

Remote Sensing and GIS at Farm Property Level: Demography and Deforestation in the Brazilian Amazon

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Abstract

Analysis of remotely sensed data at the level of individual farm properties provides additional insights to those derived from a landscape approach. Property-level analysis was carried out by overlaying a property boundary grid in a GIS. Data were derived from aerial photographs for 1970 and 1978 and Landsat Thematic Mapper images for 1985, 1988, and 1991. The study area contains approximately 3,800 properties, but this paper is based on a subset of 398 properties in the Brazilian Amazon. Analysis at the property level found patterns of land-cover classes that reflect differences in farming strategies of households. Data analysis at the household level was useful in explaining apparent mature forest to advanced secondary succession degradation in three years, not readily apparent from landscape analysis of remotely sensed data. The change was due to property-specific selective logging and the spread of fire from pastures into the adjacent forest.

Introduction

The results of road building, farming, ranching, and logging have been devastating to the tropical forests of the Brazilian Amazon (Fearnside, 1983; Fearnside, 1987; Browder, 1989; Mahar, 1988; Uhl and Vieira, 1989). Little deforestation had occurred in Brazil's Amazon before the 1970s. As of 1975, only 30,000 square kilometers or about 0.6 percent of Amazonia had been cleared. Since 1975 the rate of deforestation has accelerated steadily, with a four-fold increase to 125,000 square kilometers by 1980, and twenty-fold to 600,000 square kilometers by 1988 (Mahar, 1988). Both Booth (1989) and Setzer and Pereira (1991) have reported that up to eight million hectares of forest were burned in 1987. Rates declined by half between 1989 and 1991 as a result of economic recession in Brazil. Since 1993, deforestation has increased steadily, and in 1995 surpassed the peak levels of 1987 (INPE, 1998).

The major driving force for deforestation in the tropics is human population growth (Myers, 1984). In the African and Asian tropics, it is generally associated with high rates of natural increase (i.e., high net rates of population growth due to high fertility) and, in the Amazon, it is assumed to be the high rates

of in-migration followed by subsequent intergenerational high rates of natural increase (Gillis and Repetto, 1988). This paper questions these general assumptions. Over the past 20 years, a number of investigators (Moran, 1981; Smith, 1982; Schmink and Wood, 1992; Pichon and Bilsborrow, 1992) have observed what appear to be different dynamics within the context of population growth. It has been observed that, as households age and their children leave to form new households, land use shifts from high labor to low labor activities and from clearing forest and opening new land to managing fallows. In the study area, our past environmental research on deforestation and regrowth of vegetation suggests that the population is, after an initial period of rapid land clearing, deforesting at significantly lower rates and has shifted activities towards management of fallows (Moran *et al.*, 1994a). The dominant assumption would interpret this decline in deforestation as a product of declining population and point to the aggregate high rates of rural to urban migration within the Amazon region for evidence. However, population is still steadily increasing due to both in-migration and high fertility. The hypotheses proposed in this study are that environmental changes, such as deforestation, secondary succession, and forest-to-pasture conversion, should be understood as products of the age and gender composition of households (i.e., their developmental cycle) as families migrate to, settle, and age on an agricultural frontier.

This study, in contrast with other approaches which focus on broad scale changes in the landscape (e.g., Lean and Warri- low, 1989; Booth, 1989; Setzer and Pereira, 1991), seeks to understand frontier occupation and environmental change as *process*. Land clearing begins with the initial migration of colonists. But subsequent land clearing will be a product of the farming strategies that households employ, given their consumption needs and their production possibilities, as their age and gender composition changes over time. This approach to households highlights the need to study environmental change on the frontier as resulting from both temporally defined *period effects* (e.g., fluctuations in migration flows, changing credit policies, etc.) and *cohort and age effects* associated with the aging and transformation of households and their farms.

The question we address in this paper is whether knowledge about property-level analysis provides us with insights into landscape change not available by landscape-level analysis. This investigation is part of a larger research project, which

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is investigating the relationships between the demography of families, agricultural strategies, and patterns of deforestation. A brief overview of this research project provides a conceptual approach that suggests why patterns of deforestation may be different if one took a property-level analysis rather than a landscape approach.

The study is driven by a recognition that the simple association of net immigration flows with increases in deforestation fails to explain the dynamics of deforestation and land use (Bilborrow, 1987). Researchers have observed that it is possible to see very large differences in deforestation trajectories on properties adjacent to each other and sharing the same physical environmental characteristics (Moran, 1981; Smith, 1982). This would suggest that differential rates of deforestation may be associated with differences in the composition of households and/or their access to capital. The latter, while likely to be implicated, is unlikely to explain most of the variance. Earlier work in the area suggests that households are commonly decapitalized within six months of arrival on the frontier by their decisions to invest their scarce capital in maximizing the area purchased, as well as the area initially deforested (Moran, 1981). Thus, within six months, households experience a leveled field from the perspective of access to capital and begin to be constrained as households by their internal supplies of labor. Neighboring farms often had quite different patterns of land use. Some of these differences could be explained by differences in initial capital of migrant families and previous experience of farmer colonists (Moran, 1977; Moran, 1981). Access to water, distribution of soils, and distance to markets appeared to be important to the pattern at a landscape level, but not at the property level. A recurring factor that seemed to contribute to these differences was the amount of household labor on these farm properties (Moran, 1978). In general, large farm families are more likely to be involved in perennial crop production (fruit trees, cocoa, or black pepper, and, in a very few cases, hardwood trees). Smaller families typically place greater long-term cash and labor investments in the creation of pasture and the grazing of cattle and continued involvement in annual cash crop production. Furthermore, agricultural strategies involving different combinations of annual crops, perennial crops, and pasture appear to be related to the pattern and level of deforestation on the farm property.

During the initial stages of settlement, farmer families are typically involved in annually clearing 2 to 5 hectares of forest, and growing cash crops. They commonly use these plots for two to three years for annual crops until soil fertility declines. These plots are then either (1) left as fallow to be used again in later years or allowed to return to forest, (2) turned into pasture for cattle grazing, or (3) converted into perennial crop production.

