and sex composition through time. In addition, dichotomous data was collected on access to farm capital (e.g. vehicle, chain saw) and government credit for the years 1986, 1990, 1993, 1996, and 1997. Using the

figures for each of these years, data for the interim years were interpolated. In this way, the percent of time for which the relevant dichotomous variable was in effect could be approximated for any given interval corresponding to the dates of the satellite imagery.

Completion of the second section involved a guided tour of the agricultural plot of the respondent. Using a global positioning system (GPS), the interviewer created a geo-referenced sketch map detailing the configuration of land uses, including the area allocated to commercial and subsistence crops. Having several GPS points recorded along the borders of the plot made it possible to directly link these plots with the satellite data. The digitized plot borders were then extracted and superimposed on available images from previous years, thereby yielding a longitudinal database of land use change. Thus, only those pixels associated with households from which socio-economic data were elicited are included in the sample. By overlaying this database with other GIS layers containing features such as: the road network, digitized from a 1:50,000 Mexican government (INEGI) map; soil quality measures, digitized from a 1:250,000 INEGI map; slope and elevation from a digital elevation model; and rainfall extrapolated from rain gauge data; it was possible to create spatial explanatory variables to augment the data collected during the interview.

Results

As suggested in the theoretical model presented above, the land clearance decision will be based on a comparison of discounted utilities from forest and non-forest land uses. There are several testable socioeconomic and environmental factors that could influence this comparison, which we conceptually group into four categories derived

from the data elicited by the questionnaire: household demographic composition; physiographic characteristics of the plot; farm capital (human and physical); and the political-economic environment. To capture the effect of unobserved, inter-temporal factors affecting land-use choices, we also include a variable that measures the duration of the household's occupancy as of the end of the time interval. The square of this variable is also included to allow for non-linearities. Finally, the specification includes dummy variables for each interval to control for the fact that they are of differing lengths (Allison, 2000).

Table 2 presents results of a complementary log-log model that estimates the effect of these determinants on the hazard of forest clearance. A more intuitive interpretation of the estimated coefficients from the complementary log-log hazard model is to calculate the "risk ratio". Let β_i be the coefficient associated with explanatory variable, X_i , then the risk ratio associated with β_i is $\exp(\beta_i)$. For dummy variables the risk ratio is the ratio of the hazard rate for a pixel with the dummy variable equal to one to the hazard rate for a pixel with the dummy variable equal to zero, again holding other variables constant. For continuous variables, a more intuitive statistic is calculated by subtracting one from the risk ratio and multiplying by 100 (Allison, 1995) and equals the percent change in the hazard rate with a one unit change in X_i , holding other variables constant.

Three indices capture the influence of demographic composition: children under 12, males over 11, and females over 11. These indices are measured as the average

number of members in each age/sex category over the corresponding time interval of the imagery and accordingly vary across households and through time. Two of the three indices are seen to be positive and statistically significant determinants of the hazard of deforestation, an unsurprising result given that the majority of households in the region are semi-subsistent producers, for whom which family members simultaneously represent a source of labor as well as an overhead cost. Specifically, we find that each additional male increases the hazard of deforestation by 3.2%, with a similar magnitude for children. The coefficient on females is not statistically significant.

Six time-invariant variables control for the effects of physiographic characteristics: a dummy indicating whether the pixel was categorized as primary or secondary forest at the start of the interval; a soil dummy which serves to distinguish between higher quality upland soils and lowland soils; the elevation and slope of the pixel; the 30 year average of rainfall; and the size of the plot that the pixel is in. All of the measures are statistically significant, and, in some cases, confirm findings identified elsewhere in the literature. For example, the estimated coefficients for slope and elevation are both negative, similar to findings of Chomitz and Gray (1996) and Nelson and Hellerstein (1997) in their studies of deforestation in Belize and Mexico, respectively. Likewise, as identified by Chomitz and Gray, the variable rainfall has a negative effect on the hazard of deforestation, a result that may be interpreted as reflecting increased difficulty in working with wetter soils. Superior upland soils increase the hazard of clearance while a larger plot size has a negative effect, although the effect on the hazard, using the transformation noted above, is small: for every ten

percent increase in plot size, the hazard of deforestation decreases by 0.3%. Finally, the negative coefficient on the primary dummy suggests that farmers prefer to clear secondary growth, an interesting finding given that secondary growth is generally supported by less fertile soils. One possible explanation is a desire to avoid higher clearance costs associated with primary forest even given higher weeding costs associated with inferior soils, a trade-off analyzed at length in the fallow-cycle literature (e.g. Dvorak, 1992).

