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Deforestation Trajectories in a Frontier Region of the Brazilian Amazon

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LINKING PEOPLE, PLACE, AND POLICY
A GIScience Approach

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Myers, N. 1988. Threatened bota: hotspots in tropical forests. *The Environmentalist*, 8(3): 1-20.
Myers, N., Mittermeier, R., da Fonseca, G.A., Kent, J. 2000. Biodiversity hotspots for conservation priorities. *Nature*, 403: 853-858.
Moran, E.F, Brondizio, E., Mausel, P., Wu, Y. 1994. Integrating Amazonian vegetation, land-use, and satellite Data. *BioScience*, 44(5): 329-338.
O'Callaghan, J.F. and Mark, D.M. 1984. The extraction of drainage networks from digital elevation data. *Computer Vision and Image Processing*, 28: 323.
Pan, W.K., Murphy, L., Sullivan, B. and Bilsborrow, R. 2001. *Population and Land Use in Ecuador's Northern Amazon in 1999: Intensification and Growth in the Frontier*. Paper presented at Population Association of America annual meeting, Washington DC.
Parker, A.J. 1982. The topographic relative moisture index: an approach to soil-moisture assessment in mountain terrain. *Physical Geography*, 3(2): 160-168.
Pattison, W.D. 1969. Four Traditions of Geography. *Annals of the Association of American Geographers, 59.*
Pichón, F. and Bilsborrow, R.E. 1999. Land Use Systems, Deforestation, and Demographic Factors in the Humid Tropics: Farm-Level Evidence from Ecuador. In, *Population and Deforestation in the Humid Tropics*, R.E. Bilsborrow, ed. Liège, Belgium: International Union for the Scientific Study of Population.
Rudel, T. and Horowitz, B. 1993. *Tropical Deforestation: Small Farmers and Forest Clearing in the Ecuadorian Amazon.* New York: Columbia University Press.
Seul, M., O'Gorman, L. and Sammon, M.J., 2000. *Practical Algorithms for Image Analysis: Description, Examples, and Code.* Cambridge University Press, Cambridge.
Southgate, D. and Whitaker, M. 1994. *Economic Progress and the Environment: One Developing Country's Policy Crisis.* Oxford: Oxford University Press.
Walsh, S.J. 1999. Deforestation and Agricultural Extensification in Northeast Thailand: a Remote Sensing and GIS Study of Landscape Structure and Scale. In *Proceedings, Applied Geography Conference*, Schoolmaster, F.A. (Ed.), 22: 223-232.
Walsh, S.J., Evans, T.P., Welsh, W.F., Entwisle, B., and Rindfuss, R.R. 1999. Scale-dependent relationships between population and environment in northeastern Thailand. *Photogrammetric Engineering and Remote Sensing*, 65(1): 97-105.
Walsh, S.J., Bilsborrow, R.E., McGregor, S.J., Messina, J.P., Pan, W., Frizzelle, B.G., Crew-Meyer, K.A., Mena, C. 2001. *Landscape dynamics in the Ecuadorian Amazon: characterizing Ddforestation and agricultural extensification through space & time dependent models.* LBA-Ecology Open Meeting, Atlanta.
Wolfram, S. 1984. Cellular automata as models of complexity. Nature, 311: 419-424.
Wood, C. and Skole, D. 1998. Linking Satellite, Census, and Survey Data to Study Deforestation in the Brazilian Amazon. In, *People and Pixels: Linking Remote Sensing and Social Science,* Liverman, D., Moran, E.F., Rindfuss, R.R., and Stern, P.C., editors, Washington, DC: National Academy Press.

Chapter 10

DEFORESTATION TRAJECTORIES IN A FRONTIER REGION OF THE BRAZILIAN AMAZON

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Abstract This chapter provides a conceptual framework for a micro-level approach for studying farm-level and landscape change in the context of an agricultural frontier region of the Brazilian Amazon. The development of a property grid overlay (with 3913 properties) facilitates the extraction of data on land cover change derived from the analysis of a time-series of remotely sensed images from 1970 to 1996. Time-segments between remotely sensed images permits the identification of the period of initial clearing and for analyzing the amount of farmland that is cleared annually by approximate age of the farm for the 25-year period. Deforestation is greatest in the beginning of farm settlement and slows down in subsequent years followed by a leveling off around year 18-20. The analysis suggests that by the year 2020, after 50 years of colonization, there will be between 24-32 percent of the original forest remaining.

INTRODUCTION

Over the past 30-years, more than 15 percent of the Amazon Basin's tropical moist forest has been cut down. This has had impacts on atmospheric composition (Andreae and Schimel 1989, Crutzen and Andreae 1990), on regional climate (Dickinson 1987, Gash et al. 1996), on biological diversity (Wilson 1988), and on the lives of native and immigrant human populations (Moran 1988 1993). Deforestation rates have been highest in Ecuador, but total amounts deforested in Brazil dwarf what is happening elsewhere in the tropical world. The total area of deforestation in Brazil is five times that of Mexico, the second most deforested country in Latin America, according to FAO estimates.

Estimates of the nature and extent of deforestation vary (Dickinson 1987, Malingreau and Tucker 1988, Skole and Tucker 1993, INPE 1998 1999). Booth (1989) and Setzer and Pereira (1991) reported that up to 8 million hectares of forest were burned in 1987 – and this peak was surpassed by a substantial margin in 1995 (INPE 1998). Little deforestation had taken place in the Brazilian Amazon before the 1970's, with as little as 30,000 square kilometers deforested, or 0.6 percent of the region. Between 1978 and 1988 deforestation increased to 6 percent, and from 1988 to the end of the century, this amount had surpassed 15 percent.

Deforestation has not proceeded across the Brazilian Amazon in a random fashion. Rather, it has followed the roads associated with national development planning. First, along the Belém-Brasília highway, then along the Transamazonian highway, along the Cuiabá-Santarém highway, and along the Cuiabá-Porto Velho (BR-360) highway connecting Rondônia to the south of Brazil and to Manaus. It is particularly along the Belém-Brasília and along the Cuiabá-Porto Velho highways that the highest rates have been observed along what has come to be called the "arc of deforestation" (see Figure 1 for a Basin-wide analysis that highlights the arc). Deforestation along this arc represents the advance of the cattle pasture frontier from the Center-West of the country into the southern part of the Amazon Basin. Most of the deforestation in the Basin is associated with conversion of forest into extensive cattle ranching on very large properties. Elsewhere we have shown that many of these deforested areas revert to secondary successional vegetation, because of the aggressive invasion of pioneer species (Moran et al. 1994 1996, Tucker et al. 1998). However, where enough labor and capital is available for continued reclearing of these areas, there is floristic impoverishment through repeated burning episodes, and greater probability of persistence in pasture.

Alongside these large cattle ranching projects, there has also been a considerable inflow of immigrants from all over Brazil to claim land offered by colonization agencies (Moran 1981, Smith 1982). This has been particularly true along the Transamazon highway and in Rondônia along the BR-360 highway. Here, too, we find a preponderance of total land deforested in pasture (and degraded pasture) following short cycles of cultivation (Moran 1981, Moran et al. 2000). The relationship between population and the environment is not a direct one. Rather, it is mediated by many other factors such as the land tenure system in place, the economic and environmental uncertainties, the limitations posed by a particular age and gender household structure on the labor and capital available, the past experience of household members in the new habitat, and the role of capital and macroeconomic policies.

This paper will present results of research in one of the regions along the Transamazon Highway in an effort to elucidate the spatial and temporal dynamics of deforestation trajectories as mediated by the demographic characteristics of immigrating households. Unlike much of the literature currently available, the analysis presents not only a landscape analysis of deforestation, but also a property-level analysis. The trajectories of deforestation are based on time-series analyses of Landsat Thematic Mapper (TM) images overlaid on the property grid in a GIS for the 3913 properties in the study area. The demographic analysis is based on a survey of 402 sampled farm households. The final section of the paper makes deforestation projections to 2010 and 2020 for the entire study region based upon the trajectories of deforestation examined at property level.

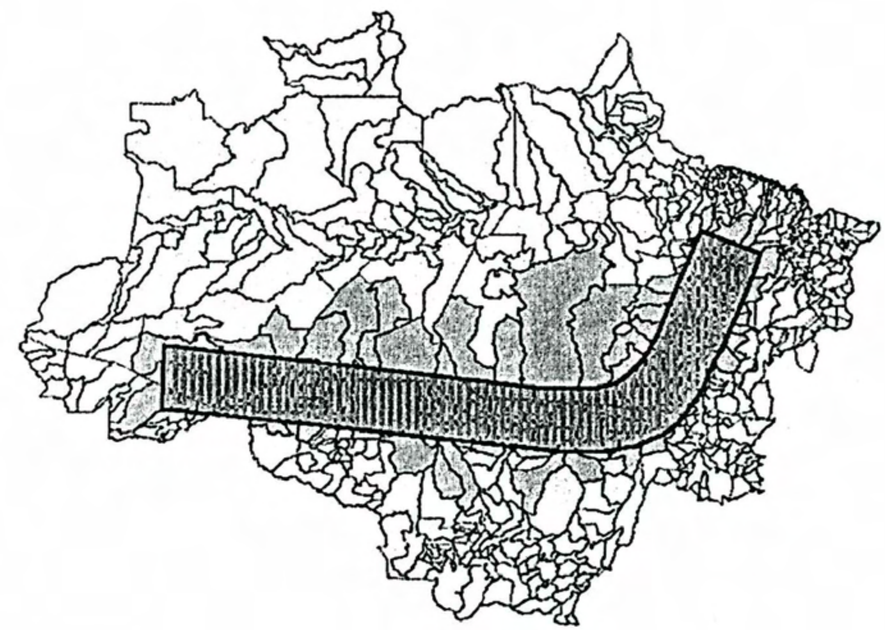

Figure 1. Amazon-wide Arc of Deforestation (Source: Instituto de Pesquisa Ambiental da Amazônia -IPAM).