Agricultural strategies that emphasize perennial crops typically involve lower rates of deforestation and, relative to other farms of similar age, lower levels of overall deforestation. Pasture development and cattle raising involve higher rates of deforestation but less than farm activities which rely on annual cash crop production. Families that depend on annual cash crops must continually open new sections of their land for planting, whereas families involved in either cattle raising or perennial crops must devote a large share of their efforts to maintaining orchards and pastures. Maintaining pasture is a seasonal activity often involving the use of temporary labor, while perennial crop activities require more continued efforts on the part of family members.

From these ideas we developed a conceptual model of household-farm land use (i.e., annual crops, perennial crops, and cattle grazing) based on household labor over the course of the domestic life cycle. While the labor supply of households plays a central role in the model, other factors, such as initial capital, credit availability, distance/transportation to markets,

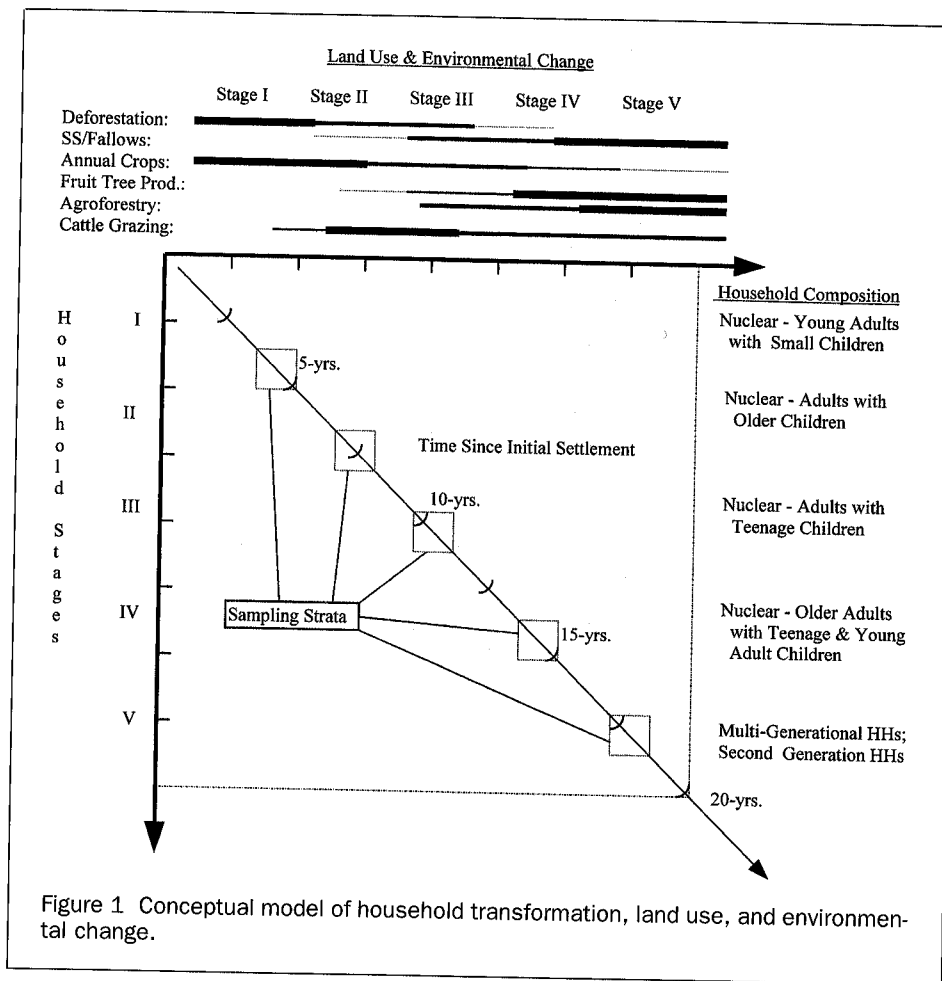
topography, soils, and water availability, are considered as important contributing and conditioning factors in the land-use strategies pursued.

Figure 1 provides a conceptual model linking household composition and the domestic life cycle to transformation of individual farms and local environment. We describe this as representing a demographic and an environmental transition on the frontier. In general, we anticipate that newly arriving colonist households are disproportionately composed of small, young nuclear families. As these families grow and age, children increasingly contribute labor to farm activities and then, as they reach adulthood, begin to leave the domestic unit. Labor is a key factor in land use and in the capitalization and transformation of the farm. We characterize the changes in composition and aging of the households by describing five stages of a domestic life cycle. Each of these stages is hypothesized to have distinct implications for land use and environmental outcomes. These household land-use stages also are hypothesized to have direct consequences for infant mortality, fertility levels, and the nature of entries/exits from the household unit through migration and marriage. The diagonal line in the conceptual diagram suggests a general trajectory expected for cohorts of households as they arrive on the frontier, grow from small nuclear families, develop their farms, and change their local environment.

The model anticipates that all settler families will be involved in the conversion of forest into annual cash crop production upon arrival. Slowly, families will begin to diversify into cattle grazing (often simply as a capital saving strategy) and perennial crops (e.g., black pepper, fruit crops). Perennial crops require a relatively long period before they produce, and substantial labor investment on the part of households. The types of soils and the availability of water also limit this activity. Farm families must generate an income from annual cash crops while investing labor and capital in the development of perennial crops. In contrast, development of pasture requires less labor investment - and temporary, seasonal labor is more important - and appears to be a more viable strategy for families with a smaller labor supply. Households that are unable to accumulate enough capital for investment in raising cattle or in perennial crop production, it is anticipated, continue annual cash crop production. The trajectories of agricultural strategies are not nearly as clear as that suggested by the conceptual model; households combine agricultural and pastoral strategies over the course of farm development. The question remains as to how different families pursue agropastoral activities, given (1) the soils, water availability, topography of their farm lands; (2) distances to markets, credit, and agricultural produce prices; and (3) household and other labor availability. Observations of patterns of use and patterns of changes in use at the property level will aid us in developing a typology of trajectories of land use and land cover among properties. We anticipate that land-use/land-cover trajectories will be related to temporal and spatial aspects of settlement of farm families (e.g., length of use [age-cohort effect]), timing of arrival and period effects (e.g., credit), topography, hydrology, and distance to local market centers. We can begin to understand these patterns of use and patterns of change by studying individual properties.