Ownership of a chain saw and vehicle, the education of the household head, the number of members in the household with a high school education as of 1997, and a dummy indicating whether the head is a native Spanish speaker control for the effects of physical and human capital. While the first two measures vary across households and through time, the latter three are time-invariant. Ownership of a chain saw and vehicle both increase the hazard of deforestation, which is consistent with the idea of lower labor costs in forest clearance and in access to the plot. A somewhat surprising result is the positive effect of the two education variables on deforestation. To the extent that higher education implies a higher opportunity cost of on-farm labor due to increased wage-earning potential, we would have expected these variables to carry negative coefficients. In fact, if the model is estimated on primary growth only (not presented), this expectation is confirmed, suggesting potentially important mitigating effects of vegetation attributes on the determinants land-use decisions. Being a Spanish speaker decreases the hazard of deforestation, which may result from a greater reliance of indigenous farmers on the resource base as opposed to off-farm wage earning opportunities.

The influence of the political-economic environment is captured by a variable measuring access to government credit, a tenure dummy that indicates a communal system of land tenure as opposed to universally recognized plot boundaries within the *ejido*, a measure of the distance separating the household from the plot, and a measure of on-road distance from the *ejido* center to the nearest market. All variables other than that measuring government credit are time-invariant. The estimated negative coefficients on the two distance measures are consistent with the intuition that higher travel costs decrease the returns from agricultural land use, through a reduced farm-gate price of output. The estimated negative coefficient on credit could be capturing the increased ability to purchase land-saving inputs such as chemical fertilizers. The estimated positive coefficient of the tenure dummy lends support to the hypothesis that insecure property rights increases incentives to clear forest as a means of establishing access.

We explored different specifications of the variable measuring duration of occupancy by means of a nested likelihood ratio test and determined the quadratic functional form to be optimal in terms of fit and parsimony. Our estimates indicate that the conditional probability of forest conversion decreases with the passage of time at a decreasing rate, with some evidence of a reversal after 26.5 years. This result may reflect a confluence of factors, including fallow cycle strategies and adaptation to local market opportunities and ecological constraints.

Conclusion

This paper has presented an application of a hazard model as a means of analyzing continuous time processes using discrete time data. By specifying the optimal timing of forest clearance as the choice variable, the empirical model identified several potentially important farm-level determinants of deforestation. After estimating the complementary log-log specification of the hazard model, it was determined that the data is characterized by non-linear duration dependence, with the hazard of deforestation first decreasing and then increasing with time. In this regard, one important avenue for future research with this style of model is investigation of fallow cycle dynamics. In order to do this, a more sophisticated theoretical model of decision-making is required. Empirically, this could be pursued through alternative specifications of time as well as through tests of parameter consistency according to whether primary or secondary forest is cleared.

Table 2: Complementary log-log model of forest clearance

Explanatory variable	Estimated coefficient	Risk ratio	z-score
Average # of males > 11 over interval	0.032	1.033	3.867
Average # of females > 11 over interval	-0.009	0.991	-1.075
Average # of children < 12 over interval	0.031	1.031	6.337
Primary forest	-0.652	0.521	-31.050
Upland soil	0.383	1.467	17.767
Elevation	-0.014	0.986	-64.054
Slope	-0.021	0.979	-5.602
Precipitation	-0.064	0.938	-24.868
Plot size (# of pixels)	-0.0003	1.000	-26.147
Percent of interval owning chain saw	0.386	1.471	14.011
Percent of interval owning vehicle	0.159	1.172	4.759
Education of household head	0.021	1.021	8.379
# of household members w/ > 8 years education	0.035	1.036	6.113
Native Spanish speaker	-0.163	0.850	-7.380
Percent of interval receiving government credit	-0.415	0.660	-16.311
Common property tenure	1.151	3.161	22.144
Distance household to plot	-0.062	0.940	-44.913
Distance ejido to nearest market	-0.024	0.976	-40.496
Duration of occupancy	-0.053	0.948	-17.708
Duration of occupancy squared	0.001	1.001	12.023
Interval 2	-0.939	0.391	-26.044
Interval 3	0.343	1.409	4.721
Interval 4	0.913	2.492	14.197
Interval 5	0.146	1.157	5.466
Interval 6	0.315	1.370	9.310
Constant	6.161	473.902	37.133

Number of observations: 115017

LR chi²: 15998.24

Log likelihood: -41606.60

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