STUDY AREA

The study area is the region west of the city of Altamira in the lower Xingu Basin of the Brazilian Amazon. The area was viewed as a showcase for colonization in the 1970s when the military began its Program of National Integration. The implementation of these colonization programs attracted researchers interested in monitoring the process of land occupation (Moran 1976 1981, Smith 1982, Fearnside 1987). After the initial four years, the government blamed the farmers for the low grain yields in the first three years, and reduced the subsidies of the settlement scheme. Over the next 25 years, many of the immigrants abandoned or sold their properties, while a steady flow of new immigrants continued to arrive – buying the land of those who desisted, and occupying new properties further on. Settlement has followed a very orderly spatial pattern in large part due to the gridded property demarcation pattern imposed on the settlement scheme; settlement took place first along the highway closest to Altamira and then along nearby side roads. Settlement proceeded in layers extending outward from the main road and from the emerging towns of Brasil Novo and Medicilândia. All properties are approximately 100 hectares in size with predictably similar rectangular layouts of about 500 by 2000 meters (Figure 2). The result is one associated in the literature with what has come to be known as the "fishbone pattern" of Brazilian colonization.

As settlers arrive they begin to clear forest in their property to make a farm. They tend to do so from the front of the lot towards the back. When the project started, farmers were told that they must keep the back half of their 100-hectare lots as forest reserve. However, over the years settlers have interpreted this view in a variety of ways, with the end result being that a growing number of properties have cleared virtually all of their mature forests. Remaining areas tend to be secondary forests near water sources or areas unsuitable for cultivation. Over the period from 1970 to 1996 we can see the steady pace of deforestation in Figure 3 in an area of some 384,000 hectares.

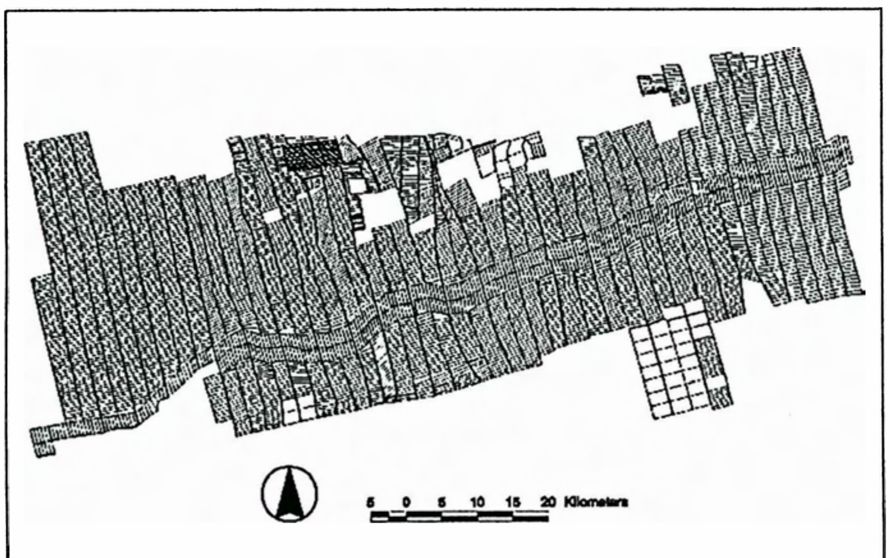

Figure 2. Property grid overlay developed for study area, colonization along the Transamazon Highway, Altamira, Pará.

The area's above-average soils have near neutral pH, and relatively favorable base saturation (i.e., nutrients available to plants). These soils (i.e., alfisols) are interspersed with the proverbial acid low nutrient soils, chiefly oxisols. Portions of the study area also have areas of rugged topography for the Amazon, where steep gradients make transportation and farming more difficult. The road was built so that it cut through some of the best soils and early settlers were able to

make claim to these soils. Elsewhere we have shown that farmers who were able to identify or claim the alfisols have been able to stay on their properties far more often than those who selected properties with poor soils, and that land turnover on properties with poor soils is high (Moran et al. 2000). We have also shown that over time farmers have learned that properties with very poor soils can support pasture but little continuous cropping, whereas properties with alfisols have a more diversified farming strategy with equal amounts of land in pasture and in intensive cultivation (mostly cocoa and sugar cane). The persistence of cattle even on the best soils seems to be a risk aversion strategy at the farm level since cattle prices and these two commodities seem to follow opposite trajectories in the economy (Moran et al. 2000).

Figure 3. The observed pace of deforestation among frontier farms along the Transamazon Highway, km 20-140, 1970-96.

The population has changed over time in area of origin, economic status, and demographic structure as evidenced from information from our sample survey of 402 households. The aging process of households over time is illustrated in the current age-sex composition of households arriving since 1985 compared to those arriving before 1976. Recent arrivals are typically made up of small nuclear households made up of young and middle-aged adults with a large number of children (Figure 4a). Households that arrived before 1976 are now (in 1998) much older with young adult children and teenagers and an increasing number of adult children having left the farm (Figure 4b). The parents, the initial colonists, are now in their 50s and 60s. As these households age there is a tendency to maintain male children on the farm as a labor-retention strategy while marrying daughters out and sending them to nearby towns for employment or schooling. The changing age-sex composition associated with aging of households can be expected to result in changing labor composition of households and changing agricultural strategies and patterns of deforestation over the domestic life course.

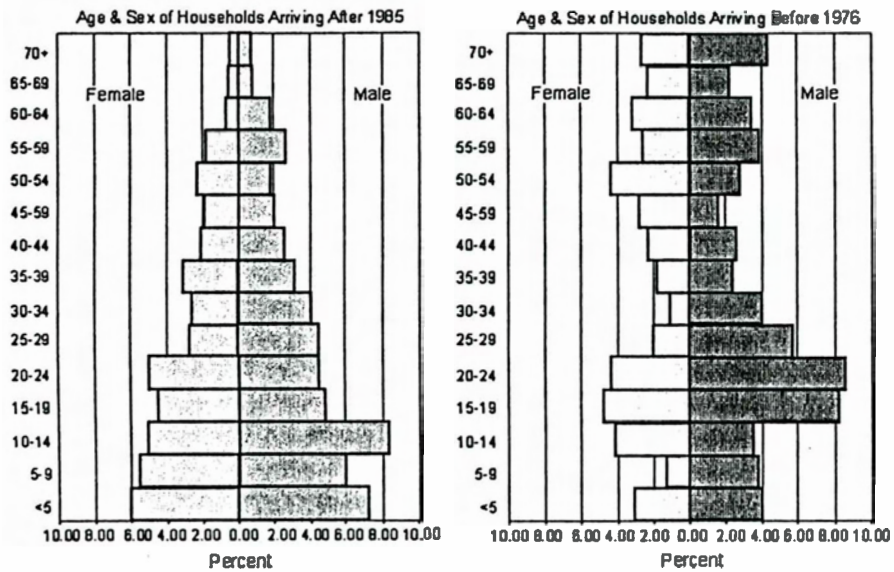

Figure 4a (left). Current composition of households arriving after 1985; *Figure 4b (right),* current composition of households arriving before 1976.

Our methodology reflects a conceptual model underlying our project. (McCracken et al. 1999). In this conceptual model (Figure 5), we propose that households in the frontier follow a trajectory of changing land use that reflects the changing composition of the household and its labor and as their development cycle interacts with features of their social, political, economic and biophysical environment. We suggest that cohorts of farm settlement pass through stages of the domestic life cycles and farm development as their households age over a 25-year or generational time-span. From young adults with young children to older adults beginning to pass their farm property to their children, we hypothesize a steady shift in land use from annual crops favored by young households, followed by strategies made possible by accumulation of capital and more household labor as children are old enough to work and shifts to labor saving land uses as children begin to exit the household through marriage and parents' increasing age. The latter would favor agroforestry, and plantation agriculture (sugar cane, cocoa, and increasingly coffee) and pasture and raising cattle over annual crops. As frontier households develop and consolidate their family farms deforestation subsides; families are increasingly involved in managing fallows, maintaining pastures and developing their agroforestry activities

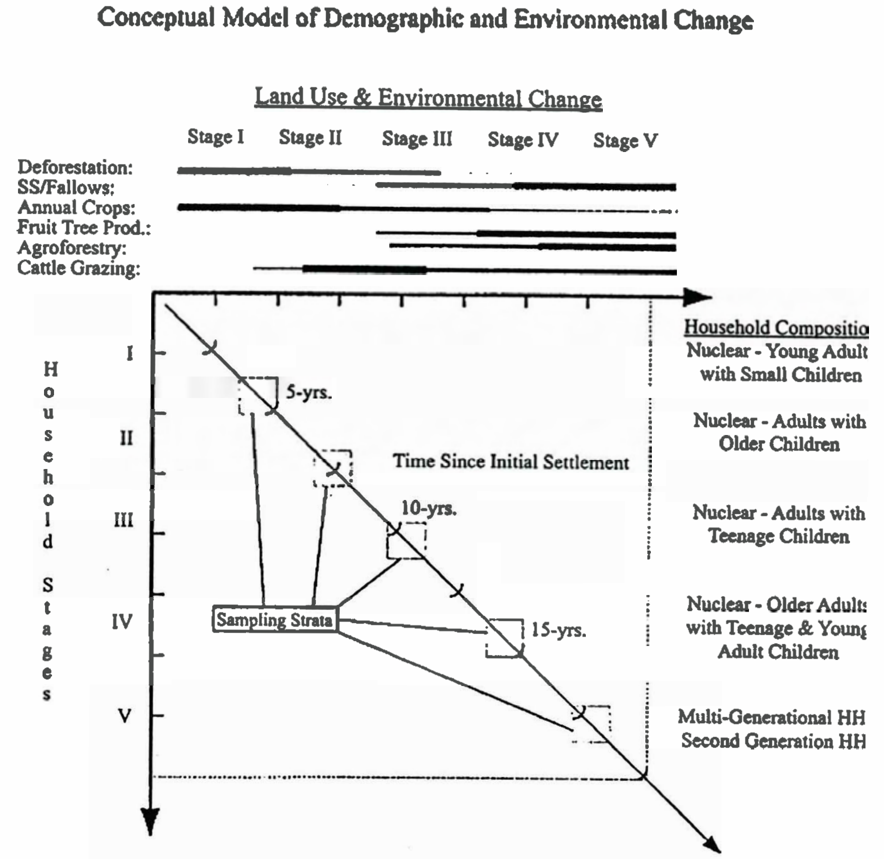

Figure 5. A conceptual model of the domestic life cycle of households, and expected trajectory o land use and environmental change at the farm-household level.