Study Area

The study area is located along the Transamazon Highway in the Lower Xingu Basin, near the town of Altamira, State of Pará, Brazil. It covers an area with nearly 4,000 households. The pilot study area for this paper includes 398 farm properties. In the study area, highway construction began in 1970 and frontier colonist families began settling the region in 1971 through a colonization program (Moran, 1981; Smith, 1982). The majority of farm properties were initially settled in the



first five to eight years while later migrants moved further down the highway or further out along the secondary side roads. The pattern of deforestation and land use/land cover exhibits the "fish-bone" pattern of many land-distribution colonization projects in the Brazilian Amazon (Moran *et al.*, 1994a and Plate 2, this article).

The use of remotely sensed digital images has become an important tool in environmental assessment and resource management (Lillesand and Kiefer, 1979; Lindgren, 1985; Estes and Cosention, 1988; Aber and Melillo, 1991). Remote sensing is particularly valuable for research in inaccessible regions of the Amazon Basin where assessment of vegetation and soils is both urgent and difficult if carried out solely by means of field studies (Danjoy, 1984; Nelson and Holben, 1986; Woodwell *et al.*, 1986; Woodwell *et al.*, 1987; Helfert and Lulla, 1990).

Remotely sensed data from Earth-observing satellites are typically used to track changes in land cover for landscapes (Liverman *et al.*, 1998). The use of satellite sensors to measure the magnitude and trajectory of land-cover change has been particularly relevant in the Amazon, a region of difficult access, experiencing the highest rates of deforestation worldwide (Wood and Skole, 1998; Skole and Tucker, 1993). Cast at the landscape level, investigations of the patterns of land-use and land-cover changes may miss much of the underlying dynamics and mechanisms of change that make up and drive these changes, i.e., those taking place at the individual household farm level. In macro-level studies, change in land use and land cover often focuses on road construction, credit and taxation policies, market location, population growth and migration, types of agricultural practices (e.g., traditional versus mechanized) or agropastoral activities (e.g., cattle grazing versus

annual cash crop production, or perennial crops), topography, and soil distribution. These are important contextual factors that shape processes that affect landscape land use/land cover over medium to long time spans.

An alternative and complementary approach is to understand change as the result of actions of particular user groups and individual households (Turner *et al.*, 1994; Liverman *et al.*, 1998). At this level, investigations may indicate a variety of specific mechanisms involved in the transformation of land uses, as well as indicate divergent patterns of use and transformation. These heterogeneous patterns of use and mechanisms of change may not be readily identifiable if we focus our attention on the broad transformations in the landscape. However, property-level analysis sheds new insight only where households use land within well-defined boundaries year after year. Where people live in villages and exercise communal property rights or work very small parcels, a landscape approach may be the only mode of analysis (Entwistle *et al.*, 1998; Sohn *et al.*, 1999).

Methods

Our current work-linking remote sensing and GIS at the household-property level with the use of sample surveys and a property boundary map/grid-draws heavily on previous work of our research group on secondary succession (Mausel *et al.*, 1993; Moran *et al.*, 1994a; Moran *et al.*, 1996; Brondizio *et al.*, 1994; Brondizio *et al.*, 1996; Tucker *et al.*, 1998). Image classification was based on a hybrid approach and involved the use of ground information (i.e., 300 training samples) during fieldwork in 1992 and 1993. In addition to the training samples for image classification, a detailed vegetation inventory of 25 areas rep-

representing land-cover classes in the area was undertaken. In each vegetation area, we used ten plots of 150 square meters to sample, with subplots of five by two meters randomly located within five of the ten plots. Because the emphasis was on secondary succession, forest and 1- to 5-, 6- to 10-, and more than 11-year successional vegetations were sampled. Plots and subplots were randomly distributed, but nested inside each other to account for the detailed inventory of trees (dbh, diameter at breast height, equal or above 10 cm), saplings (2 to 10 cm dbh), seedlings (less than 2 cm dbh), and herbaceous vegetation (as a percent of ground cover). In the plots, all trees were identified, and were measured for dbh, stem height, and total height. In the subplots, all saplings were identified and counted, diameter and total height were recorded for all individuals with dbh above 2 cm, and all seedlings and herbaceous vegetation were identified and counted.

Training samples representing the proposed land-cover classes were evaluated with statistical separability analysis (transformed divergence was applied to verify training sample suitability) to ensure accuracy during classification (see Mausel *et al.* (1993), Brondizio *et al.* (1994), Brondizio *et al.* (1996), and Brondizio (1996) for further details). The final classifications were compared to other thematic maps of the area, with an overall accuracy above 85% percent for all classes (Mausel *et al.*, 1993). Land-cover classes were developed first by unsupervised classification procedures using ERDAS7.5, followed by collection of training samples in the field in two research expeditions and supervised classification incorporating half of the training samples. It was not possible to distinguish accurately secondary succession of 1 to 2 years from that of 3 to 5 years, but combining these it was possible to achieve an accuracy of 88.3 percent. After an additional season of fieldwork, it was possible to move away from the years since abandonment criteria used initially in interviews, to a structural criteria based on height of the vegetation. The following seven classes of land use/land cover were derived from Landsat Thematic Mapper satellite images through a combination of hybrid classification and detailed field inventories:

- Water,
- Mature Forest,
- Initial Secondary Succession (average height 2.5 to 5.0 meters),
- Intermediate Secondary Succession (average height 6.0 to 11.0 meters),¹
- Advanced Secondary Succession (average height 12 to 16 meters),
- Pasture, and
- Bare Soils.

Two additional sources of forest cover were obtained from aerial photographs for 1970 and 1978. Interpretation of these two sources targeted only three classes: water, forest, and non-forest. These various sources provide a time series of five coverages for the analysis of land-use/land-cover change over the course of settlement and farm development for this region.