METHODS

For our analysis we have used a set of 10-images at approximately three-to-six-year intervals that cover the period 1970 to 1996. Aerial photographs fo 1970 and 1978 were acquired and the cover of forest and non-forest areas wa visually interpreted using a mirror stereoscope (Fairchild Type F-71B). A controlled mosaic of the interpreted photos was produced. The controlle mosaic interpretation map was scanned and map development undertaken including thematic coding, resulting in a georeferenced map in digital form wit 4-classes of land cover that distinguished: forest, non-forest, river, and road These data were then integrated into a GIS. Landsat Multispectral Scanne

(MSS) digital data were acquired for 1973, 1975, 1976, 1978 and 1979. Landsat Thematic Mapper (TM) digital data were acquired for 1985, 1988, 1991 and 1996 for this analysis. Because of incomplete coverage of different image sources the classifications for 1975 and 1976, and 1978 and 1979 were combined to yield a composite of land cover for January 1976 and 1979.

The development of the property grid GIS data layer (see Figure 2) followed a process similar to that used for deriving the 1970 and 1978 forest cover data layers. The property grid used for this analysis was created from a series of scanned property maps provided by the Colonization Agency (INCRA). The original purpose of these grids did not foresee these applications. Rather, they were a rapid and topographically unverified layout of the numbered properties used to know which farmers had claimed what properties. Initially, the surveyors attempted to lay the lot markers along this ideal grid, but over time adjustments were made to take into account topographic and hydrologic features ignored at the outset. These maps were georeferenced to previously geo-corrected spatially referenced scanned topographic maps of the study area. The scanned and geo-corrected property grid was then used as a base on which to manually digitize a vector polygon property grid in Arc/Info GIS.

We found in the field that even the road network from the available maps did not always conform to reality given local adjustments by farmers and road builders to the topography and hydrology. To define the properties, we began by identifying the rear of the properties. This was done by making a mathematical interpolation of distance. Using a slope/aspect algorithm in IDRISI, we identified the lines that defined the midpoints between the side roads, and this was used to represent the rear property lines that were commonly under a thick cover of primary forest. The next step was to ensure that the satellite images were all georeferenced correctly and were registered to each other so that there were no discrepancies between years in the location of the properties. Once this was accomplished we digitized the properties on-screen in ERDAS Imagine. The time-series helped identify most of the properties because of distinctive patterns of land clearing on each property up to the boundary lines. We then assigned a unique ID to each property to assist us in developing our sampling framework. During fieldwork in December of 1998, we collected differentially-corrected GPS points, using a base-station and back-pack Trimble GPS equipment, at property boundaries along every feeder road at intervals of 5-10 kilometers, in the re-georeferencing of the property grid.

This process illustrated many problems with our original mapping of properties based on INCRA colonization maps and greatly improved the overlay of a new property grid for extracting data at the property level. Because the original INCRA maps did not have adequate cartographic information and geographic references, the final fit between the property maps (based on the INCRA land distribution scheme), GPS points, and satellite images was based on an iterative process of successively fitting the property grid to the GPS points collected in the field until an acceptable fit was achieved. Our successive

evaluation of the final property grid was based on visual examination of its overlay on multiple image classifications, where property boundaries are often discernable from differences in clearing and land-cover. Getting a perfect fit is extremely difficult given the imperfect geographic features of the original colonization maps and the large area covered in this study. Visual inspection suggests that the majority of properties are within a pixel (30 meters) of the proposed boundaries. Pixel-level accuracy is better than one might obtain from maps generated at 1:100,000 scale, and ideally, better than those produced with maps at a scale 1:25,000. Based on visual inspection of remotely sensed imagery and intimate knowledge of the primary investigators about individual properties and the landscape leads us to suggest a acceptable fit for near 90 percent of farms in the area. Our approach may not work everywhere, given the unusual circumstance. In this colonization scheme, land is divided into equal rectangular plots along a network of roads, and evenly spaced along the highways. These regular patterns make definition of the property boundaries more apparent than in other areas where it may be difficult to ascertain the size and shape of properties without doing property-level topographic surveying. The end result of this two-year effort of GIS layering and field verification is a useful tool for extraction of data at the property level.

We believe that the development of a farm property grid within a GIS and a satellite time-series dataset represents a substantial breakthrough for conceptualizing and interpreting social science and environmental questions about land use and land cover change (Liverman et al. 1998). Previous work for an area this size, 3,840 sq km, typically analyzes and describes land use and land cover change from a landscape perspective at best, without addressing the highly variable land uses that farmers engage in. We have been able to clarify in this manner, evidence for forest degradation from logging and fire invasion, and to understand the impact of soil fertility on crop choice in the study area (McCracken et al. 1999, Moran et al. 2000).

One of the objectives of this project was to develop a robust geographic information system for understanding population-and-environment dynamics. In addition to the property grid layer discussed above, we have developed the previously described GIS data layers for 1970 and 1978 with 2 classes (forest and non-forest); Landsat TM-based classification layers with forest, advanced secondary succession, intermediate secondary succession, initial secondary succession, bare soil, pasture, and cropland. Topographic and hydrographic layers were developed from maps from the Instituto Brasileiro de Geografia e Estatistica (IBGE).

The property grid overlay, combined with remotely sensed land cover classification, provides two unique opportunities for research endeavors. First, in contrast with more traditional approaches to analysis of population-and-environment that focus primarily on landscape or pixel level analyses, a property grid provides an opportunity to analyze changes at a more appropriate level of analysis, at the level of the individual actors. In the context of this research, it is farms and settler-households. Within a GIS with land cover classifications, the property grid can be used to extract information associated with all farm lots for analysis. Data extractions, using ArcView3.2 and an interface with ACCESS, and statistical analysis using STATA have been used in our research activities. Secondly, the property grid also provides advantages for drawing systematic random samples in areas where developing sampling frames can be very difficult. In our particular case, we were interested in drawing a sample of colonist households who had arrived on the frontier over the entire period of colonization for detailed interviews on socio-economic and demographic characteristics of households, agricultural strategies, and land-use history.

A key component of the research project seeks to disentangle the period, cohort and age effects associated with trajectories of deforestation at the farm level. For example, we are interested in whether different government policies or market changes differentially affect agricultural strategies of households on farms in different stages of development or in different stages of the domestic lifecycle. Based on area deforested in a farm lot between satellite images we were able to identify the period of initial occupation of each farm property in our study area. We used evidence of the clearing of 5 hectares as a signal that farming activities had begun, based upon field experience that households cleared a minimum of 3 hectares per year during the beginning of settlement. This allowed us to define cohorts of farm properties and their respective colonist-households based upon when clearing of property began (see Figure 6 for a view of the cohorts that were identified for our study area). These "farm-property cohorts" in turn were used to draw a disproportionate stratified random sample of 402 households for detailed interviews on socio-economic and demographic characteristics of households, agricultural strategies, and land-use history. We used a disproportionate stratified random sample to ensure that relatively equal shares of the surveys were carried out among each cohort of

Figure 6. Map of properties by period forest clearing was initiated (Farm Cohorts).

settlers. Equal shares of households among each cohort of farms, and, to a considerable extent, cohorts of settlers, will enable analyses of potential period and cohort effects at different stages (or ages) of farm development.

The analysis for this paper focuses simply on the age effects of farm development on the individual-level patterns of deforestation and predicts individual and landscape level patterns of deforestation from information derived from all the farm properties identified in the property grid. A simply and exploratory way to arrive at an age pattern of deforestation is to regress the number of years of activity on the farm area or percent farm area deforested based on the latest satellite image classification available, in our case, 1996. This approach yields high R-squares, on the order of 60+ percent, and suggests a very linear pattern of deforestation – of about 2.5-3.0 hectares of forest cleared annually. While areas of clearing, on the order of 2.5-3.0 hectares annually, is quite consistent with general information from farmers, this approach is heavily influenced by the accumulated outcome rather the underlying age pattern associated with deforestation over the course of farm development. An alternative approach, used here, takes advantage of the time-series of remotely sensed image classifications and captures the higher levels of deforestation during the initial years of farm occupation and the subsequent declines in deforestation after several years of farming activities, which are consistent with knowledge from many years of field experience with these farming households.

Farm size, and area in forest were extracted for each of the 3,913 farm properties identified in the property grid for each remotely sensed image. The area deforested between dates of each remotely sensed image were used to estimate the percent of farm area deforestation during each interval (between satellite images). These are not "true rates" in that they are based on farm area and not area remaining in forest at the beginning of each period. Since the average size of the farm properties approximates 100 hectares, the percent farm area deforested represents the number of hectares cleared on a farm. This approach avoids the problem of exponential decay associated with a true rate and more appropriately reflects the amount of area a household clears to put into productive activities as they carry out their farming activities. This information was divided by the number of years in the interval to obtain a "mean annual rate of deforestation" for each property for each period of observation (pre-1970, 1970-73, 1973-76, 1976-1979, 1979-85, 1985-91, 1991-96). The "start-date" for each property was established by taking the mid-point for the interval in which they were first noticed as having had farm activities. For example, farm properties settled between July of 1985 and July of 1991 when the satellite images were collected, initiated activities over the period with a mean number of years of activity around three. The mean annual rate of deforestation would be the percent of forest cleared by July 1991 divided by 2.5. In the subsequent interval, between 1991 and 1996, the additional percent farm area deforested is divided by five, and is associated with these approximately eight-year-old farms.

Using the time interval between satellite images, appropriately associated with the approximate age of the farm at the end of the interval, we end-up with 13,383 time intervals for the analysis based on the 3,913 farm properties in the study area. Four hundred and eight farm lots that were not as yet occupied by 1996 are not included in this analysis of the age pattern associated with farm settlement and development.

The objective of this analysis is to obtain an age pattern of deforestation at the farm level over time in much the same way demographers develop mortality curves for predicting age structure in the future or in the development of life tables. The result is the trajectory of land use and land cover change that are the focus of this paper. Figure 7 (and Figure 6) illustrates the number of farm properties occupied by 1996 by the period in which farm activities began, of farm cohorts. The pattern is not uniform – rather it shows the increasing occupation of new farm properties through the end of the 1970s associated, first, with the initial government-directed colonization, and followed by the continued distribution of land through the mid-to-late 1970s. Settlement of new areas declined in the early 1980s and was revived by increases in cocoa prices in the

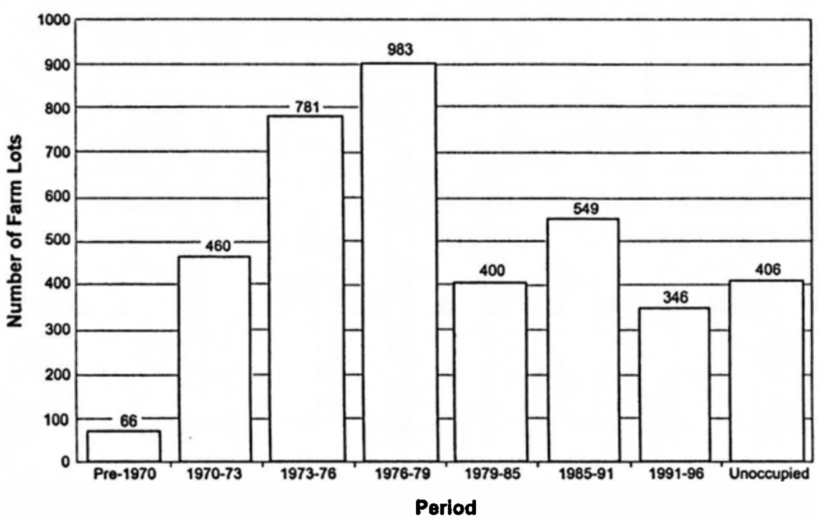

Figure 7. Properties by period forest clearing was initiated (Farm Cohorts).

1980s. Disease and declining cocoa prices resulted in reduced occupation of new farm properties in the first-half of the 1990s. These fluctuations represent important "period" effects on farm occupation and deforestation at the landscape level. In the absence of considerable changes in government policies or market prices for products from the area, we can expect farm occupation to continue slowly as 2nd generation households are formed and move to unoccupied

properties in our study area and beyond. We can expect continued occupation in older consolidated frontiers to be driven by the natural increase of the local population as children of the initial colonists come of age and move on to establish their own farms.

RESULTS AND DISCUSSION

To obtain an age pattern of deforestation at the farm level, we fitted our mean annual rates of farm area deforested with ordinary least-squared regression (OLS) with a simple linear model based on age, and curvilinear models with the inclusion of age-squared and a quadratic equation with an age-cubed term. The results are presented in Table 1. In Figure 8, the observations for each interval (between remotely sensed classified images) are presented by approximate age of the farm, and a line from the quadratic equations is used to illustrate the general age pattern associated deforestation on frontier farms. The satellite image for 1996 had several properties with cloud cover in 1996. In this case, we estimated the percent area that was in forest in 1991 that was under cloud cover in 1996. The inclusion of this variable had no considerable impact on the results and was not in included in this presentation. An important observation from both the table and the figure is that there is substantial variation about the regression line; the models explain only 13 to 16 percent of the mean annual age patterns of deforestation. As can be seen in Figure 8, there are substantial variations below and above the line; many individual farms experienced mean annual rates above 10 percent during their initial settlement. These fitted lines simply reflect an average tendency on these farms that translate into highly

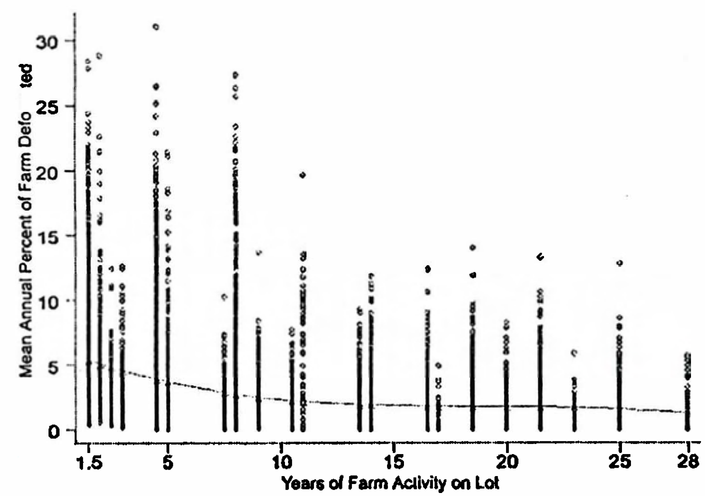

Figure 8. Mean annual percent of farm area deforested by years of farm occupation.

variable rates that occur on any given real farm. What occurs on any given farm is a result of complex dynamics that include: the quality of soils on the property and their location; the amount, age, and gender composition of household labor; and their access to credit or capital – to name but a few of a number of factors that influence the behavior of households. Investigation of these factors is being carried out in separate analyses with information from the 402 surveyed farm households. Other variables for consideration and developed in the GIS are topography and distances to the highway and Altamira. Exploratory analysis of mean slope of the property and various distance measures indicate that they are statistically significant but the associated coefficients are quite small in this analysis of mean annual percent of farm area cleared. Distances to the highway and to Altamira are also highly correlated with age of the farm and importance of distance to farmers, it can be expected, is likely to have changed over the years. Both distance and ruggedness of the farmland are more likely to affect overall levels of deforestation at the farm level rather than specific rates during the course of farm development. This will be discussed further in the analysis of predicted versus actual areas deforested by 1996 in the subsequent section. The fitted regression lines for percent of farm area in forest cleared annually are presented in Figure 9. The figure illustrates the very different implications they have for finding an age pattern of deforestation and for predicting deforestation at the farm level into the future.

Table 1. OLS Regression on mean annual percent of farm area deforested.

Mean Annual % Farm Area Deforested	Linear	Curvilinear-Sq.	Quadratic
Independent Variables			
Years on Lot	-0.1724	-0.4667	-0.7200
Years-squared		0.0125	0.0374
Years-cubed			-0.0007
Constant	4.7712	5.8458	6.3826
Observations	13383	13383	13383
F	2007.24	1269.45	870.43
Prob > F	0.0000	0.0000	0.0000
Adj. R-squared	0.1304	0.1594	0.1631

All results were significant at the 0.01 level

The simple linear regression suggests that farms clear approximately 4.8 percent of the land during the 1st year (year 0) based on the y-intercept. In each subsequent year, the percent of farm area cleared declines by 0.17 (4.8-0.17). By the 12th year, percent of farm annually cleared falls to less than three percent;

by the 20th year, it falls to around 1.5 percent per year. This model suggests that additional clearing stops by the 30th year of farming. Applying these rates to a 100-hectare farm suggests that 32 percent of farmlands would remain in forest.

The subsequent models based on age-squared and age-cubed suggest curvilinear patterns, but with very different consequences for long run expectations about deforestation. Both suggest that deforestation is greater in the beginning and declines to about 2 percent by the 12th year (year 13) and begin to level off by about year 18-20. After the 20th year, the simpler model using age and age-squared, suggest that deforestation would gradually increase by year 25 and then accelerate. The implication is that by the 36th year of farm activities, there would be no more original forest remaining on the farm. The line fitted by the quadratic equation provides a different portrayal of an expected age pattern associated with farm development. It begins with high rates of farm clearing in the initial years, levels off by around years 18-20 at about 2 percent, and then declines slowly after 30 years with no more additional deforestation after 35 years. Applying these rates to a typical farm of 100 hectares suggests that about 24 percent of the farm would continue in forested area.

The fitting of regression lines yields quite different scenarios for the future of farm development and deforestation in agricultural areas on the frontier. The linear regression fits the data well, but understates the amount of deforestation associated with initial settlement of the family farm and overstates the amount of forest remaining in future years. The curvilinear model suggested, by inclusion of a squared-term for age, indicates an increasing deforestation after 20 years that would result in complete deforestation of these farms by year 36. The quadratic model provides a general pattern consistent with field observation and knowledge of the area.