Development of the Property Grid

We decided to proceed with developing the property grid overlay from perceived boundaries in individual satellite images and through their temporal comparison. Pre-fieldwork development of the property grid was carried out in three stages: (1) table-digitizing of roads, (2) on screen property definition and

digitizing, and (3) property identifier assignment. The techniques outlined here may not necessarily work in all regions. The Altamira colonization scheme divided land into roughly rectangular lots of similar spatial extent, distributed around a network composed of feeder or side roads evenly spaced along the highway. The farm lots average 100 hectares in size (500m by 2,000 m) and are, therefore, represented by approximately 1,100 pixels in a TM image. These similarities make the definition of properties more apparent than in other areas, where it may not be possible to approximate the size and shape of properties ahead of time. However, where plat maps are available, the approach should be similar.

The property grid GIS layer with assigned IDs is a powerful tool for data extraction from the five images (1970, 1978, 1985, 1988, and 1991) for exploratory data analysis at the property level. Exploratory analysis of these data permitted the development of a stratified sampling frame for selecting properties and households based on (1) timing of settlement based on period of initial forest clearing and (2) extent of deforestation. Other sampling methods could be developed with these data based on patterns of land cover and land use or for identifying farm properties that have unique or unusual characteristics.

For the purposes of generating a stratified sampling frame congruent with our conceptual model of the life cycle of households, agricultural strategies and deforestation, property level analysis of remotely sensed data were very useful. Explicit in our model is the need to disentangle *period effects* (e.g., credit policies for cattle and cocoa) from *cohort and age effects* that may be related to farm development and stages of the domestic life cycle of households. Because in this region the majority of farm properties were settled between 1970 and 1978, we were particularly interested in over-sampling early and late colonist households for comparison and analysis. By stratifying our sampling frame first by timing of initial clearing and subsequently by level of deforestation in 1991, we were able to obtain a sample to address our research questions. With this strategy, we are able to compare households at similar stages of farm development and stages of the household life cycle that arrived during different periods. A series of hypotheses have been developed to understand how households differentially respond to credit policies in their agricultural strategies.

In fieldwork, a number of teams were involved in data collection. One set of teams carried out extensive interviews with the male and female heads of households with two survey instruments, one on land use history and another on demographic characteristics of households. Another team focused on collecting differential GPS points along side roads and at property boundaries to test the accuracy and correct the property grid developed in advance of fieldwork when appropriate. The team used a Trimble Pathfinder system set up by one of the co-authors who is a GPS specialist with the International Tropical Forestry Institute. We also had a Magellan ten-channel differentially capable pair of units as a back up system. These GPS data were collected in a differential mode (with a base station in town and a mobile unit) to ensure accuracy. This often included looking at land titles with the respective farmers and permitted the redevelopment of a geo-corrected property grid based on differentially calculated GPS points.

The pre-field property grid, in addition to aiding in developing a stratified sampling frame, helped the interview team locate households and farms for interviews. In the field we carried laminated composites of bands 5-4-3 of the 1991 TM image to discuss land use and land cover with farm families. We also collected GPS points at the houses where we interviewed and, in discussion with farmers, were often able to identify their properties and evaluate our property boundary development as well as investigate the quality of our remotely sensed land-cover classification. In many cases, we were able to show farmers single-page printouts of the composite and classified land-

¹While it has been common to think of successional stages in terms of years, variation in land-use practices has been shown to affect the rates of regrowth. Two areas may have very different ages but the same tree structure (Tucker *et al.*, 1998). It is thus preferable to think of successional areas in terms of their structure rather than their age if we plan to undertake inter-site comparisons.

cover class images for each date for their farm and adjoining properties. These were particularly useful in verifying our previous classification procedures and for refining this work after leaving the field. These printouts also aided in the land-use history interviews carried out with farmers, often improving recall of previous use of the land.

While in the field, we obtained more recent property maps from the INCRA agency. These maps were developed over different periods for different sections of the Transamazon highway and feeder roads and pieced together to cover the entire area covered by our study area. These maps, although pieced together, appear to be much more accurate survey maps of the region. Sections of the map were scanned, digitized, and georeferenced to the GPS points collected in the field. Resampling and geo-referencing resulted in overall RMS errors on the order of 39 meters, suggesting a very good fit of these maps and the satellite images. Work on a new property grid, independently of the pre-field work grid, has been completed for the older colonization area 20 to 40 kilometers west of Altamira. We refer to this area as the Pilot Study Area for the exploratory analysis of remote sensing, GIS, and property boundaries presented in this paper (Figure 2).

A comparison of the pre-field and "new" property grids indicates that digitizing property boundaries from satellite images worked relatively well, but contains errors along some feeder roads (see Figure 2). Here our on-screen work led us to digitize side-boundaries of properties diagonally across neighboring properties. Also note the islands created by detours in the roads. In some instances, farmers left these pieces of land idle. Others allowed neighboring farmers to use them or have re-negotiated property boundaries. These changes are not surprising given the gap between 1991 and 1998 fieldwork, and

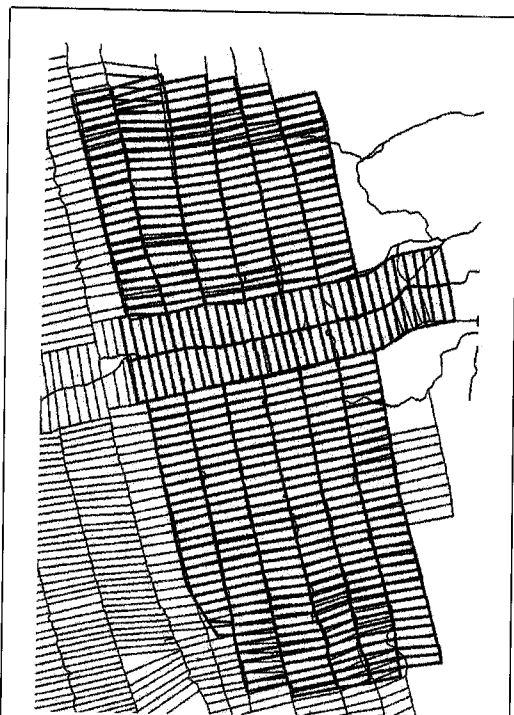


Figure 2 Property grid development. Pre-field grid based on TM on-screen digitizing (in regular lines) and post-fieldwork grid based on differentially corrected GPS data and INCRA property maps (in bold lines).

the probability that farmers adjust roads to meet their transportation needs and the local hydrological patterns.