In the initial stages of colonization many families sought to establish their farms quickly and invested the capital they brought with them in clearing large areas of the property. Within a few years many found that they were unable to manage the land they had cleared as weed invasion occurred. Later cohorts of colonist families appear to be taking a more conservative approach, often based on knowledge gained elsewhere in the Amazon. Now many new arrivals purchasing older farm properties and focus their attention on clearing secondary succession left by previous owners. Often these areas are close to the house and more accessible than remaining forested areas in the back of the farm lot. As an increasing share of farmland is placed in productive activities, particularly labor-intensive activities such as cocoa and coffee, or maintaining pasture and caring for cattle, an increasing share of family labor is devoted to these endeavors and less to clearing forested land. As children of initial colonists become adults and begin to form families, we may witness new patterns. Further deforestation on the parental farm may continue, but fragmentation of properties in this area is uncommon. Most adult children who remain in agricultural activities typically purchase neighboring farmland or move to new areas of colonization. During the course of interviews, particularly during conversations with older and 2nd generation colonists, many voiced concerns with retaining some forested areas for future lumber needs, and for conserving areas around sources of water. The maintenance of a near quarter of the land in forest in an older frontier, after the majority of farms have been established, may suggest some optimism. It also must be remembered that these are now highly fragmented areas with substantial loss of biodiversity and have important implications for the local climatic and hydrologic systems.

If we take the regression results in Table 1 and Figures 8 and 9, we can calculate predicted area deforested for the area over the last 26 years for each property based on initial period of occupation to compare our results with observed levels of deforestation. We chose to use the results from the quadratic equation based on their intermediate estimation of the age pattern of deforestation; these are presented in Figure 10. The predicted amount of area remaining in forest is overstated for 1976 and 1979, when compared with the observed levels, and understated in 1991 and 1996. This can be explained in part by the ambitious efforts of the early colonists, and by renewed deforestation on these farms associated with the increase in cocoa prices in the late 1970s and early 1980s. Establishing a very general baseline of deforestation associated with the age pattern of farms now provides us with the opportunity to further explore "period" effects associated with temporal changes in policy and market fluctuations as well as "cohort" effects that distinguish different waves of settlement. By projecting out the percent of area deforested on these farm properties, we anticipate that nearly 37 percent of the area will remain in forest by 2010. If new settlement takes place on the remaining properties (408) during the first part of this decade, we can expect only 31 percent of the area remaining in forest. Barring major changes in policies and prices, this will fall to 24 percent and level out.

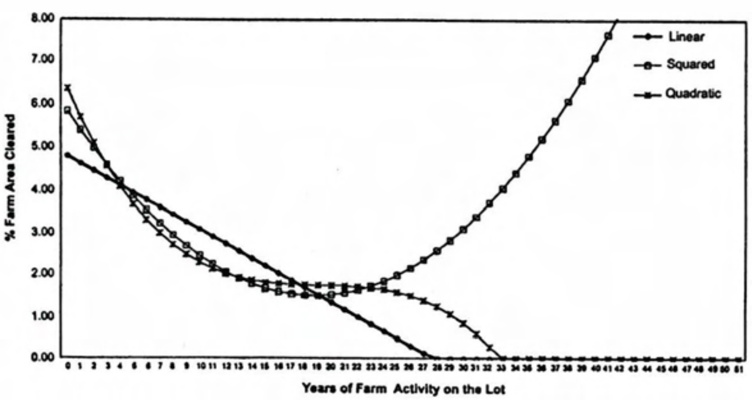

Figure 9a. Estimated percent farm area cleared annually from regression results; various methods.

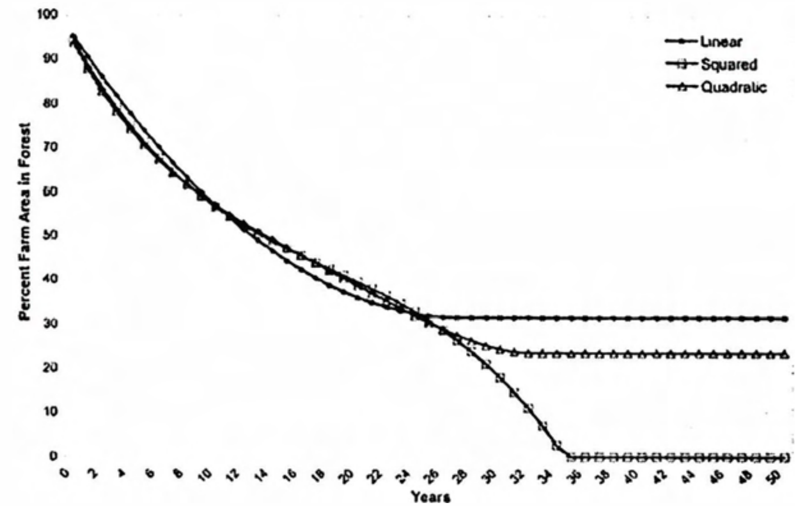

Figure 9b. Predicted forest remaining based on regression results; various methods.

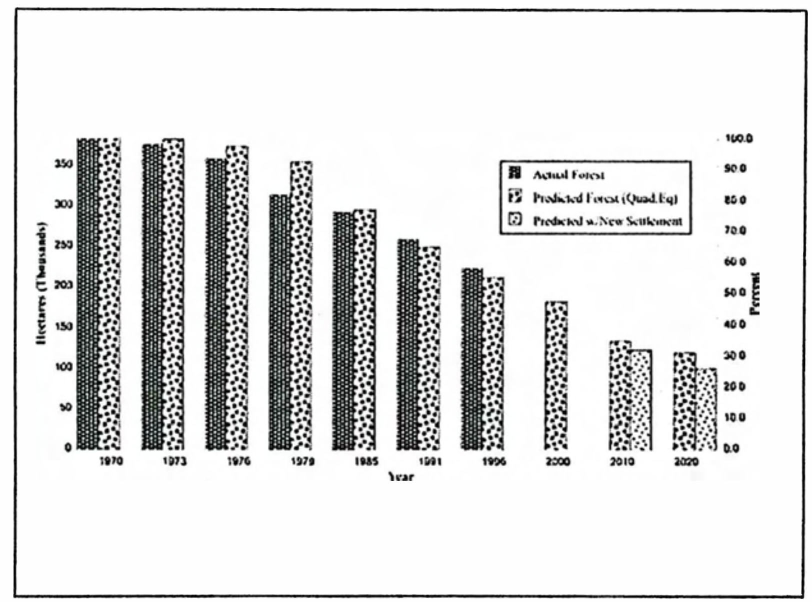

Figure 10. Observed and expected area of remaining forest in the study area, 1970-96, and predicted for 2010 and 2020; based on farm level projections.

Fitting the regression lines and deriving a general pattern of deforestation by age of the farm also provides an opportunity for exploring spatial patterns not directly identifiable when working with tabular survey data. A map of residuals of observed minus predicted deforestation in 1996 (Figure 11) illustrates interesting spatial patterns. Areas with light gray shading represent farms with smaller-than-expected deforestation, given the length of settlement, while dark gray shading represents areas with greater levels of deforestation, whereas white represents areas within one standard deviations of the expected value.

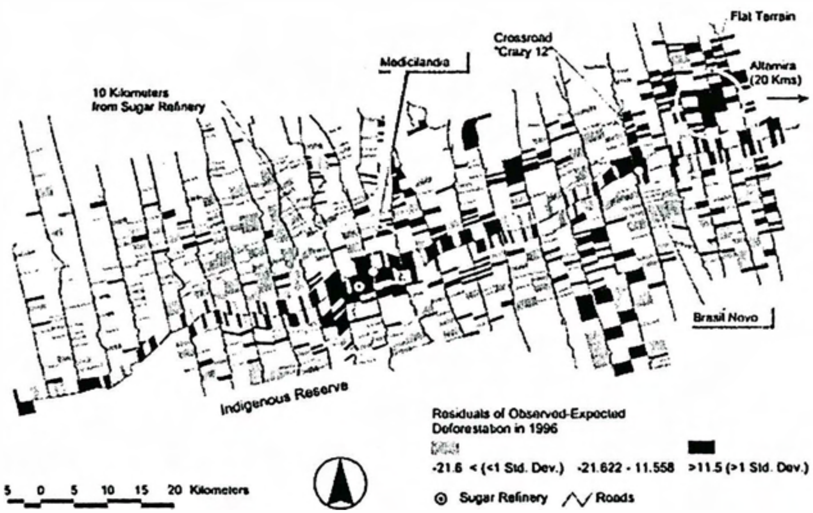

Figure 11. Map of residuals of observed-predicted deforestation in 1996 based on quadratic equation regression line.

Visual inspection indicates that patterns of deforestation are related to distance, soil quality, topography, and agglomeration of farms into cattle ranches. Note first, a higher-than-expected level of deforestation near the sugar cane refinery near Medicilândia. Sugar cane, once cut, has diminished potential for sugar production the longer it is not processed. Areas within 10-kilometers of the sugar refinery are, as a result, associated with higher levels of deforestation. Similarly, we note areas of deforestation greater-than-expected in the northern section of the property grid closest to Altamira. This area is flat, and given its proximity to Altamira, is an area where large-scale cattle ranching activities are increasing on agglomerated farm properties. In contrast the extreme southern fringe of the study area, bordering the indigenous reserve, is very rugged terrain and has more forest given the age of the farms. Topography may be important in the particular farming strategies pursued, and the overall amount of area cleared, but it also affects transportation routes. Properties on side roads leading southward from the town of Brasil Novo, for example, have lower-than-expected deforestation while north of the town one group of

properties has higher-than-expected deforestation while another group, on a parallel road, has lower-than-expected deforestation. This area, to the north of Brasil Novo, is known as the "Crazy 12" in reference to the road numbered 12. Variability in road conditions impact farm families differently in addition to issues related to distance and the topography of their farms.

CONCLUSIONS

In this paper, we analyzed the relationship between length of time on the farm and pattern of deforestation. The tightness of the fit illustrates that there is substantial variation among farmers in developing their homesteads overtime, but that a general pattern emerges that is associated with age or length of time on the farm (Brondizio et al. in press, McCracken et al. in press). Future work will combine these estimates with survey data to better understand the complex array of factors at the household level that affect these patterns. Similarly, the baseline estimate of the age pattern of deforestation among frontier farms will serve to disentangle "period and cohort effects" associated with changing policies and market prices and differences among the various waves of colonists' settlement. Future analysis with a property grid will be used to analyze transition matrices of forest-conversion to annual crops, pasture and perennial crop production observable with multiple satellite images. Ultimately we envision analyses of these transitions between various land covers through the construction of multistate life tables to analyze the flows between different types of land-use. The very general age-pattern of deforestation on farm properties provides the base line for this work.

Our predictive analysis of deforestation suggests that over a 50-year period (i.e., from 1970 to 2020), total original forest cover will decline to 24-32 percent (based on quadratic and linear model fits, respectively). Our analysis based on individual properties, suggests that rates of deforestation slow down considerably over time, but as new roads and communities are created, new pockets of frontier expansion and consolidation are established. As Brazil undertakes in 2001 a new, and ambitious program of road-building (i.e., Avança Brasil), the implications of these findings for future deforestation should give considerable pause to development agencies. The rates for the area studied here could very well become the rates for the Amazon as a whole as more of the region becomes road accessible.

REFERENCES

Andreae, M. O. and D. S. Schimel (eds.) 1989. *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere.* New York: Wiley-Interscience.

Booth, W. 1989. Monitoring the Fate of Forests from Space. *Science* 243:1428-1429.

Brondizio, E., S. McCracken, E.F. Moran, A.D. Siqueira, D. Nelson, and C. Rodriguez-Pedraza. In press. The Colonist Footprint: Towards a conceptual framework of deforestation trajectories among small farmers in Frontier Amazonia. In: *Land Use and Deforestation in the Amazon*. C. Wood and R. Porro (eds.) Gainesville, University of Florida Press.

Crutzen, P. J. and M. O. Andreae. 1990. Biomass Burning in the Tropics: Impacts on Atmospheric Chemistry and Biogeochemical Cycles. *Science* 250:1669-1678.

Dickinson, R. E. (ed.) 1987. *The Geophysiology of Amazonia: Vegetation and Climate Interactions*. New York: Wiley.

Fearnside, P.M. 1987. Causes of deforestation in the Brazilian Amazon. In: *The Geophysiology of Amazonia*. R.E. Dickinson (ed.) Pp. 37-57. New York: Wiley

Fearnside, P. M. 1996. Amazonian Deforestation and Global Warming: Carbon Stocks in Vegetation Replacing Brazil's Amazon Forest. *Forest Ecology and Management* 80(1-3):21-34.

Gash, J. H. C., C. A. Nobre R. L. Victoria, and J. M. Roberts (eds.) 1996. *Amazonian Deforestation and Climate*. New York: Wiley.

Instituto Nacional de Pesquisas Espaciais. http://www.inpe.br/ Website consulted 1998, 1999.

Liverman, D. E.F. Moran, R.R. Rindfuss and P.C. Stern (eds.) 1998. *People and Pixels: Linking Remote Sensing and Social Science*. National Academy Press: Washington D.C.

Malingreau, J. and C. J. Tucker. 1988. Large Scale Deforestation in the Southeastern Amazon Basin of Brazil. *Ambio* 17:49-55.

McCracken, S., E. S. Brondizio, D. Nelson, E. F. Moran, A. D. Siqueira, and C. Rodriguez-Pedraza. 1999. Remote Sensing and GIS at Farm Property Level: Demography and Deforestation in the Brazilian Amazon. *Photogrammetric Engineering and Remote Sensing* 65(11):1311-1320.

McCracken, S., A.D. Siqueira, E.F. Moran, and E.S. Brondizio. In press. Land-use Patterns on an Agricultural Frontier in Brazil: Insights and Examples from a Demographic Perspective. In: *Land Use and Deforestation in the Amazon*. C. Wood and R. Porro (eds.) Gainesville, University of Florida Press.

Moran, E. F. 1976. Agricultural Development in the Transamazon Highway. Bloomington: Indiana University/Latin American Studies Working Papers.

Moran, E. F. 1981. *Developing the Amazon*. Bloomington: Indiana University Press.

Moran, E. F. 1993a. Deforestation and land use in the Brazilian Amazon. *Human Ecology* 21:1-21.

Moran, E. F. 1993b *Through Amazonian Eyes: The Human Ecology of Amazonian Populations*. Iowa City: University of Iowa Press.

Moran, E. F., E. S. Brondizio, P. Mausel and Y. Wu. 1994. Integration of Amazonian vegetation, land use and satellite data. *BioScience* 44:329-338.

Moran, E. F., A. Packer, E. Brondizio and J. Tucker. 1996. Restoration of vegetation cover in the Eastern Amazon. *Ecological Economics* 18:41-54.

Moran, E. F., E. S. Brondizio, J. M. Tucker, M. C. Silva-Forsberg, S. McCracken, I. Falesi. 2000. Effects of Soil Fertility and Land use on Forest succession in Amazonia. *Forest Ecology and Management* 139: 93-108.

Moran, E.F., E.S. Brondizio, and S. McCracken. In press. Trajectories of Land Use: Soils, Succession, and Crop Choice. In: *Land Use and Deforestation in the Amazon*. C. Wood, and R. Porro (eds.) Gainesville: University of Florida Press.

Setzer, A.W. and M.C. Pereira. 1991. Amazonia biomass burnings in 1987 and an estimate of their tropospheric emissions. *Ambio* 20:19-22.

Skole, D. and C. Tucker. 1993. Tropical Deforestation and Habitat Fragmentation in the Amazon: Satellite Data from 1978 to 1988. *Science* 260:1905-1910.

Smith, N. 1982. *Rainforest Corridors*. Berkeley: University of California Press.

Tucker, J., E. Brondizio and E. Moran. 1998. Rates of Forest Regrowth in Eastern Amazonia and a Comparison of Altamira and Bragantina Regions. Pará State, Brazil. *Interciencia* 23(2):64-73.

Wilson, E. O. (ed.) 1988. *Biodiversity*. Washington, DC: National Academy Press.

Chapter 11

MULTI-RESOLUTION CLASSIFICATION FRAMEWORK FOR IMPROVING LAND USE/COVER MAPPING

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Keywords: Multi-resolution analysis, land use/cover, classification, spatial analysis.

Abstract Airborne and satellite remotely sensed data have been the major source for generating land use/cover maps. With the development of new remote sensing systems, hyper-spectral and very-high spatial resolution images will soon provide a source for continuously sampling of the earth surface from local, regional to global scales. A considerable amount of previous research has been devoted to exploring the magnitude and impact on image analysis when shifting scale from coarse to fine resolutions. This chapter presents a multi-resolution analysis and classification framework for selecting and integrating suitable information from different resolutions and analytical techniques into classification routines. The multi-resolution approaches were tested using simulated multi-resolution images for a portion of the rural-urban fringe of the San Diego Metropolitan area. We demonstrate that the multi-resolution classification approaches developed in this chapter can significantly improve landuse/cover classification accuracy when compared with those from single-resolution approaches.

INTRODUCTION

Human activities such as urban, industrial, energy, or agricultural expansions, driven by increasing resource consumption from increasing affluence and population growth, have dramatically changed land use/cover patterns on the surface of the earth. Concern about the impact of these activities and their immediate, as well as long-term, consequences makes the analysis and prediction of land use/cover a basis for the rational management of our environment.