Property Level Analysis

Our work on land-cover change in this area has proceeded along two primary modes of analysis. The first involves investigating landscape changes in land use and land cover through the use of a transition matrix. This involves pixel-to-pixel comparisons of transitions in cover classes between dates for the series of aerial photographs and Landsat TM images. The second approach is to incorporate the use of cross-sectional information at each point in time and transition matrix data at the individual property level. These data can be analyzed with standard tabular statistical software.

By cross-tabulating images and constructing a transition matrix, we observed that nearly 47 percent of deforested area between 1988 and 1991 had been converted into what appeared to be advanced secondary succession (i.e., forest regrowth of 13.5 meters on an average [Tucker *et al.*, 1998]). Fallow and secondary succession is an important feature of land-cover change and forest regrowth in this region. Estimates based on a transition matrix for the pilot study area suggest that nearly 20 percent of forest cover in 1991 was the result of forest regrowth. But a large forest to advanced secondary succession (SS3) conversion was an unexpected result of constructing the landscape transition matrix.

This Forest-to-SS3 conversion (Plate 1) suggests that forests have somehow been degraded to a vegetation structure resembling fallow areas of more than ten years, i.e., of 13.5 meters height on average. A better understanding of this phenomenon was not readily apparent until we had begun to think about landscape change, empirically and conceptually, as the result of individual properties. At first, this pattern of Forest-to-SS3 conversion raised doubts about classification. Other possible explanations include (1) selective logging, (2) reduction in ground water or rainfall, or (3) spreading of fires into forest areas. Further investigation for Forest-SS3 conversion for previous periods (1978 to 1985; 1985 to 1988) indicate similar patterns and differences between periods that could not be explained by rainfall patterns.

Furthermore, we might expect changes in ground water or in rainfall, or from classification errors, to affect broad areas. If, on the other hand, these Forest-SS3 conversions were isolated to specific properties, we can expect them to be related to selective logging or to the spread of fires from fields into forest areas. This seems to be the case, and will be a topic for further investigation during up-coming fieldwork. While this understanding of Forest-SS3 conversion noticed in the transition matrix is not unique to a property boundary approach, identification of the problem and development of alternative hypotheses for the phenomenon was possible because we were analyzing landscape change at a property level.

Analysis of Remotely Sensed Land-Cover Classes at the Property Level

Ultimately, the goal of integrating remote sensing analysis at the property level with household surveys is to establish links between land cover and land use to make it possible to relate land-use strategies and farm development to the demography of families and economic and environmental factors. The property grid is useful for extracting areas of land-cover classes for cross-sectional and prospective/transitional analysis with standard tabular statistics at the property level. A variety of spatial and descriptive statistics can be constructed as a means to describe the farm plot and various combinations or patterns of land-cover classes associated with individual farms. In this exploratory analysis, we begin developing typologies of land

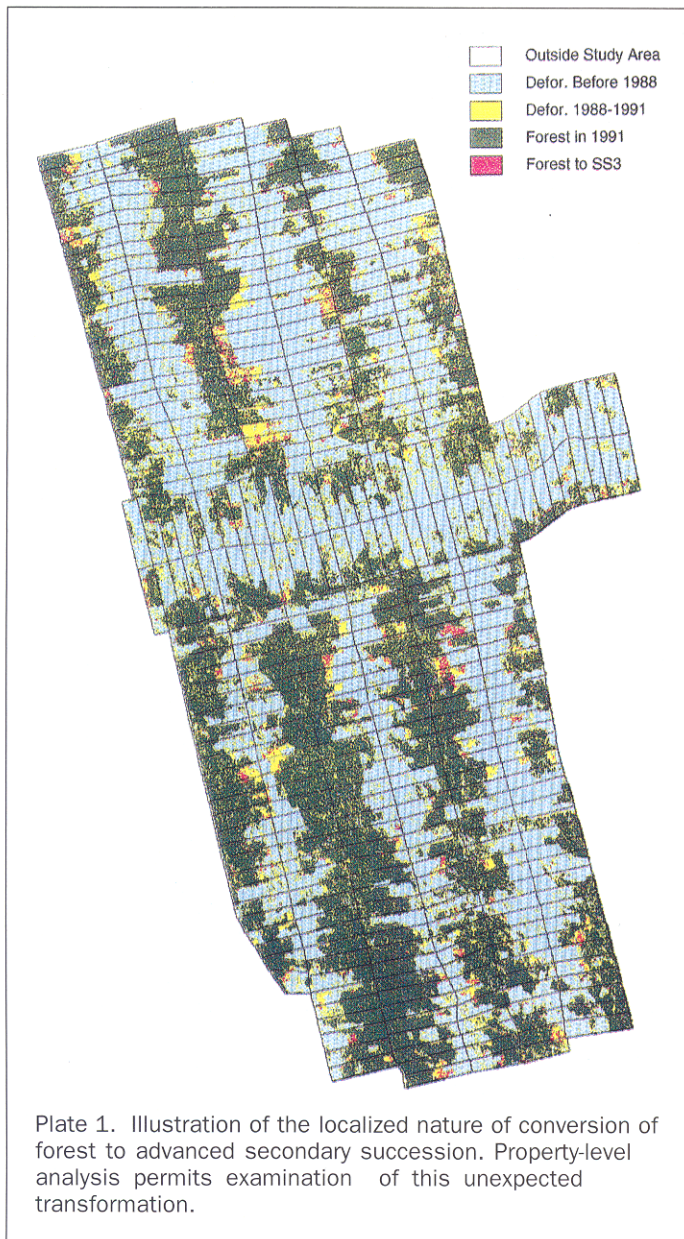


Plate 1. Illustration of the localized nature of conversion of forest to advanced secondary succession. Property-level analysis permits examination of this unexpected transformation.

cover by examining how land-cover classes of previously deforested areas are associated with deforestation and afforestation at the farm property level. Data extraction for the 398 properties in the pilot study area was carried out using IDRISI for Windows in conjunction with Microsoft ACCESS (a relational database program). Subsequently, we carried out standard tabular ordinary least-squared regression analysis. Plate 2 illustrates the overlaying of the property grid for the extraction of areas associated with remote sensing analysis and GIS products developed from the aerial photos and Landsat TM images.

Data on forest area were extracted from the aerial photographs of 1970 and 1978. Land area for land-cover classes developed with the satellite data were extracted from the classified Landsat Thematic Mapper images for 1985, 1988, and 1991. The following variables were constructed:

Dependent Variables

- Area of Forest Annually Deforested between 1988 and 1991
- Forest Area in 1991
- Area Previously Deforested with Forest Regrowth in 1991

Independent Variables

- Forest Area in 1988

Related to Farm Activities

- Percent of Previously Deforested Area in Intermediate Secondary Succession (SS2)
- Percent of Previously Deforested Area in Bare Soils
- Percent of Previously Deforested Area in Pasture

Distance to Markets

- Distance to the city of Altamira in kilometers and distance-squared and distance-cubed

Timing of Settlement

- Period of Initial Clearing of More than 5 hectares coded as 1 = Early Settlement (before 1970), 2 = Middle (1970–78), and 3 = Late (1978–1991).

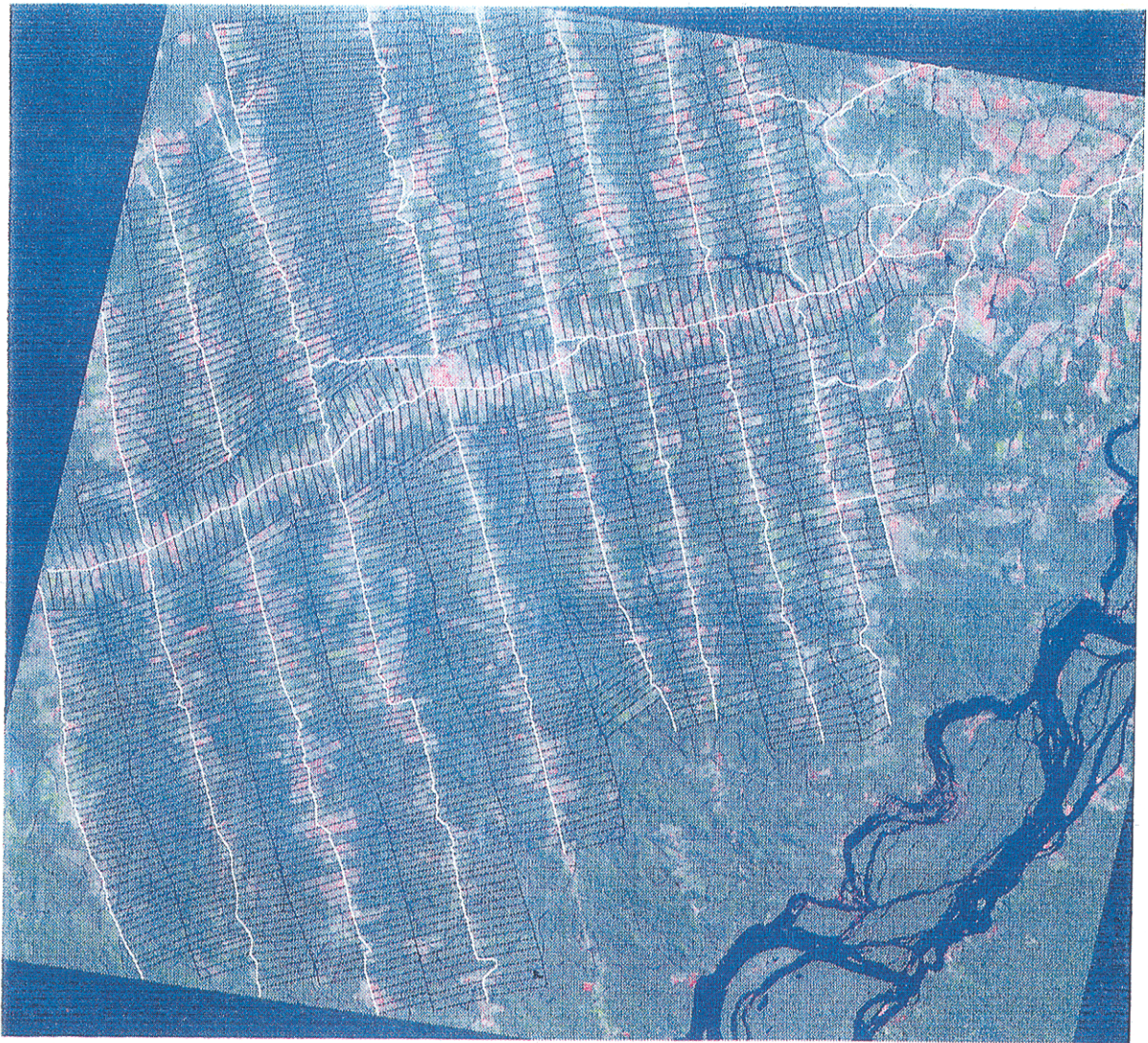
Of particular interest to this exploratory analysis of the pattern and level of deforestation are (1) the mean annual area deforested between 1988 and 1991, (2) the overall level of deforestation in 1991, and (3) the area previously deforested that has returned to forest in 1991. The independent variables of interest are related to pasture, bare soils, and secondary succession and were constructed as percentages of the area previously deforested. The rationale for this type of independent variable construction is that we are interested in how households make use of land areas that have been taken out of forest for agricultural activities. Moreover, these land-cover classes, as a percentage of previously cleared area, reflect the intensity and composition of farm activities in the three categories of land use (namely, cattle grazing, annual crops, and perennial crop production) developed in our conceptual model of patterns of deforestation. This exploratory analysis of land-cover classes and patterns of deforestation represents an initial analysis of how agricultural strategies and land use may be associated with patterns of deforestation. For the regression on mean annual area of deforestation between 1988 and 1991, the indicators of farm activities are based on percent of land-cover classes in 1988. For the regressions on forest area and area of forest regrowth in 1991, these variables are based on the land-cover classes of the 1991 image.