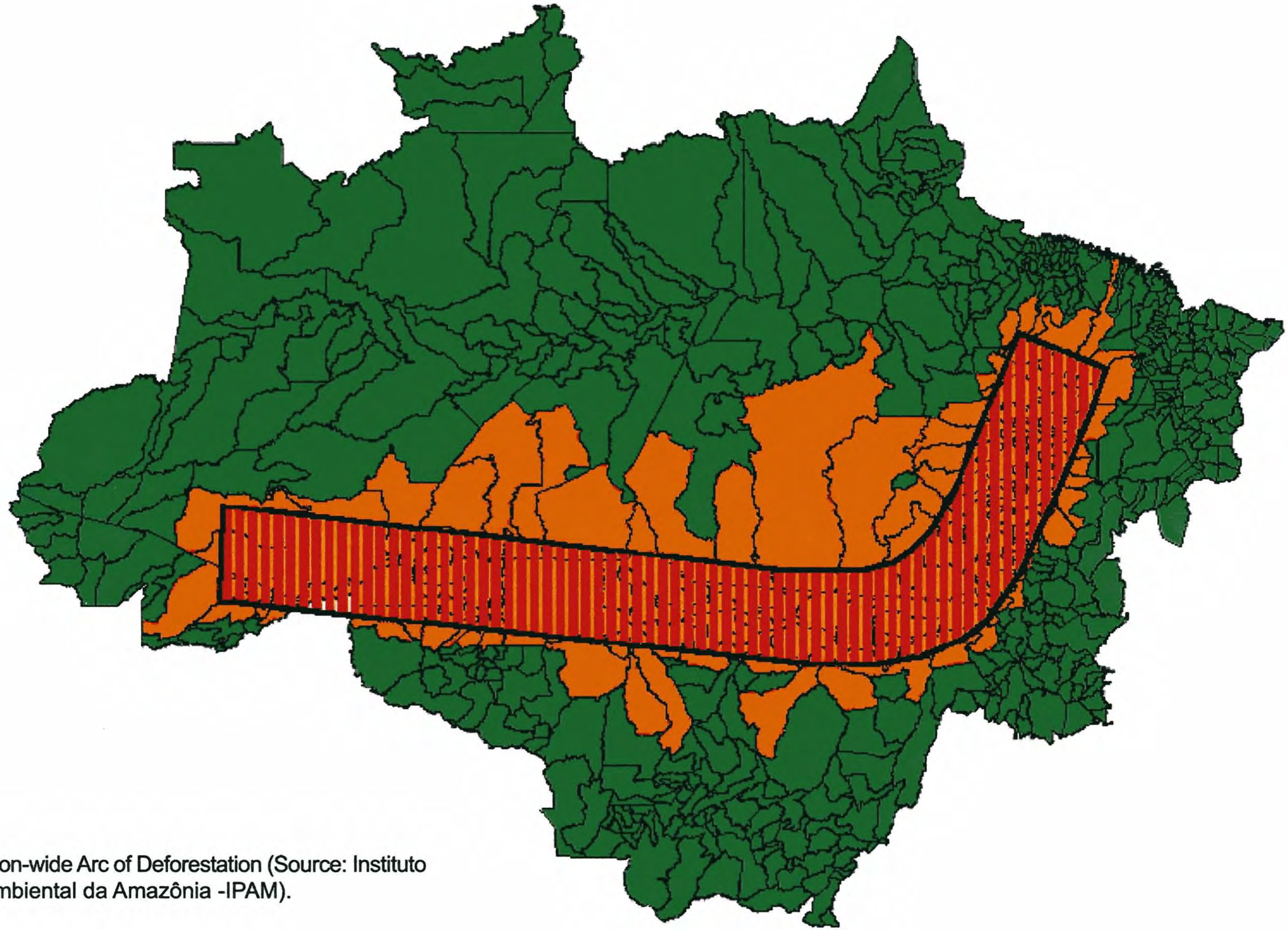


Figure 1. Amazon-wide Arc of Deforestation (Source: Instituto de Pesquisa Ambiental da Amazônia -IPAM).

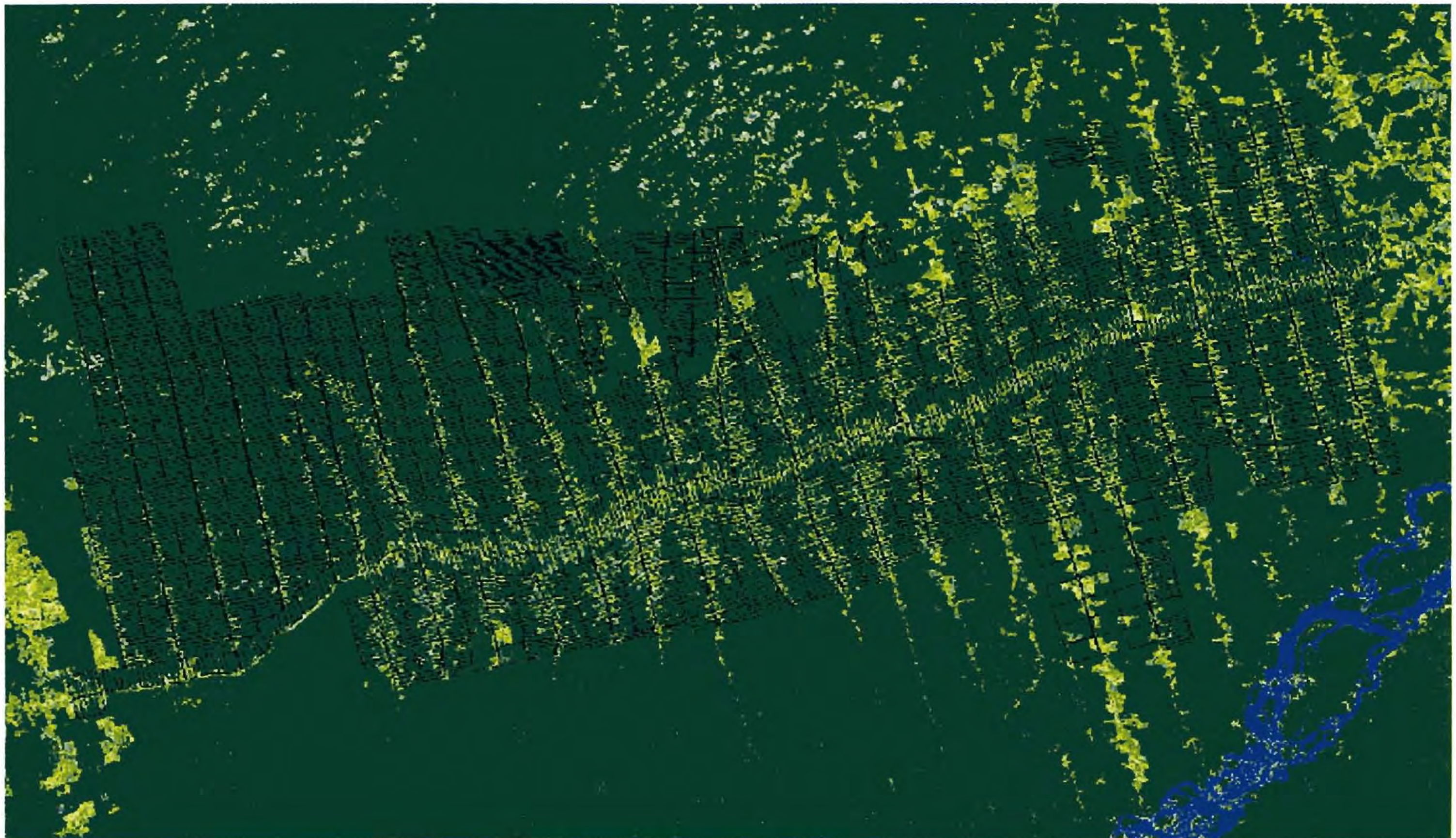
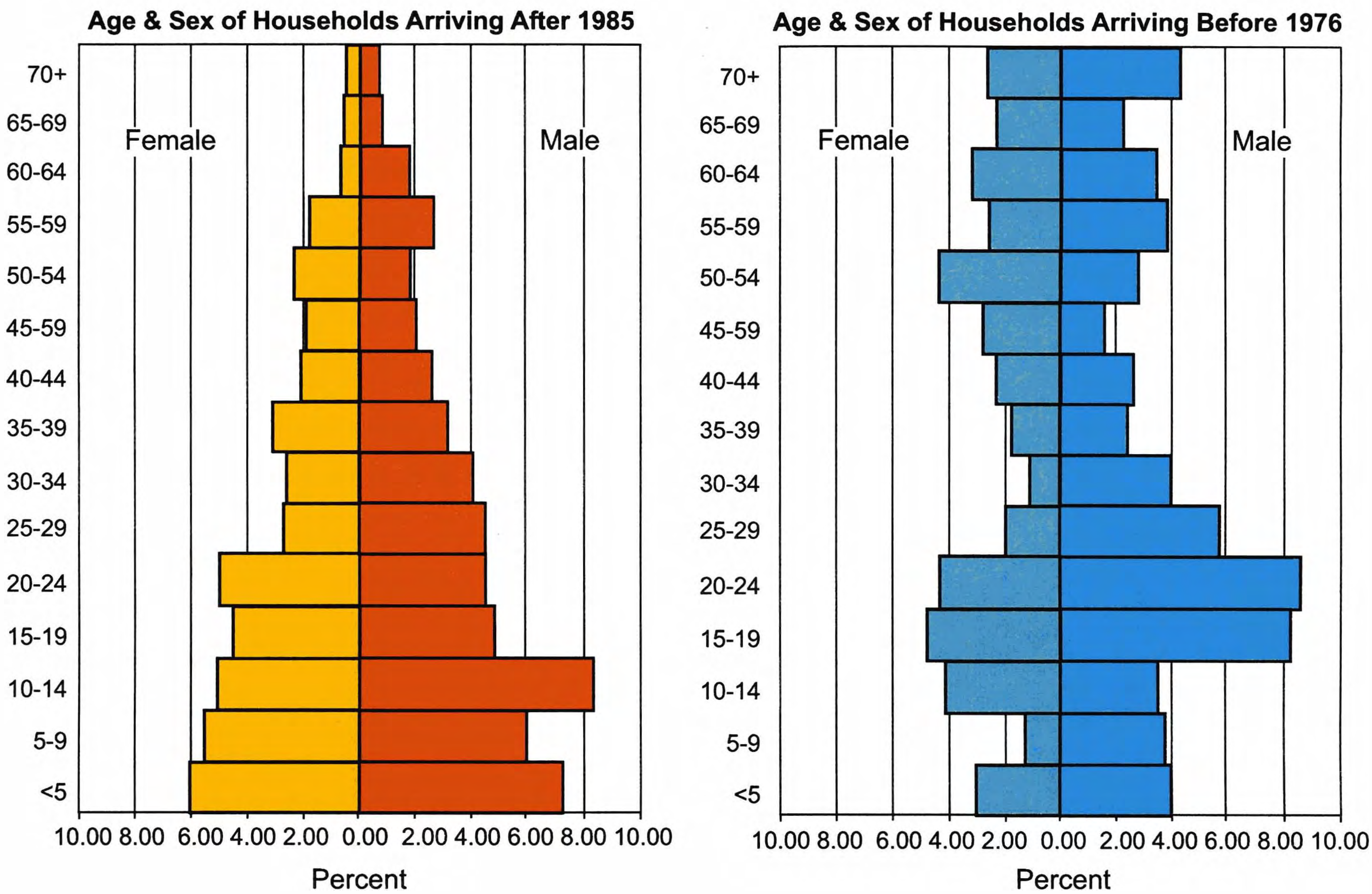


Figure Property grid overlay developed study area, colonization Transamazon Highway, Altamira, Pará.