Exploratory Regression Analysis on Patterns of Deforestation/Afforestation

For the 398 properties in the pilot study, the average area in forest in 1991 was 35.3 hectares. Between 1988 and 1991, approximately 3 hectares were cleared annually, with the range of area deforested running from "no-deforestation" to 13.6 hectares per year. With regard to forest regrowth, on average the farm properties had approximately 7.5 hectares of secondary successional forests, with ranges from none to 25 hectares.

Regression results are presented in Table 1 for analysis of the mean annual area deforested, total forest area in 1991, and area of forest regrowth in 1991 in each of the three columns, respectively. The sign and statistical significance of the coefficients associated with the percent of previously cleared area in intermediate secondary succession (SS2), pasture, and bare soils for each of the regressions conform to the expected pattern derived from the conceptual model discussed in Figure 1 of this paper.

In the regression on annual area of deforestation, the amount of forest at the beginning of the period is included as a control for assessing the relative importance of other variables in the analysis. As might be anticipated, having more area in forest is positively associated with larger annual areas of deforestation. Each additional hectare of forest cover is associated with a 0.05 hectare larger area of annual deforestation. This means that a farm with 20 more hectares of forest cover than a similar farm (e.g., with similar farm activities, distance from Altamira, and timing of settlement) would deforest approximately 1 hectare more each year. Controlling for total forest



Idrisi for Windows - Database Workshop

File Modify Query Link Help

Output map window: [NONE]

IDRISI DATABASE IMPORTED FROM ASCII

IDR ID	ErdasID	PID	x	y	roads	roads
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3	1120810	394	325358.7	9652202	325245	9652
4	1141050	395	324938.0	9652261	320169	9651
5	1100610	327	330761.4	9651871	330435	9652



Plate 2. Illustration of data extraction at property level, ID assignments in IDRISI for Windows for each property. 1991 Landsat TM image 5-4-3 composite of study area with grid overlay. Each property has a distinct identifier that permits data querying at the property level, as well as aggregate landscape analysis of changes in land cover. This study currently has ten dates, covering a period of 26 years to study changes in deforestation rates.

TABLE 1. REGRESSIONS ON ANNUAL AREA OF DEFORESTATION, 1988-91; TOTAL AREA IN FOREST, 1991; AND AREA OF FOREST REGROWTH IN 1991

Independent Variable	Area of	Area	Area
	Annual Deforestation (1988-91)	Forested (1991)	Regrowth (1991)
	Coef.	Coef.	Coef.
Forest Area in 1988	0.0543**		
Land-Cover Classes as % of Previously Deforested Area (Indicator of Farm Activities in 1988)		(Indicator of Farm Activities in 1991)	
% of Cleared Area (1988)		% of Cleared Area (1991)	
SS2	-0.0207*	-0.6266**	-0.0514**
Pasture	-0.0130	-0.8087**	-0.2093**
Bare Soil	0.0318**	-0.7786**	-0.3135**
Distance Measures to Altamira			
Km. to Altamira	0.8290*	-0.9458	
Km. Squared	-0.0258*	0.0452	
Km. Cubed	0.0002	-0.0003	
Timing of Settlement			
Pre-70	-0.5107	-4.7369*	1.4799**
Post-78	0.9846*	-1.5335	-1.8129**
Constant	-6.830	54.1239	11.4419**
Number of obs =	398	398	398
F =	18.40	32.49	25.67
Prob > F =	0.0000	0.0000	0.0000
R-squared =	0.2991	0.4006	0.2467
Adj R-squared =	0.2828	0.3882	0.2371
Root MSE =	1.762	13.486	3.7736

*Statistically significant at the 0.10

**Statistically significant at the 0.05

area, distance, and timing of settlement, compositional characteristics of land cover associated with farm activities are significantly also related to the annual area deforested. Percent area of previously cleared land in "bare soils" is significant and positively associated with increased rates of deforestation. The coefficient of 0.03 for percent area in bare soils indicates that a farm with 32 percent of its previously cleared area in bare soils might have one additional hectare of forest cleared each year compared to a farm with the same age and distance but no bare soil. A possible explanation is that annual crop production associated with bare soils is often associated with a pattern of rotating fields crops as soil fertility declines after a couple of years of use. Percent previously cleared area in intermediate secondary succession (i.e., about 6 to 11 meters in height [SS2]) is significantly and negatively associated with the area annually deforested. This is anticipated as families invest their labor efforts in perennial crop production. An additional reason for this association is that forest clearing is a difficult and costly activity; many farm families prefer clearing fallow for annual crops or for preparing pasture once they have a sufficient area in fallow for rotation. The coefficient of -0.02 suggests that farms with a larger share of previously deforested land in SS2 (e.g., 50 percent) would have lower annual areas of deforestation. The percent area previously deforested and now in pasture was not significant and as such has an intermediate association to annual deforestation *vis-à-vis* bare soils and secondary succession. This may be explained by the fact that farmers typically use annual crops as a first step after deforestation and subsequent pasture development.

The regression results indicate that farms with similar area in forest and similar composition in land-cover classes are more likely to have higher rates of deforestation the further they are from the major city in the area, Altamira. This is a counter-intuitive and intriguing result. Most scholars have taken for granted that the rate of deforestation will be greater when closer to towns and markets. Our results, though preliminary, suggest that there may be exceptions to this general pattern. Further empirical examination of the association is necessary. The coefficients associated with distance indicate a curvilinear rela-

tionship between distance and annual area deforested. These results are particularly strong. Among farms similar in other respects (e.g., composition of land-cover classes and timing of settlement), a farm 5 kilometers further out along a feeder road could be expected to have 3.5 hectares ($(5 \times 0.83) + (25 \times -0.026) + (125 \times 0.0002)$) more area deforested each year. Moreover, if the land was settled more recently, i.e., since 1978, the mean annual area deforested is approximately 1 hectare higher, controlling for other factors. The timing of settlement and length of agricultural activity on the farm lot suggest that farm development and consolidation play a role in reduced rates of forest clearing. These insights tend to be missed in a purely landscape analysis where there is considerable heterogeneity of farming systems.

These results for annual area of deforestation are paralleled in the regressions on forested area in 1991 and the area of forest regrowth with a few exceptions. Controlling for the timing of settlement and distance to Altamira, the percent area previously cleared in pasture and in bare soils are significant and negatively associated with both forest area and forest regrowth in 1991. That is, people that have a larger proportion of previously deforested area in pasture and annual crops relative to those with larger proportions in SS2 have less forest and less forest regrowth. Furthermore, both of these are similar in magnitude, suggesting that annual crop production and cattle grazing may play similar roles in the overall patterns of deforestation and afforestation, perhaps because the two are often associated with each other as steps in farm development. The interpretation of these results is that for each percent of previously cleared forest in pasture or bare soils there is an associated 0.8 hectare reduction in remaining forest. The coefficient for SS2 is significant and negative but smaller than those for pasture and bare soils as expected. Each percent of previously cleared area in SS2 is associated with -0.6 hectares of remaining forest. Use of fallow and perennial crop production associated with SS2 appears to play a reduced role in deforestation and afforestation when compared to the stronger and negative roles associated with bare soils and pasture. With these compositional characteristics of land cover controlled in analysis, distance to

Altamira plays no role in the overall pattern of deforestation and forest regrowth, while timing of settlement continues to play a significant role. Again, the age of the farm (based on timing of initial clearing) is significant and strong, and suggests that farm consolidation may be important to the overall level of deforestation and the pattern of forest regrowth. Farms that were settled early on, compared to other farms of similar land-class composition, have significantly less remaining forest (i.e., a difference on the order of 5 hectares) and more forest regrowth (i.e., a difference on the order of 1.5 hectares more) in 1991.

This exploratory analysis suggests that the land-cover classes at the property level can aid in our investigation of deforestation and afforestation. These results also suggest an important role for distance and age of farm. While these results are exploratory, they serve to illustrate the potential for investigating remotely sensed data at the property level.

More sophisticated use of remotely sensed data can be incorporated at the property level using GIS cross-tabulation methods to develop a transition matrix between different classes of land cover (Brondizio *et al.*, 1994). This involves the pixel-by-pixel comparison of changes between land-cover classes between images and can be useful in the development of land-cover trajectories for individual properties. In particular, it would be interesting to know how different combinations of land cover in bare soils, secondary succession, and pasture are associated with clearing forest versus fallow for cultivation of annual crops or formation of pastures. Comparison of multiple images through the use of a transition matrix at the property level will permit the development of trajectories of land cover associated with land-use strategies and farm development on the agricultural frontier. The conceptual model developed for this research suggests that households begin with clearing forest for annual cash crop production and subsequently shift to perennial crops and/or cattle grazing. Combined with land-use histories and socio-demographic data from household surveys, the relationship between land cover and land use can be advanced.

Conclusion

The preceding discussion and analysis is an initial exploration of the insights to be gained by combining remote sensing analysis with information at property scale in a GIS to make more explicit the dynamics of land-use and land-cover change. The underlying reasons for examining these landscape data at a property level is that, in addition to macro-level economic factors and environmental factors, individual households use their lands differently over time and space as a result of their shifting supply of labor within the household. Understanding these changing patterns may prove important in understanding and predicting future landscape change. It is anticipated that prediction based on landscape analysis will identify very different dynamics than those based on property-level analysis. Land-use patterns among individual households may be linked to external economic factors (e.g., credit, prices), to environmental characteristics (e.g., soils, topography, and water availability), and to distances to urban places and markets but may also be linked to internal dynamics of families (e.g., labor over the course of the domestic life-cycle). In future work, we plan to link data gathered from remote sensing at the property level with information on land use and households collected in sample surveys in order to study how the demography of families is related to agricultural strategies. More extensive use of the transition matrix approach at the property level (i.e., between specific land-cover classes) can provide a wealth of information about more complex use patterns practiced on farm properties. A look at each class-to-class transition between each date with our current coverage could have ($2 \times 2 \times 7 \times 7 \times 7$) possible cells. At a landscape level, it can be useful to understand overall trends in land-use/land-cover conver-

sion; at an individual property level, it may be useful for understanding different patterns of conversion among different types of farm families. We hope to pursue this analytical possibility in future investigations to develop typologies or trajectories of different agricultural strategies.

We anticipate that this investigation will permit much more refined and detailed information on different trajectories of land use by different types of households and how these are conditioned by, and interact with, economic and environmental variables. Linking land-use trajectories and households will permit extrapolation of findings to farm properties not surveyed which are characterized by similar land-use trajectories. This allows for predictions of land-use/land-cover change for the entire landscape.

The preceding analysis was based on a sub-set of our study area. In it we show how the use of property boundaries can aid in understanding patterns of deforestation. First, we were able to make use of the property grid visually to investigate unexpected results of our transition matrix at the landscape level. A large portion of the deforested area (i.e., in the range of 30 to 50 percent) in the region is converted, or degraded, to vegetation similar to advanced secondary succession. Visual analysis with the property grid indicates that this forest-to-advanced-secondary-succession conversion is not a widespread phenomenon, but is often property-specific. This suggests that the unanticipated conversion from forest to advanced secondary succession is probably not related to rainfall, reduced levels of ground water, or errors in classification methods. A much more likely scenario is that this large, area-specific conversion of forest is the result of either selective logging or unintentional spread of localized fires (see Sorrensen (1998) for a detailed assessment of similar nearby regions of Amazonia, and the importance of unintentional spread of fires in these unintentional conversions of land cover). The second contribution of the property grid to our analysis of remotely sensed data was the possibility of exploring how particular combinations of farm activities (e.g., annual crops, perennial crop production, and cattle grazing) are associated with the level and rates of deforestation and forest regrowth. This is a preliminary step in constructing land-cover trajectories associated with farms.

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