Figure 3. The observed pace of deforestation among frontier farms along the Transamazon Highway, km 20-140, 1970-96.



Figures 4a &4b. (a) Current composition of households arriving after 1985; (b) current composition of households arriving before 1976

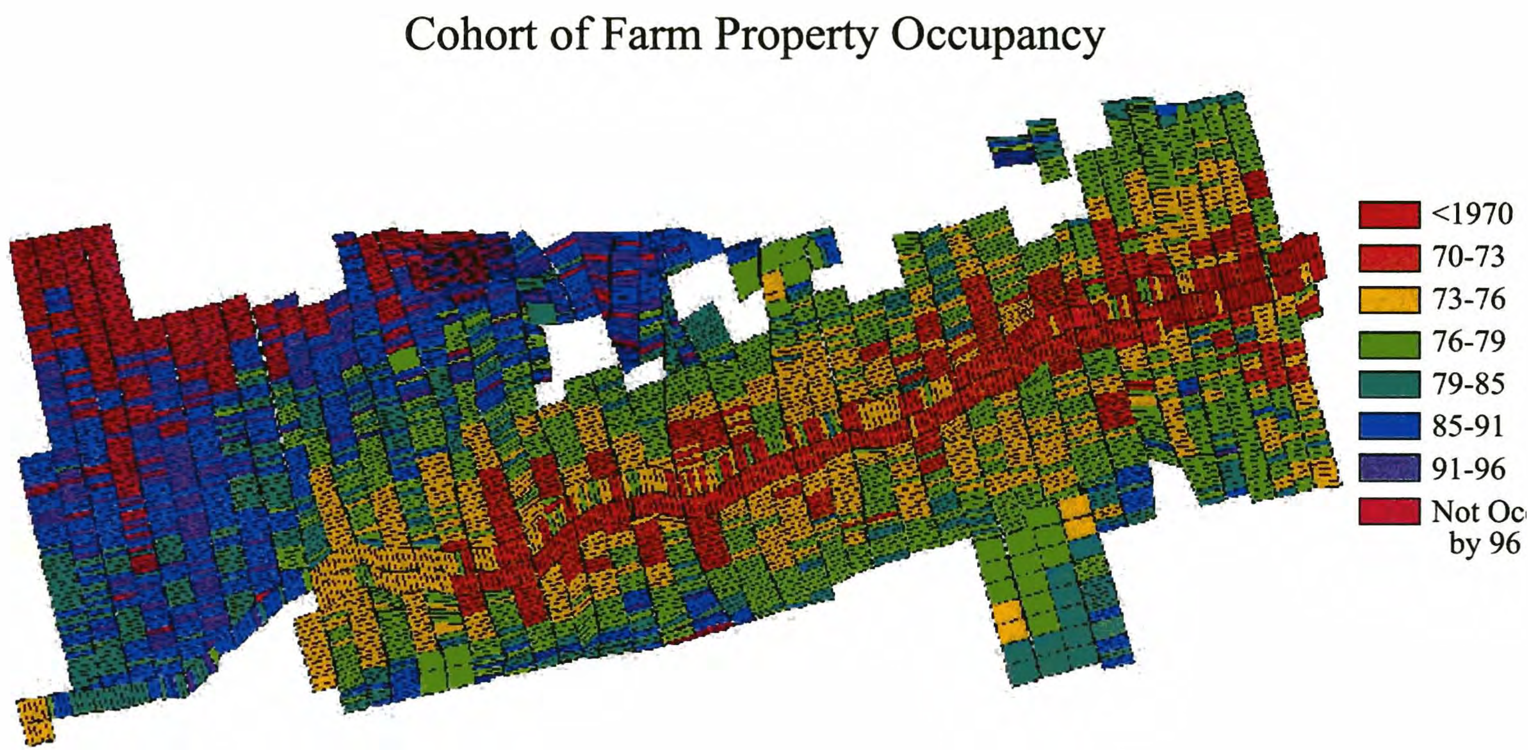


Figure 6. Map of properties by period forest clearing was initiated (Farm Cohorts).

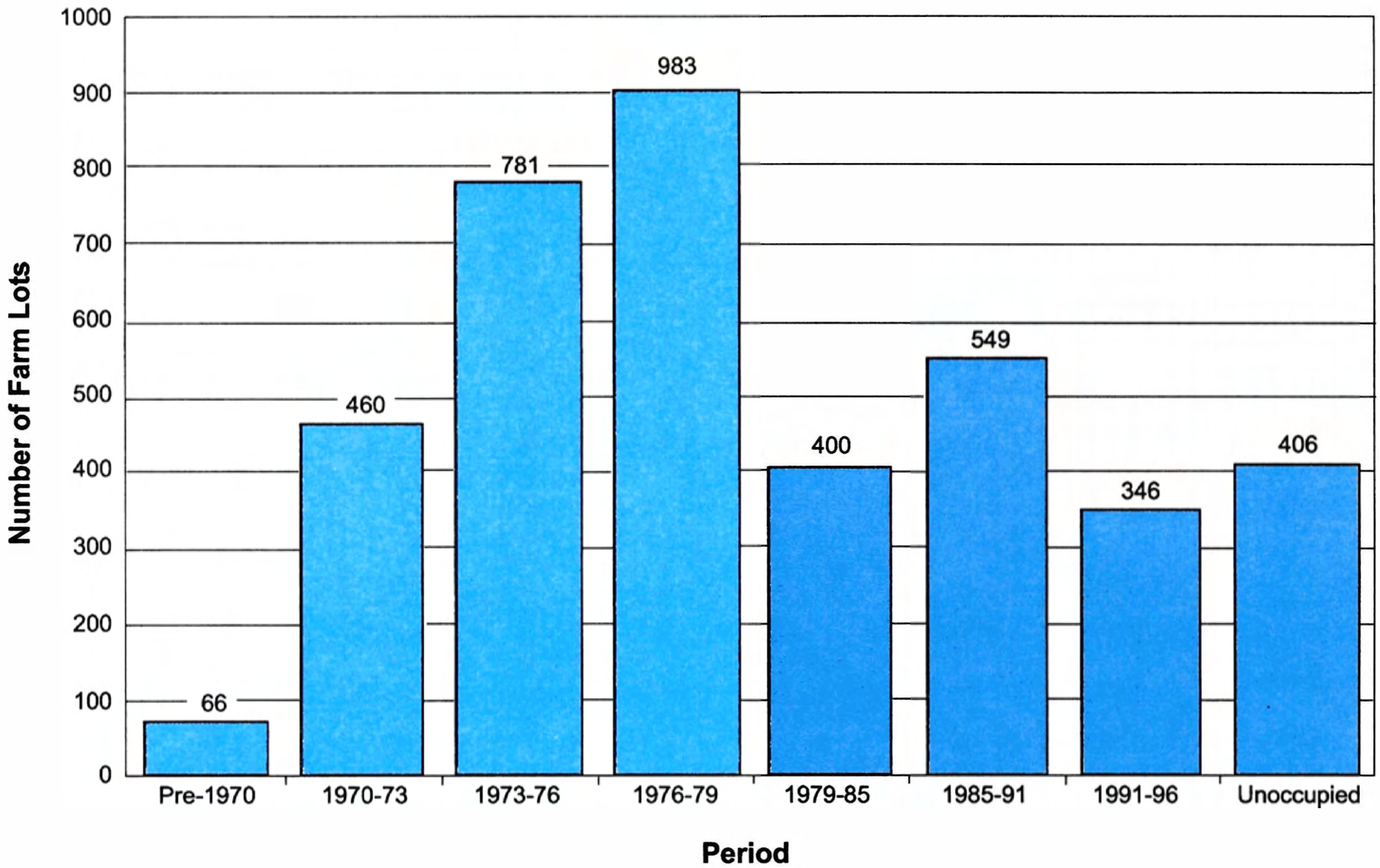


Figure 7. Properties by period forest clearing was initiated (Farm Cohorts).

ACT Publications 2001

No. 01-01
Haberl, H., S. Batterbury, and E. Moran. 2001 Using and shaping the land: a long-term perspective. *Land Use Policy*. 18:1-8

No. 01-02
Moran, E.F. and E.S. Brondizio. Human Ecology from Space: Ecological Anthropology Engages the Study of Global Environmental Change. In: Ecology and the Sacred: Engaging the Anthropology of Roy A. Rappaport. Edited by E. Messner and M. Lambeck. Pp. 64-87. University of Michigan Press, Ann Arbor.

No. 01-03
Gurri, F.D., G.B. Pereira, and E.F. Moran. Well-Being Changes in Response to 30 Years of Regional Integration in Maya Populations from Yucatan, Mexico. *American Journal of Human Biology*. 13:590-602

No. 01-04
Evans, T.P., A. Manire, F. de Castro, E.S. Brondizio, and S.D. McCracken. A dynamic model of household decision-making and parcel level land cover change in the eastern Amazon. *Ecological Modelling*. 143:95-113